

IMPACTS OF IONIC STRENGTH ON FACILITATED TRANSPORT  
OF Cd BY KAOLINITE COLLOID IN SATURATED SAND COLUMN

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รักษ์เกียรติ วิภิญชารัตน์ : ผลกระทบของความเข้มข้นไอออนต่อการเคลื่อนที่ของแคดเมียมโดยมี  
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การวิจัยนี้ทำการศึกษาผลกระทบของความเข้มข้นไอออนต่อการเคลื่อนที่ของแคดเมียมโดยมีคอลลอยด์  
 ของดินขาวเป็นพาหะในคอลัมน์ทรายชุ่มน้ำ การทดลองการดูดซับแบบแบดจ์ถูกใช้เพื่อศึกษาไอโซเทอมการดูด  
 ซับแคดเมียมโดยใช้ดินขาวและทรายเป็นตัวดูดซับภายใต้ความเข้มข้นไอออนที่แตกต่างกัน (0.0 – 3.6  
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 (0.0 – 0.9 มิลลิโมลาร์) ผลการทดลองพบว่า การเพิ่มขึ้นของความเข้มข้นไอออน ลดค่าตัวประกอบความหน่วง  
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 อัตราส่วนนี้ลดลงเมื่อความเข้มข้นไอออนเพิ่มสูงขึ้น นอกจากนี้ปริมาณของแคดเมียมที่ถูกดูดซับบนคอลลอยด์  
 ของดินขาวที่ไหลออกจากคอลัมน์ลดลงจาก 0.15 มิลลิกรัม เหลือ 0.04 มิลลิกรัม เมื่อความเข้มข้นไอออน  
 เพิ่มขึ้นจาก 0.0 มิลลิโมลาร์ ถึง 0.9 มิลลิโมลาร์ และการปรากฏของคอลลอยด์ของดินขาวเพิ่มค่าตัวประกอบ  
 ความหน่วงของแคดเมียมจาก 3.61 เป็น 3.71, 3.16 เป็น 3.38 และ 2.23 เป็น 3.33 ภายใต้ความเข้มข้นไอออน  
 0.225, 0.45 และ 0.9 มิลลิโมลาร์ ตามลำดับ ในทางตรงกันข้ามคอลลอยด์ของดินขาวลดค่าตัวประกอบความหน่วง  
 ของแคดเมียมจาก 4.04 เหลือ 3.93 ภายใต้ความเข้มข้นไอออน 0.0 มิลลิโมลาร์ ดังนั้นคอลลอยด์ของดินขาว  
 สามารถส่งเสริมการเคลื่อนที่ของแคดเมียมภายใต้สภาวะที่ความเข้มข้นไอออนต่ำมาก แต่ในทางกลับกันเมื่อความ  
 เข้มข้นไอออนเพิ่มสูงขึ้นคอลลอยด์ของดินขาวมีแนวโน้มที่จะลดความสามารถในการเคลื่อนที่ของแคดเมียม

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This study investigated the impacts of ionic strength (IS) on co-transport of Cd and kaolinite colloid through water-saturated sand column. Batch equilibrium sorption experiments were conducted to obtain the sorption isotherms of kaolinite clay and sand under different IS of  $\text{CaCl}_2$  (0.0 – 3.6 mM). The results displayed that Cd sorption by kaolinite clay and sand was nonlinear and fitted with Freundlich model. Column experiments were performed under different IS of  $\text{CaCl}_2$  (0.0 – 0.9mM) using 10 ppm of Cd without kaolinite colloid and 10 ppm Cd mixed with 100 ppm kaolinite colloid. According to column test, the results showed that the increase in IS reduced retardation factors of both Cd and Cd mixed with kaolinite colloid. In addition, the relative concentration ( $C_i/C_0$ ) of Cd-bearing kaolinite colloid in the column effluent was not higher than 0.25 under IS of 0.0 mM, and this relative concentration ( $C_i/C_0$ ) of Cd-bearing kaolinite colloid decreased as increasing in IS. Futhurmore, the amount of Cd-facilitated kaolinite colloid in the column effluent (Cd sorbed onto kaolinite colloid) decreased from 0.15 mg to 0.04 mg with increasing IS from 0.0 to 0.9 mM. The presence of kaolinite colloid increased the retardation factors of Cd from 3.46 to 3.71, 3.16 to 3.38 and 2.23 to 3.33 under IS of 0.225, 0.45 and 0.9 mM., respectively; on the other hand, kaolinite colloid decreased the retardation factor of Cd from 4.04 to 3.93 under 0.0 mM. Hence, kaolinite colloid can increase Cd mobility under extremely low IS condition; on the contrary, kaolinite colloid tends to decrease Cd mobility at high IS.

Field of Study: Environmental Management Student's Signature.....

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Co-advisor's Signature.....

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**LIST OF ABBREVIATIONS**

$Q_e$	Amount sorbed (mg/g),
$C_e$	Concentration at equilibrium (mg/L)
$C_0$	Initial concentration (mg/L)
$Q_m$	The maximum amount of sorbed metal ion per mass of sorbent (mg/g)
$K_L$	The Langmuir constant (L/mg)
$K_F$	The Freundlich constant (L/mg)
$n$	Freundlich equation exponent (-)
$v$	Volume (L)
$m$	Mass (g)
$C_i$	Concentration in the effluent (mg/L)
$PV$	The number of pore volume (-)



# CHAPTER I

## INTRODUCTION

### 1.1 Rationale

Contamination of groundwater and soil caused by mobilization and transport of inorganic, organic and biological contaminants are released from many sources like spillage, waste disposal sites and land application is a well known problem. The occurrence and movement of contaminants also establish a possible threat to human health and ecosystems (Sen et al., 2004). Moreover, there are many reasons why heavy metals contaminate the soils and eventually leach into groundwater; for example, impact of acid rain (Edmunds et al., 1992), ore mining (Brown et al., 1998), and dispersion and deposition from smelters (Wilkins and Loch, 1997). Especially, soil, surface water and groundwater in several sites of mining and smelting have been contaminated with heavy metals (McGowen and Basta, 2001).

Colloidal particles have surface charge, and they are generally smaller than inter-granular pores and fractures in rock; therefore, they can transport with long distance via groundwater flow (Sen et al., 2004). Transport of soil colloids in subsurface environment potentially enhance the migration by adsorbing onto colloids (McCarthy and McKay, 2004). In addition, the colloidal particles might be significant in facilitating transport of the contaminants strongly sorbed onto their surface and the contaminants may be cations (i.e.,  $\text{Cu}^{2+}$ ,  $\text{Cs}^{2+}$  and  $\text{Cd}^{2+}$ ), anions and nonpolar and polar organic compound; moreover, the cationic metals are the most usually found influenced by “colloid-facilitated transport” (Kersting et al., 1999; Sen et al., 2002) since cationic forms of metals have a great tendency to sorb to soil colloids such as clay minerals which can act as a carrier for contaminant (Bradl, 2004; Sen et al., 2004; Usman et al., 2005). Heavy metals adsorb to colloids in a similar mechanism as they do to the immobile solid phase and can transport in subsurface media at rate similar to or greater than the mobile aqueous phase (McGechan and Lewis, 2002). Saiers and Hornverger (1996) found kaolinite colloid enhances Cs migration in a

packed sand column. Noell et al. (1996) found that amorphous silica colloid increase Cs transport through glass bead columns.

However, in natural porous media, colloidal particles are commonly fixed during usual water flow and electrolyte conditions. Although they may release into the aqueous phase and be transported through the porous medium, as the electrostatic repulsion between particles is also increased because of lowering the ionic strength (IS) (Roy and Dzombak, 1996). Nowadays, there are many articles have been published about colloid transport and there are many articles have been published to address contaminant transport.

Over the last ten years, colloids from mine wastes and soils have attracted an interest because of their high affinity to heavy metals and risks to human health (Hu et al., 2008) but there are a few studies about the transport and fate of natural colloids (Zhou et al., 2011), the influence of colloids to the transport of heavy metals in groundwater, and the effects of IS on co-transport of colloids and heavy metals like kaolinite and Cd (II). Failure to estimate the mobility of contaminants may result in wrong predictions of concentration and arrival time. The understanding of colloid-facilitated transport is necessary for predicting the transport of heavy metals in groundwater system.

Therefore, in this study, we investigated the influence of IS and kaolinite on the sorption and migration of Cd in saturated quartz sand both in batch and column experiments.

## **1.2 Objectives**

- To evaluate the effects of solution IS on the co-transport of Cd with kaolinite colloid in saturated sand column.
- To investigate the effects of mobile kaolinite colloid on the Cd transport in the water-saturated sand column.

### **1.3 Hypothesis**

The hypothesis of this research is that the presence of kaolinite colloid and the solution IS will retard the Cd transport through the saturated sand column because of the retention of kaolinite colloid in the saturated sand, and the sorption capacity of Cd onto kaolinite colloid.

### **1.4 Methodology**

This study is divided into 3 parts:

1. Chemical properties of kaolinite clay and sand which were used in this experiment were analyzed by using X-ray diffraction (XRD) and X-ray fluorescent (XRF) to obtain chemical properties.
2. Batch sorption experiments were conducted to estimate the equilibrium time of Cd sorption and sorption parameters for various IS conditions on sorption of Cd onto kaolinite clay and sand.
3. Column experiments were conducted to study the effect of solution IS and the presence of kaolinite colloid in sand column saturated with water.

### **1.5 Research Assumption**

This research was assumed that Cd leaked from the mining site where kaolinite colloid was generally found and transport through the unconfined aquifer under acidic condition.

## **1.6 Organization of report**

The report is organized into five chapters. The first chapter is the Introduction. The second chapter is the Literature review. Moreover, the third chapter is the Materials and Methods, and the fourth chapter describing the effect of solution IS on Cd sorption onto kaolinite clay and sand, and the effect of IS and kaolinite colloid on Cd transport in the saturated sand column. The impact of IS on facilitated transport of Cd by kaolinite colloid in saturated sand column was described in this chapter. The last chapter is the general conclusions and recommendation.

## **CHAPTER II**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

One of serious pollutants in water, especially in waste water is heavy metals which have become a public health concern because it is non-biodegradable and persistent (Jiang et al., 2010). Heavy metals have been introduced to aquatic system by human activities in many ways. For instance, heavy metals exist widely in the industrial effluents such as from metallurgy and mining areas (Kabata-Pendias and Pendia, 2001). Heavy metals tend to accumulate in organisms and can cause various disorders and diseases (Kwon et al., 2010). Heavy metals are elements which have a specific gravity at least 5 times of specific gravity of water; for instance, the specific gravity of cadmium (Cd) and lead (Pb) is 8.65 and 11.34 respectively (Lide, 1992). Heavy metals can cause adverse health effects, but some heavy metals are commonly necessary in environment and food in small amount of them. The toxicity of heavy metals is that the mental and central nervous function are reduced or damaged and blood composition, lungs liver, kidneys and other organs are damaged. For long term exposure, the effects of heavy metals can be slowly progressing physical, muscular, and neurological degenerative processes that mimic Alzheimer's disease, Parkinson's disease, muscular dystrophy and multiple sclerosis. Moreover, long-term contact with some metals or their compounds may cause cancer (International Occupational Safety and Health Information Centre 1999). When heavy metals which can not be metabolized and accumulate in the tissues, they become a toxic. Humans can contact heavy metals in many ways such as eating, drinking and absorption through the skin (Roberts 1999).

## 2.2 Cadmium (Cd)

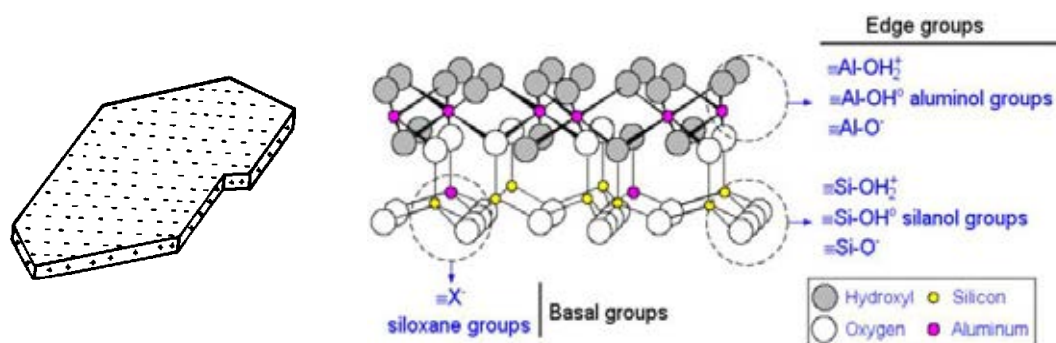
Cd is one of the most toxic and commonly presents in contaminated environments (Srivastava and Singh, 2010). WHO's Guidelines for Drinking-water Quality point out standard setting and drinking-water safety for Cd. The concentration of Cd in drinking water should not be higher than 0.003 mg/L (WHO, 1993). Cd occurs naturally in the earth's crust, especially in lead zinc and copper bearing ores (Forstner and Whittmann, 1981). Moreover, it may come from human activities such as metal planting, smelting and mining industries, cadmium-nickel battery manufacturing, paints and pigments and alloy industries (Kadirvelu and Namasivayam, 2003). In addition, Cd may come from phosphatic fertilizers in crop production, which is the major source of Cd in agricultural soils (Syers and Cisse, 2000). Pure Cd is a metal with soft silver-white color, but it is hardly found naturally in pure form. Cd can cause many symptoms like vomiting, nausea and many diseases such as lung disease, renal disease, and fragile bones (Roberts, 1999).

## 2.3 Kaolinite

Clays play a key role in the environment by acting like a scavenger of pollutants through adsorption or ion exchange (Bhattacharyya and Gupta, 2008). The natural clay adsorbent like kaolinite drew much attention on sorption of heavy metals from contaminated water because its cost is lower than another process like solvent extraction or electrolytic process (Bhattacharyya and Gupta, 2008). There are many studies about adsorption of heavy metals onto kaolinite colloid.

Kaolinite is a 1:1 non-swelling clay mineral which is predominant in tropical weathered soils and can exist as mobile or immobile colloid (Kaplan et al., 1995). Kaolinite is generally used in many industries; for example, the paper industry used kaolin for its high whiteness and low abrasion and kaolin is also used in construction, ceramics, rubber and porcelain manufacturing (Vaculikova et al., 2011). The empirical formula for kaolinite is  $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$  and the theoretical chemical composition is  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{H}_2\text{O}$  accounted for 46.54%, 39.50% and 13.96%, respectively (Vaculikova et al., 2011). One 0.72 nm thick layer of kaolinite is

composed of one silica tetrahedral sheet and one alumina octahedral sheet and the mineral is considered to be crystalline when many layers of kaolinite are hydrogen bonded together (Bohn et al., 1985; Yong and Sheremata, 1992). Kaolinite has a heterogeneous surface charge, and there are many researchers believed that the basal siloxane surfaces of kaolinite carry a constant structural charge because of isomorphous substitution of  $\text{Si}^{4+}$  by  $\text{Al}^{3+}$ ; on the other hand, the charge locating on the edges is because of the protonation and deprotonation of exposed hydroxyl groups (Ma and Eggleton, 1999). The surface charge of kaolinite particle is globally negative charge which is commonly located on the basal plane (figure 2.1); in contrast, the positive charges are located on the edge of kaolinite surface (Nabzar, 1985). The zero point of charge of kaolinite determined by the titration method, usually presents around pH 3 (Coles and Yong, 2002). In 2005, Srivastava et al. reported that the permanent negative charge is generated due to the isomorphous replacement of  $\text{Si}^{4+}$  by  $\text{Al}^{3+}$  in the silica tetrahedral sheet or of trivalent metal ions by divalent ions in the alumina octahedral sheet. The alumina octahedral sheet and the crystal edges have a pH-dependent variable charge depended on protonation and deprotonation of hydroxyl groups located on the surface (White et al., 2000).



**Figure 2.1** – Structure and proposed charged of kaolinite clay (Gu and Evans, 2008)

## 2.4 Sorption of Heavy Metals onto Kaolinite

The surface of kaolinite is expected to have two mechanisms of binding sites which could bind metal ions (Srivastava et al., 2005). Schindler et al. (1987) proposed that constant-capacitance model assuming two kinds of binding sites could describe the binding of Cu, Cd and Pb onto kaolinite. The first adsorption site involves the inner-sphere bind to ampholytic surface hydroxyl groups; on the other hand, the second adsorption site is ion exchange. The study of Angove et al. (1997; 1998) supported this view. They have tested possible surface reaction of metal ions sorbed onto kaolinite by applying a surface complexation model to adsorption data obtained from three kinds of experiments. The results showed that there are two different processes governing the Cd(II) adsorbs onto kaolinite. The first one is ion exchange on the siloxane surface and the second one is complexation to silinol and alumina groups occurring at the crystal edges. Moreover, Angove et al. (1998) have studied the adsorption of  $\text{Cd}^{2+}$  and  $\text{Co}^{2+}$  onto kaolin. Their results showed two different kinds of adsorption operate depending on the pH. At low pH, the metal ions were adsorbed by ion exchange at permanently charged sites on the siloxane surfaces. At high pH,  $\text{Cd}^{2+}$  and  $\text{Co}^{2+}$  adsorb to spaced variable charge groups at the crystal edges with the formation of inner sphere complexes.

In 2005, Srivastava et al. have also studied the adsorption behavior of divalent metals which is Cd, Cu, Pb and Zn that commonly occur in contaminated soils (Naidu et al., 1998). They have examined the adsorption of Cd, Cu, Pb and Zn onto kaolinite in single and multi-element systems. They reported the results of aqueous speciation of Cd as a pH function using the computer program Visual MINTEQ, Version 2.30 (Gustafsson, 2004) that Cd presents predominantly as  $\text{Cd}^{2+}$  species over the pH range (3.5 – 10.0) studied in single and multi-systems and the concentration of Cd species is very low. Moreover, they found that the adsorption of Cd onto kaolinite increased as increasing pH which was varied from 3.5 to 10.0. In addition, Cd ions sorbed onto permanent negative charged sites by ionic exchange reaction at low pH; on the other hand, at high pH Cd sorbed onto crystal edge by forming inner-sphere complexes.



Jiang et al. (2009) have studied the effects of contact time adsorption of Cd, Pb, Ni and Cu to kaolinite clay adsorbent at various time intervals and they reported that the equilibrium adsorption was established within 30 minutes. The results showed that the initial adsorption was very rapid and maximum adsorption was reached within 30 minutes for Pd, Cd, Ni and Cu. They had also studied the effect of IS on the adsorption of Pb, Cd, Ni and Cu onto the kaolinite clay and they found that the adsorption capacities of kaolinite clay decreased with increasing IS of solutions because of ion competition between metal ions and cations for vacant sites.

The study of Shahmohammadi-Kalalagh et al. in 2011 investigated the feasibility of kaolinite used for the removal of Pb(II), Cu(II) and Zn(II) from solution at pH 4.5. They reported that the time of getting equilibrium depends on the initial concentration of metal; for example, the higher initial concentration will have the longer equilibrium time. Besides, they evaluated the sorption capacity of kaolinite using four equilibrium isotherm models which are Freundlich, Langmuir, Temkin and Redlich-Peterson isotherm models and analyzed the sorption dynamics by using pseudo first order and pseudo second order kinetic models. The results of evaluating the correlation coefficients from the isotherm equations using two-way ANOVA at  $p < 0.05$  represented that Redlich-Peterson isotherm described the data suitable than the others, and the adsorption data of metal ions onto kaolinite indicated that the pseudo second order model was more appropriate than the pseudo first order model.

Besides, Gu and Evans (2008) have studied the surface complexation of  $\text{Cd}^{2+}$  adsorption onto kaolinite under different pH and IS. They reported that under lower pH range ( $\leq 6$ )  $\text{Cd}^{2+}$  were bound through ionic exchange reaction and formed outer-sphere complex on basal surface sites (siloxane groups); in addition, IS had strong effects on ionic exchange reaction under lower pH value. Taqvi et al. (2007) have studied the sorption of Cd(II) onto beach sand composed of calcite 70%, quartz 26% and aragonite 3%. They proposed the possible sorption mechanism for Cd(II) onto beach sand that the negative charge in the structure of calcite, quartz and aragonite in the form of oxides and carbonates cause affinity for Cd(II) ions by the electrostatic attractive force between positively charged Cd(II) and negatively charged of the sand.

## 2.4.1 Sorption Isotherms

### 2.4.1.1 Langmuir sorption isotherm

Langmuir model is the equation which is based on adsorption of metal ion on a homogeneity surface with no interaction between sorbed ions (Langmuir, 1918). The equation may be represented as

$$Q_e = \frac{Q_m K_L C_e}{1 + K_L C_e} \quad (1)$$

Langmuir equation can be rearranged to linear form as

$$\frac{C_e}{Q_e} = \frac{1}{Q_m K_L} + \frac{C_e}{Q_m} \quad (2)$$

Where,  $Q_e$  is the amount sorbed (mg/g),  $C_e$  is the concentration of metal ion at equilibrium (mg/L),  $Q_m$  is the maximum amount of sorbed metal ion per mass of sorbent (mg/g),  $K_L$  is the Langmuir constant (L/mg).

### 2.4.1.2 Freundlich sorption isotherm

Freundlich equation is the equation which is based on adsorption on heterogeneous surface (Freundlich, 1906). The equation is represented as follows

$$Q_e = K_F C_e^{\frac{1}{n}} \quad (3)$$

Where,  $C_e$  is equilibrium concentration of solution (mg/L),  $Q_e$  is the amount sorbed metal per mass of adsorbent (mg/g),  $n$  is Freundlich equation exponent, and  $K_F$  is the Freundlich constant (L/mg).

This equation can be expressed in linear form as

$$\log(Q_e) = \log(K_F) + \frac{1}{n} \log(C_e) \quad (4)$$

## 2.5 Column Transport Studies

For a long time, soil columns have been used to determine the transport models in order to monitor the fate and mobility of contaminants in soil (Jin et al., 1997; Hrapovic et al., 2005; Dontsova et al., 2006). Moreover, soil columns have been used in a theoretical framework for elaborating the transport of synthesis model colloids such as amorphous silica colloids (Elimelech et al., 2000), latex microsphere (Bradford et al., 2002; Tufenkji and Elimelech, 2005), and ceramic microspheres (Li et al., 2006) in model systems like quartz sand (Torkzaban et al., 2008) and glass beads (Bradford et al., 2002).

## 2.6 Colloid Transport

Colloids are ubiquitous in subsurface environment (Sen et al., 2004), and the natural concentration of colloidal particles in groundwater is from  $10^8$  to  $10^{17}$  particles per a liter (Kim, 1991). Most natural porous media such as aquifer materials contain some colloidal particles stuck onto the surfaces of bigger immobile particles or that are in flocculated state (Roy and Dzombak, 1996). Colloids are generally considered to be particles with approximate 10 nm to 10  $\mu$ m in diameter (DeNovio et al., 2004) including rock and mineral fragments, mineral precipitates, microorganisms and plant decay debris (Posadas et al., 2001). Concentration of colloid commonly found in natural subsurface environments varied from 35 to 100 mg/L (Zhuang et al., 2003)

There are many researchers who have studies about the factors that have effects on transport of organic and inorganic colloids such as pH (Ryan and Elimelech, 1996; Grolimund et al., 1998), IS (Ryan and Elimelech, 1996; Grolimund et al., 1998; Walshe et al., 2010) and ionic composition (Israelachvili, 1992; Elimelech et al., 1995). The IS and ionic composition are known to have a large influence on the transport behavior to colloids associated with contaminants. The concentration of monovalent cations and divalent cations is generally 1 – 10 mM and 0.1 – 2 mM respectively (Atekwana, 2004). For instance, Chang and Saiers (2010) reported that the capacity of sediment-colloids to bind  $^{137}\text{Cs}$  decreased with increasing IS, leading to a decrease of the mass of  $^{137}\text{Cs}$  released from columns packed with

Hanford coarse sand. Besides, Grolimund et al (1998) found that lower pH or higher IS of bulk solutions can increase deposition of colloids due to reducing of repulsive surface interaction energies between colloids and media, and colloids and colloids. Ryan and Elimelech (1996); moreover, reported that the deposition of colloid reduce when IS is decreased or pH is increase because of increased electrostatic repulsion and an increase in the double layer thickness. Israelachvili (1992) and Elimelech et al. (1995) reported that monovalent ions have lower effects on of colloidal transport in the medium. Walshe et al. (2010) found that increasing the IS of the solution reduces peck concentrations for both kaolinite and kaolinite-facilitated MS2 coliphage from columns composed of gravel aquifer media. In recent years nanoscale colloids like carbon nanotubes (Zhang et al., 2011), TiO<sub>2</sub> (Fang et al., 2011) and hydroxyapatite nanoparticles (Wang et al., 2011) has been attracted attention by the conception of colloid-facilitated contaminant transport in subsurface environment. Wang et al. (2011) reported the effects of ionic composition and IS on facilitated transport of Cu with hydroxyapatite nanoparticles (nHAP) that the amount of nHAP retained in the sand column increased with increasing solution concentration of NaCl and especially CaCl<sub>2</sub>.

Moreover, several researchers have examined the deposition kinetics or mechanisms of colloidal transport (Lenhart and saiers, 2003; Akbour et al., 2002; Tosco et al., 2009). Akbour et al. (2002) have studied the influence of humic acid concentration on colloids transport in pure quartz sand packed column saturated with water. They have also studied the effects of several parameters like trace metal (Cu<sup>2+</sup>, Pb<sup>2+</sup>), Ca<sup>2+</sup> and pore water velocity on the deposition kinetics of kaolinite colloids coated with humic acid in the same porous medium. They reported that the adsorption of humic acid on the kaolinite surface triggers to the increase of its mobility through the porous medium; in addition, the deposition rate of humic-coated kaolinite colloids increase as divalent metal ion concentration increases and the colloid deposition rate depend on the nature of the divalent ion.

## 2.7 Colloid-Facilitated Transport

Colloid particles might facilitate or retard the transport of contaminants; however, Ryan and Elimelech (1996) emphasized that a significant criterion for the transport of colloid associated with colloidal particles is that colloid particle must be stable and colloidal particle must be occurred in enough amount to adsorb a significant amount of the contaminant. Sources of colloidal particles in subsurface environment are naturally present and direct introduction of colloidal particles into the subsurface zone through waste management storages (i.e., landfill and septic tank) (Krestschmar et al., 1999; Sen et al., 2002). Many studies have examined the colloid-facilitated transport of strongly sorbed contaminants in soils and groundwater (Eichholz et al., 1982; McCarthy and Zachara, 1989) and discovered that colloid acts as a carrier for transporting contaminants in subsurface media. The study of Ibaraki and Sudicky (1995) published a paper in which they introduced the difference between true colloids and pseudo-colloids. They found that true colloids are originated from contaminants like radionuclides precipitated when their concentration exceeds their solubility and pseudo-colloids generated from non-contaminant sources; for example, clay particles, which become contaminants because of sorption of pollutants onto their surface. In addition, Sen et al. (2004) mentioned that previous studies have considered soil or groundwater as importantly a two-phase system of contaminants transport in subsurface environment. A two-phase system is a mobile liquid phase and immobile solid phase where the contaminants could partition between. Colloid gave rise to the three-phase model of species transport which is mobile aqueous phase, mobile colloidal phase and the immobile solid phase. Nevertheless, Kretschmar et al. (1999) mentioned in their review article that little field research provides evidence for colloid-facilitated transport of contaminants. Zhou et al. (2011) also mentioned that there are a few studies about the transport and fate of natural colloids, so they studied the effects of transient pH and ISs on the transport and re-entrainment of soil colloids in saturated quartz sand packed column.

There are some research studied about effects of mobile kaolinite colloid on heavy metals transport; for example, Sun et al. (2010) have examined the effects of kaolinite on the transport of Pb in saturated porous media by using column experiments. They reported the results of comparison of Pb and kaolinite transport in the column that the transport of kaolinite was much faster than that of Pb. The delayed Pb transport indicates that Pb had strongly interaction with the medium in the column. Moreover, they have compared Pb in the saturated sand column to kaolinite-Pb complex and the latter displayed a far faster breakthrough, moreover sorbed Pb from surface media can be scavenged by mobile kaolinite which confirmed that kaolinite or natural colloids can be a carrier to increase the mobility of Pb.

## CHAPTER III

### Materials and Methods

#### 3.1 Materials

Kaolinite clay purchased from Fisher Chemical was analyzed by X-ray diffraction (XRD) (Bruker AXS, Germany) to analyze the mineral composition, and kaolinite clay's chemical composition was measured and displayed in the compound of oxide using the X-ray fluorescence (XRF) (Bruker AXS, Germany). On the other hand, only the sand's chemical composition was analyzed using XRD. The Cd solution was prepared by dissolving  $\text{Cd}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}(\text{s})$  in ultrapure water to get 1000 ppm Cd solution.  $\text{HNO}_3$  and  $\text{NaOH}$  were used to adjust pH of solution.

The sand (Fisher Chemical) which was 0.6 mm. – 0.8 mm. in grain size diameter was cleaned by 0.01 M  $\text{NaOH}$  and 0.01 M  $\text{HNO}_3$  respectively before use in the other experiments to get rid of metal oxide and sorbed particles on the sand surface; on the other hand, kaolinite clay did not require pre-treatment by chemical or physical processes before use.

##### 3.1.1 Preparing the sand

The sand was cleansed by the procedure described by Zhou et al. (2011). The first step is that sand was ultrasonicated in 0.01 M  $\text{NaOH}$  solution for 30 minutes, and rinsed with ultrapure water. Next the sand was ultrasonicated in 0.01 M  $\text{HNO}_3$  solution for 30 minutes, and rinsed with ultrapure water. After that it was dried in a hot air oven at 105 °C over night. Finally, the cleansed sand was stored in plastic contained with silica gel inside.

##### 3.1.2 Preparing kaolinite colloid suspension

Kaolinite clay 0.25 g. and 500 mL. of ultrapure water were added into the 500 mL. volumetric flask. The suspension was shaken and then placed in an ultrasonic bath for 30 minutes. After that the suspension was left to stand for 24 hours. After 24 hours, an upper half of suspension was siphoned into a new container.

The concentration of kaolinite colloid was determined before diluting the solution to 250 mg/L. The evaporating dish was heated at about 550 °C for 1 hour and cooled in oven for 15 – 20 minutes. After that the evaporation dish was brought in a desiccator and weighted until a constant weight was achieved. Next, 50 mL. of kaolinite colloid suspension was added into the evaporating dish and evaporated in hot air oven at 100 °C over night then the evaporating dish was cooled in the desiccator after that weighted and re-weighted to achieve a constant weight.

### **3.1.3 Cd-bearing kaolinite suspension**

Two hundred mL. of 250 mg/L. kaolinite colloid suspension and 5 mL. of 1000 ppm Cd solution were added into the 500 mL. volumetric flask. and ultrasonicated for 1 minute. After that the solution IS of suspension was adjusted. The final volume was 500 mL. and the concentrations of Cd and kaolinite colloid were 10 ppm. and 100 ppm, respectively.

Besides, Cd-bearing kaolinite colloid suspensions were measured size and surface charge of kaolinite colloid using Zetasizer nano (Malvern) before performing the transport test.

## **3.2 Batch sorption experiments**

### **3.2.1 Effects of contact time to Cd sorption onto kaolinite clay and sand**

Batch sorption experiments of Cd onto kaolinite clay and sand was conducted under acidic condition which was initial pH value of 5.6 to estimate time for reaching equilibrium. Batch adsorption experiment was performed according to Jiang et al. (2009).

Twenty mL. of 10 ppm. Cd solution, and 0.5 g. of kaolinite clay or 1.0 g. of sand were added into capped polypropylene bottles. After that the suspensions were agitated at 200 rpm. The contact times were varying from 0.5 minutes to 1440 minutes (0.5, 1, 2, 3, 4, 5, 10, 20, 30, 45, 60, 120, 180, 360, 1080 and 1440 minutes). Next the suspensions were centrifuged at 9000 rpm for 10 minutes and filtered



through a 0.22  $\mu\text{m}$ . PTFE syringe filter. Finally, the filtered solutions were measured concentration of Cd using Atomic Absorption Spectrophotometer (AAS) (Perkin Elmer, USA). The amount of Cd sorbed by kaolinite clay and sand was determined by using the following equation

$$Q_e = \frac{v(C_0 - C_e)}{m} \quad (5)$$

Where  $Q_e$  is concentration of Cd on the kaolinite (mg/g) at equilibrium,  $C_0$  is initial concentration of Cd(II) (mg/L),  $C_e$  is Cd concentration in aqueous at equilibrium (mg/L).  $v$  is volume of Cd solution (L), and  $m$  is mass of kaolinite clay (g)

### 3.2.2 Effects of solution IS to Cd sorption onto kaolinite clay and sand

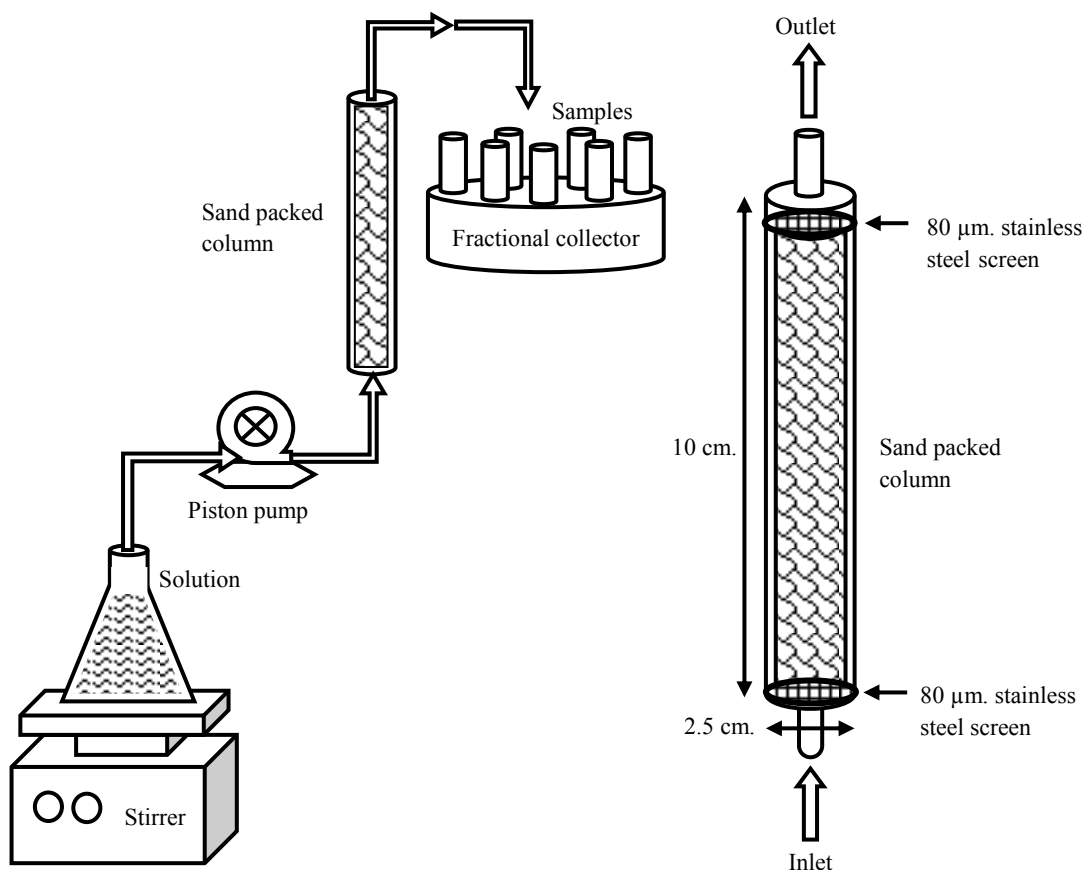
The effect of initial concentration of Cd and solution IS to Cd sorption onto kaolinite and sand was investigated under acidic condition which was initial pH value of  $5.60 \pm 0.02$ . The concentration of Cd solutions varied from 10 to 150 ppm. and the solution IS of each different concentrations was adjusted from 0.0 to 3.6 mM. (0.0, 0.9, 1.8, 2.7 and 3.6 mM) by adding  $\text{CaCl}_2$

Twenty mL. of varying concentration of Cd solutions (10, 27.5, 45, 62.5, 80, 97.5, 115, 132.5 and 150 ppm.), and 0.5 g. of kaolinite clay or 1.0 g. of sand were added into capped polypropylene bottles and agitated at 200 rpm for reaching equilibrium time obtained from batch sorption experiment: effects of contact time. After that the suspensions were centrifuged at 9000 rpm for 10 minutes and filtered through a 0.22  $\mu\text{m}$ . PTFE syringe filter. Lastly, concentration of Cd in solutions was measured using AAS. In addition, Freundlich and Langmiur isotherm models were applied to the sorption isotherm.

### 3.3 Column transport experiments

#### 3.3.1 Column set up

An acrylic column was 2.50 cm in inner diameter and 10.00 cm in length. The influent was pumped at the bottom end of column. Before conducting the experiment, column was cleansed by 0.01 M NaOH and 0.01 M HNO<sub>3</sub>. The column was packed with sand, typical quartz sand with an approximate effective porosity and bulk density of 0.32 and 1.51 g/cm<sup>3</sup> respectively. The flow rate of the influent was set approximately 0.154 ml/min. The effluent was collected using a fractional collector. Bromide was used as tracer in column experiments.



**Figure 3.1** - A schematic figure of saturated sand packed column

### **3.3.2 Effects of solution IS to Cd transport in saturated sand column**

Prior to use the packed was equilibrated by flushing several pore volumes of ultra pure water and at least five pore volumes of background solution with a fixed pH value of  $5.60 \pm 0.02$  to standardize chemical conditions and establish steady state flow. After that Cd solution which had the same solution IS as the background solution was pumped into the column upward via piston pump at a constant flow rate of influent (0.154 ml/min) for thirteen pore volumes. Then several pore volumes of background solution with the same pH and IS were applied into the column to make sure that there has no Cd in the outflow. The effluent was collected in tubes at regular time interval using a fractional collector. The concentration of Cd in each sample was measured using AAS. The breakthrough curves (BTC) were represented as the relative pore volume ( $V/V_0$ ) and concentration ( $C_i/C_0$ ).

### **3.3.3 Effects of solution IS to facilitated transport of Cd by kaolinite colloid in saturated sand column**

Prior to use the packed column, it was equilibrated by flushing several pore volumes of ultrapure water and at least five pore volumes of kaolinite colloid-free background solution with a fixed pH value of  $5.60 \pm 0.02$  was used to flush the column to establish steady state flow and standardize the chemical conditions. After that Cd-bearing kaolinite suspension solution which was adjusted solution IS was stirred while pumped into the column upward via piston pump at a constant flow rate (0.154 ml/min) for about thirteen pore volumes. After finishing this step, several pore volumes of kaolinite colloid-free background solution with the same pH and IS as Cd bearing kaolinite suspension solution was introduced into the column to make sure that there has no kaolinite colloid in the outflow. The effluent was collected in tubes at regular time interval using a fractional collector.

After finishing the co-transport experiment with 0.9 mM of solution IS, the sand excavated from the inlet was determined mechanism of Cd bearing kaolinite colloid retention in the sand column using Scanning Electron Microscopoe-Energy Dispersive X-ray (SEM-EDX) (JEOL, JSM-6400).

The concentration of Cd in each sample was measured using AAS. Furthermore, concentration of kaolinite colloid in the samples was measured using UV/vis spectrophotometer (Thermo Spectronic, England) at wavelength of 350 nm. (Sun et al., 2010; Zhu et al., 2012). A calibration curve was established by diluting 250 ppm kaolinite colloid suspension. The breakthrough curves of Cd and kaolinite colloid were plotted.

### **3.3.3.1 Concentrations of total Cd, dissolved Cd and kaolinite-facilitated Cd**

After measuring the concentration of kaolinite colloid the sample was separated into two sets. The first set was for measuring concentration of dissolved Cd in the solution and the other was for measuring concentration of total Cd in the solution.

#### *Concentration of dissolved Cd*

The sample was filtered through a 0.22  $\mu\text{m}$ . PTFE syringe filter to get rid off kaolinite colloid and the concentration of dissolved Cd was measuring using AAS.

#### *Concentration of Total Cd*

The sample was added 14.5 M  $\text{HNO}_3$  to digest kaolinite colloid in the solution after that the concentration of total Cd was measuring using AAS.

#### *Concentration of kaolinite-facilitated Cd*

Concentration of kaolinite-facilitated Cd is a concentration of Cd sorbed onto kaolinite colloid. The concentration of kaolinite-facilitated Cd was calculated from the difference between concentrations of total Cd and dissolved Cd.

### 3.3.3.2 Area method

The retardation factors of Cd onto sand were determined by area method (Nkedi-Kizza et al., 1987). The equation for calculating the retardation factor was expressed as:

$$R_{area} = PV_i - \sum_{i=0}^{PV_i} (C/C_0) \Delta PV \quad (6)$$

Where  $C$  is the concentration of Cd in the effluent,  $C_0$  is the concentration of Cd in the influent, and  $PV_i$  is the number of pore volume at the relative concentration of Cd is 1.0.

## CHAPTER IV

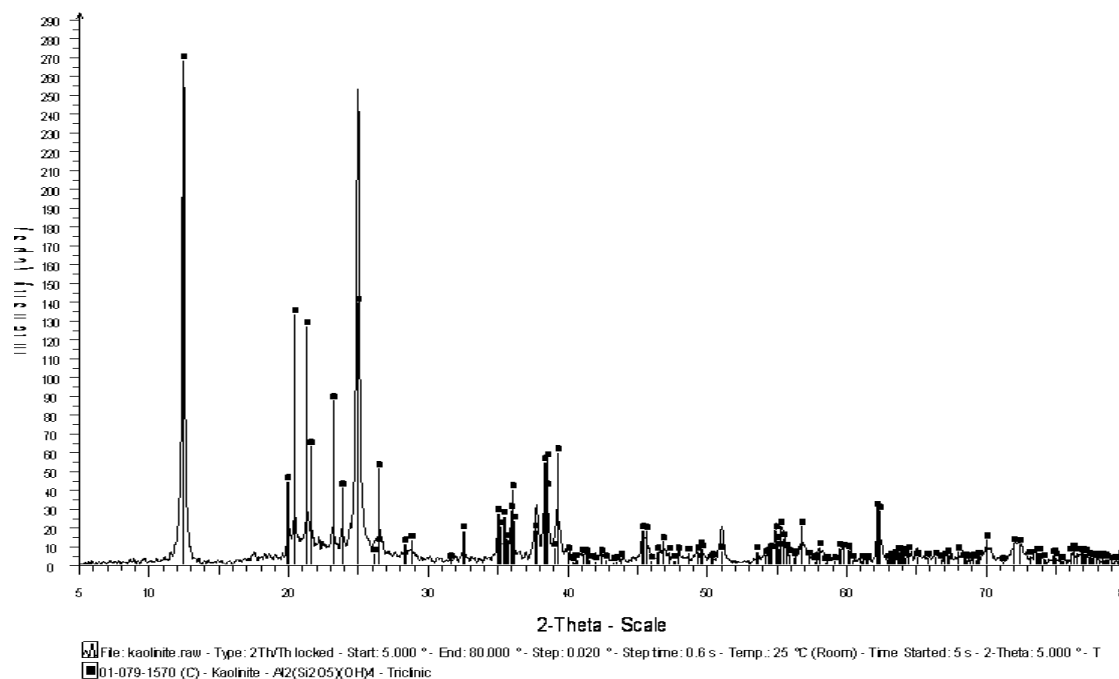
### RESULTS AND DISCUSSION

#### 4.1 Chemical properties of kaolinite clay and sand

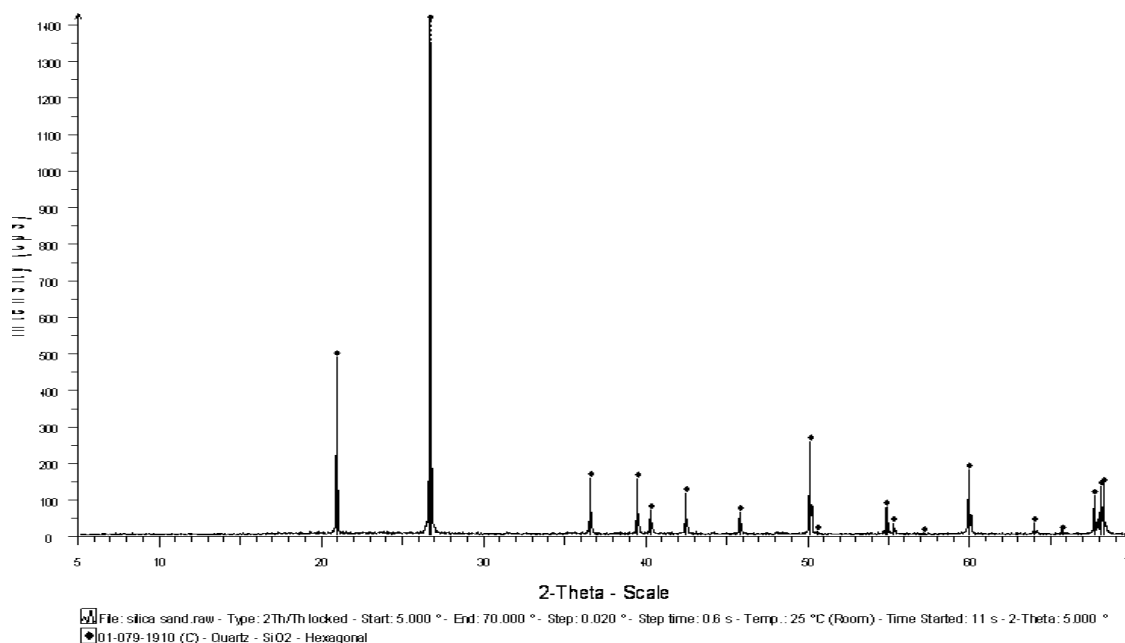
The results of XRD study represented that this kaolinite clay is kaolinite mineral (Figure 4.1) and sand is purely quartz mineral (Figure 4.2). In addition, the data of XRF for kaolinite clay shows that the major compounds of oxide in kaolinite clay were  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  (Shahmohammadi-Kalalagh et al., 2011) (Table. 4.1).

**Table 4.1** - The chemical compositions of kaolinite clay used in this experiment

Constituents	Quantity (%)	Constituents	Quantity (%)
$\text{Al}_2\text{O}_3$	39.63	$\text{P}_2\text{O}_5$	0.121
$\text{SiO}_2$	45.08	$\text{CaO}$	0.017
$\text{Fe}_2\text{O}_3$	0.499	$\text{SO}_3$	0.0791
$\text{K}_2\text{O}$	0.127	$\text{TiO}_2$	0.646
$\text{Na}_2\text{O}$	0.195	Loss on ignition	13.6



**Figure 4.1** - X-ray Diffraction pattern of kaolinite clay



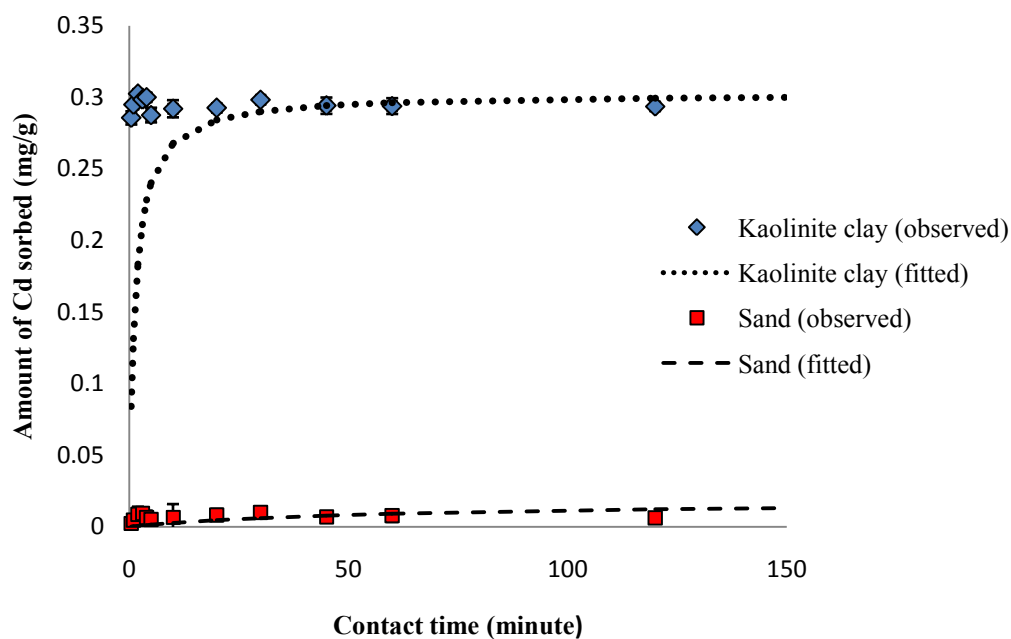
**Figure 4.2 - X-ray Diffraction pattern of sand**

#### 4.2 Kinetic sorption experiment of kaolinite clay and sand

Kinetic sorption experiment was performed under pH value of  $5.62 \pm 0.02$  and IS of 0.0 mM to obtain the time for reaching equilibrium. The effects of contact time on Cd sorption by kaolinite clay and sand were conducted for 1440 minutes.

Figure 4.3 displays the amount of Cd sorbed onto kaolinite clay and sand. At the initial phase, the amount of Cd sorbed by kaolinite clay was rapidly increased and ended up immediately with gradual variation range. The fast increase of amount of Cd sorbed by kaolinite clay is because of the presence of vast number of vacant sites when the time goes by this concentration of Cd sorbed by kaolinite clay does not change owing to the vacant sites are fulfilled with Cd (Shahmohammadi-Kalalagh et al., 2011). On the contrary, the amount of Cd sorbed by sand was roughly 30 times lower than kaolinite clay. In this study, the maximum concentration of Cd uptaken by kaolinite clay and sand were 0.3 and 0.018 mg/g sorbents. Moreover, Figure 4.3 indicated that the equilibrium for using kaolinite clay as a sorbent was reached within 120 minutes; on the contrary, sand was reached equilibrium within 1080 minutes.

Therefore the contact time of 1440 minutes therefore was selected for the study of effect of IS in equilibrium sorption experiment of kaolinite clay and sand.



**Figure 4.3** - Effect of contact time to amount of Cd sorbed by kaolinite clay and sand at initial concentration of Cd 10 ppm.

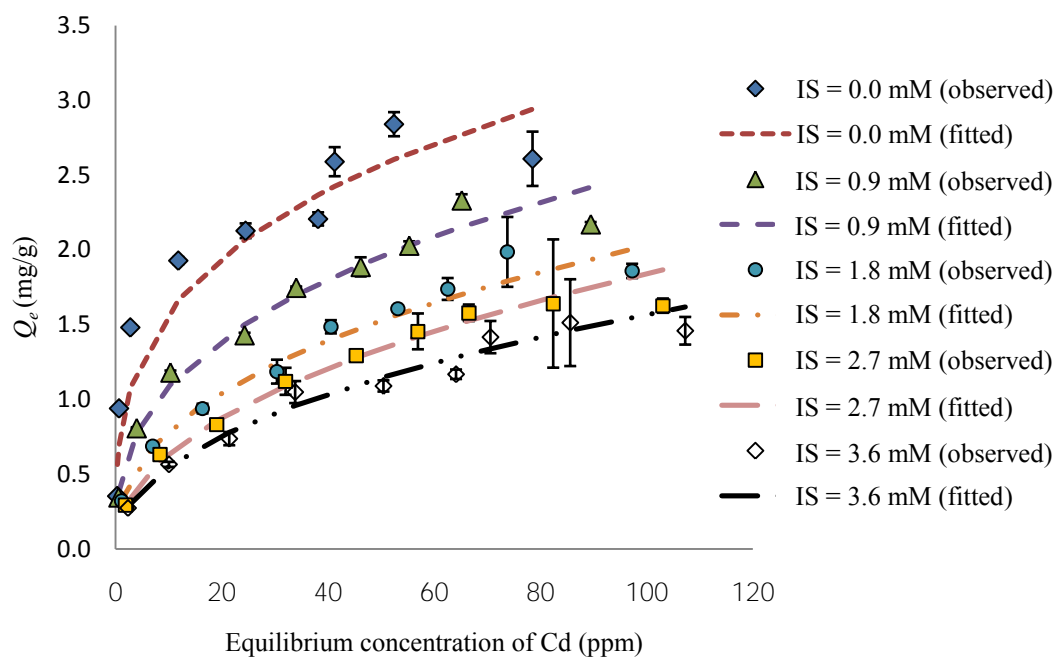
### 4.3 Equilibrium sorption experiment of kaolinite clay and sand

Equilibrium sorption experiment were performed to investigate the effect of solution IS to amount of Cd sorbed onto kaolinite clay and sand under varying IS conditions at pH value of  $5.60 \pm 0.02$ .



### 4.3.1 Kaolinite clay

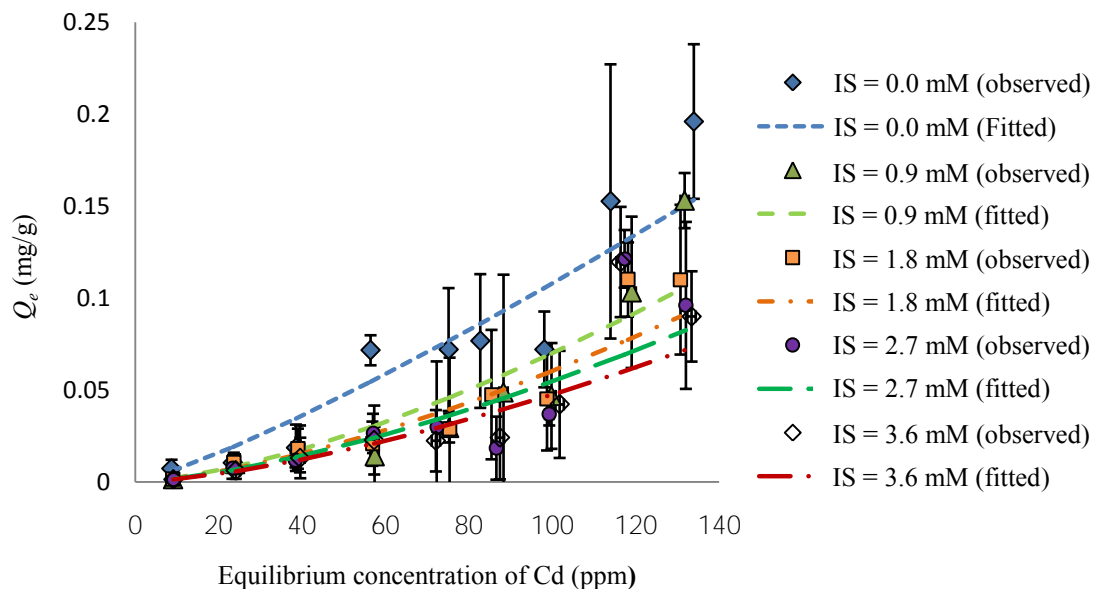
The data of this experiment show that the amount of Cd sorbed by kaolinite clay was increased when initial concentration of Cd increased from 10 to 150 ppm. Besides the results indicated that the sorption capacity of Cd onto kaolinite clay was decreased as the solution IS was increased (Figure 4.4). The effect of solution IS on Cd sorption is contributed to the ion competition between Cd ions and cations in solution for vacant sites (Jiang et al., 2010). It moreover suggests that the increase of solution IS can cause neutralizing of surface negative charge leading to a decrease in the sorption of Cd (Coles and Yong, 2002).



**Figure 4.4** - Measured and fitted curves for sorbed amount of Cd on kaolinite clay under the IS of 0.0 mM (Freundlich), 0.9 mM (Freundlich), 1.8 mM (Freundlich), 2.7 mM (Freundlich) and 3.6 mM (Freundlich).

### 4.3.2 Sand

The effect of both initial Cd concentration and solution IS to Cd sorption onto sand was shown the same trend as kaolinite clay (Figure 4.5). The amount of Cd sorbed onto sand was increased as increasing in an initial concentration of Cd. On the other hand, sorption capacity of Cd onto sand was decreased as the solution IS was increased.



**Figure 4.5** - Measured and fitted curves for sorbed amount of Cd on sand under the IS of 0.0 mM (Freundlich), 0.9 mM (Freundlich), 1.8 mM (Freundlich), 2.7 mM (Freundlich) and 3.6 mM (Freundlich).

### 4.3.3 Equilibrium sorption isotherm

The sorption isotherm is commonly used to describe the sorption equilibrium. The affinity of the sorbents and surface properties are expressed by parameters of isotherm equation.

#### 4.3.3.1 Langmuir isotherm

The Langmuir equation model assumes that sorption of metal ions presents on a homogeneous surface by monolayer adsorption without interaction between sorbed metal ions (Jiang et al., 2010). Table 4.2 shows Langmuir isotherm parameters of Cd sorption onto kaolinite clay and sand. The results suggested that Cd sorption onto kaolinite clay was non-linear and fitted to Langmuir equation model with values of  $R^2$  between 0.927 – 0.956. Moreover, maximum sorption capacity of kaolinite clay was likely declined from 2.477 mg/g to 1.817 mg/g as increasing in solution IS as well as the value of  $K_L$  was reduced from 0.466 L/g to 0.041 L/g as increasing in solution IS, indicating that increasing in solution IS reduces the sorption capacity of Cd onto kaolinite clay. Furthermore, the data suggested that Cd sorbed by kaolinite clay under lower IS condition was faster than higher IS conditions. On the other hand the Cd sorption equilibrium onto sand could not be described using Langmuir isotherm because of negative values of maximum sorption capacity of sand.

**Table 4.2** - Langmuir isotherm parameters of Cd sorption onto kaolinite clay and sand

Sorbent	IS (mM)	Langmuir isotherm		
		$Q_m$ (mg/g)	$K_L$ (L/g)	$R^2$
Kaolinite	0.0	2.477	0.466	0.937
	0.9	2.369	0.111	0.927
	1.8	2.108	0.068	0.947
	2.7	2.166	0.041	0.956
	3.6	1.817	0.042	0.939
Sand	0.0	-0.116	$5.0 \times 10^{-6}$	0.935
	0.9	-0.035	$6.0 \times 10^{-6}$	0.990
	1.8	-0.038	$6.0 \times 10^{-6}$	0.923
	2.7	-0.036	$6.0 \times 10^{-6}$	0.879
	3.6	-0.032	$6.0 \times 10^{-6}$	0.857

#### 4.3.3.2 Freundlich isotherm

The Freundlich equation model assumes that uptake of metal ions occurs on a heterogeneous surface (Jiang et al., 2010). Freundlich isotherm parameters of Cd sorption onto kaolinite and sand are shown in Table 4.3. The data shows that Cd sorption onto kaolinite clay was fitted to Freundlich equation model very well

( $R^2$ :0.961 - 0.988) and Freundlich equation described the data more suitable than Langmuir equation for Cd sorption onto sand ( $R^2$ :0.768 - 0.897). The  $K_F$  value for kaolinite clay was declined from 0.794 L/g to 0.194 L/g when the solution IS was increased from 0.0 to 3.6 mM, suggesting that sorption capacity of Cd by kaolinite clay was decreased as the increasing in solution IS because the increasing in IS reduces the negative charge on sorbent surface and can decline the adsorption of metal ions (Unuabonah et al., 2008). In addition,  $1/n$  values for kaolinite clay tended to increase when IS was increased, indicating that the preferential sorption of Cd under higher solution IS is greater than lower solution IS (Shahmohammadi-Kalalagh et al., 2011). In contrast the values of  $1/n$  for sand were higher than 1 indicated that Cd sorption by sand was not favorable, and the  $K_F$  values of sand were very low compared to kaolinite clay.

**Table 4.3** - Freundlich isotherm parameters of Cd sorption onto kaolinite and sand

Adsorbent	IS (mM)	Freundlich isotherm		
		$1/n$	$K_F$ (L/g)	$R^2$
Kaolinite	0.0	0.300	0.794	0.876
	0.9	0.367	0.466	0.973
	1.8	0.414	0.305	0.961
	2.7	0.463	0.220	0.988
	3.6	0.454	0.194	0.963
Sand	0.0	1.200	$3.10 \times 10^{-4}$	0.895
	0.9	1.500	$7.00 \times 10^{-5}$	0.864
	1.8	1.493	$6.00 \times 10^{-5}$	0.901
	2.7	1.480	$6.00 \times 10^{-5}$	0.759
	3.6	1.489	$5.00 \times 10^{-5}$	0.768

#### 4.4 Effect of solution IS to Cd transport in saturated sand column

Cd solution was injected into the saturated sand column under different solution IS conditions to investigate the effect of solution IS to Cd transport. Table 4.4 shows the column properties used in this experiment.

**Table 4.4** - Column properties for Cd transport through saturated sand experiments for solution IS of 0.0, 0.225, 0.45 and 0.9 mM.

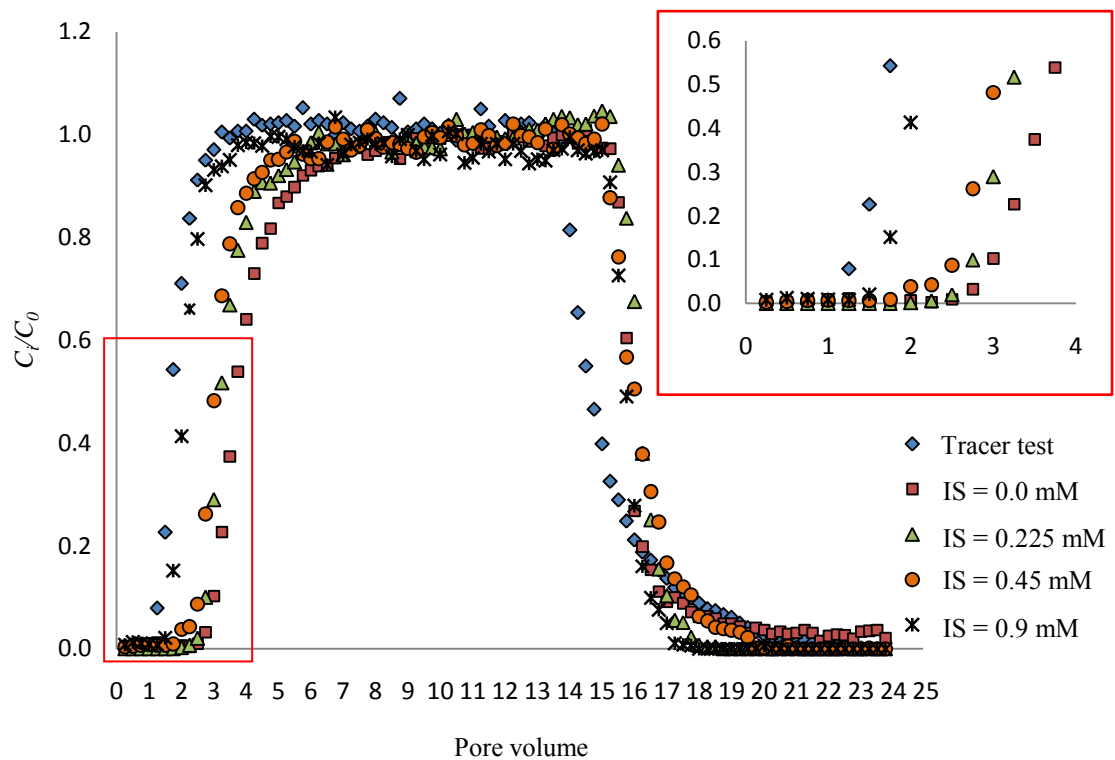
Column No.	Length (cm)	Diameter (cm)	Bulk density (g/cm <sup>3</sup> )	Porosity	Pore volume (cm <sup>3</sup> )	Seepage velocity (m/day)	pH	IS (mM)
1	10.00	2.50	1.52	0.34	17.08	1.4±0.01	5.61±0.01	0.0
2	10.00	2.50	1.56	0.32	15.66	1.5±0.05	5.60±0.02	0.225
3	10.00	2.50	1.52	0.30	14.97	1.6±0.05	5.60±0.02	0.45
4	10.00	2.50	1.52	0.35	16.98	1.4±0.02	5.60±0.01	0.9

Figure 4.6 displays the breakthrough curves of Cd transport through water saturated sand column. The maximum relative concentration of Cd ( $C_i/C_0$ ) at every solution IS in the effluent was 1  $C_i/C_0$ ; however, the duration time for reaching maximum  $C_i/C_0$  was different in each IS conditions. For example, at solution IS of 0.0 mM, 0.225 mM, 0.45 mM and 0.9 mM. Cd reached maximum  $C_i/C_0$  at 10.5 PV, 6.0 PV, 5.5 PV and 4 PV. In addition, the retardation factor and sorption capacity were calculated and the data shown in Table 4.5 which it represents that retardation factor and sorption capacity of Cd transport through saturated sand were declined from 4.04 to 2.23 and  $3.0 \times 10^{-3}$  mg/g to  $7.0 \times 10^{-4}$  mg/g, respectively, as increasing in solution IS. The result suggests that the increase of IS can promote the transport of Cd through saturated sand column due to the decreased Cd sorption onto sand.

**Table 4.5** - Retardation factor and sorption capacity of Cd transport through saturated sand

IS (mM)	Initial conc. of Cd (ppm)	Retardation factor	*Cd (Influent) (mg)	*Cd (Effluent) (mg)	% recovery	Sorbed Cd (mg)	Sand (g)	Sorption capacity (mg/g)
0.0	8.98	4.04	2.08	1.86	89.3	0.22	74.6122	$3.0 \times 10^{-3}$
0.225	9.42	3.46	2.02	1.89	93.8	0.13	76.5757	$1.7 \times 10^{-3}$
0.45	8.94	3.16	1.83	1.74	95.0	0.09	74.9068	$1 \times 10^{-3}$
0.9	8.71	2.23	2.03	1.98	97.3	0.05	74.6122	$7 \times 10^{-4}$

\*Calculated from complete breakthrough curves



**Figure 4.6** - Effect of solution IS to breakthrough curves of Cd through saturated sand column

The same phenomenon of effect of solution IS was found in another research. For instance, Acosta et al. (2011) have studied the mobilities of Cd, Pb, Zn and Cu induced by soil salinity which were  $\text{CaCl}_2$ ,  $\text{MgCl}_2$ ,  $\text{NaCl}$  and  $\text{NaSO}_3$ . They reported that the effects of the increase in solution IS by any salts on metal mobilization were drastic. For example, the increase in IS by adding  $\text{CaCl}_2$ , elevated the concentration of Cd released from soil because  $\text{Ca}^{2+}$  replaced Cd from exchange sites of soil or complexed with  $\text{Cl}^-$ . Cd has a capacity to complex with anions such as  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$  and  $\text{CO}_3^{2-}$  (Traina, 1999) and the formation of Cd-Cl complexes may promote Cd desorption and restrict resorption of Cd onto sorption sites (Makino et al., 2006). Therefore the amount of Cd sorbed onto soil was decreased when solution IS was increased.

## 4.5 Effect of solution IS to facilitated transport of Cd by kaolinite colloid in saturated sand column

### 4.5.1 Cd-bearing kaolinite colloid

The transport of Cd bearing kaolinite colloid was transported through saturated sand column. The relative concentration ( $C_i/C_0$ ) of Cd-bearing kaolinite colloid was not higher than 0.25 at solution IS of 0.0 mM, and did not exceed 0.086, 0.077 and 0.073 at solution IS 0.225, 0.45 and 0.9 mM, respectively (Figure 4.7). Furthermore, this figure shows that solution IS had strong effect on Cd-bearing kaolinite colloid transport through saturated sand column. Table 4.6 shows the column properties for co-transport test.

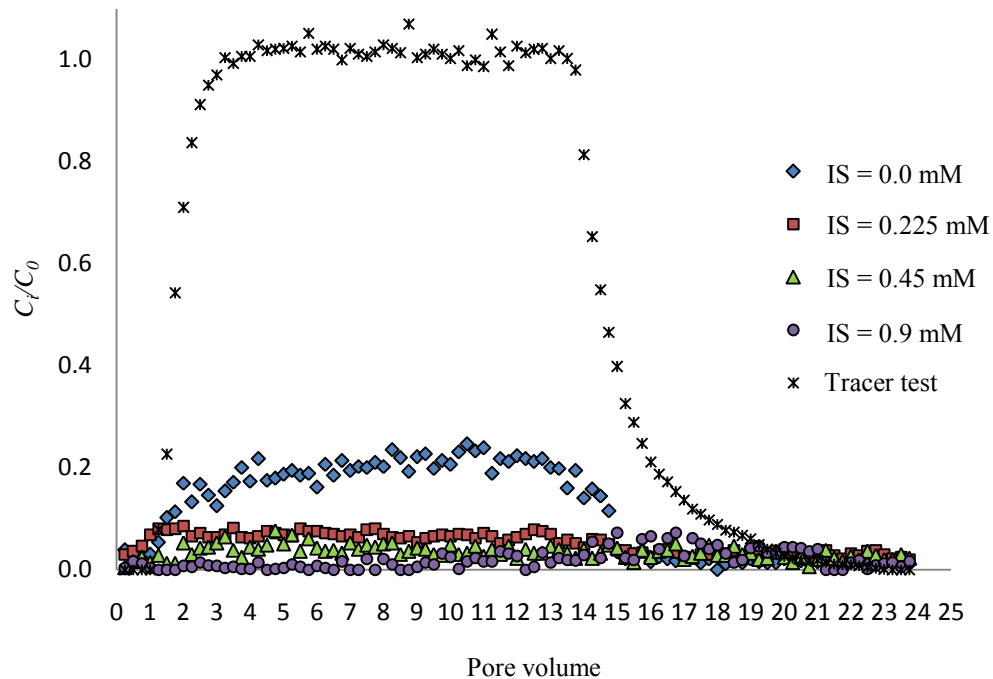
**Table 4.6** - Column properties for Co transport of Cd with kaolinite colloid through saturated sand experiments for solution IS of 0.0, 0.225, 0.45 and 0.9 mM.

Column No.	Length (cm)	Diameter (cm)	Bulk density (g/cm <sup>3</sup> )	Porosity	Pore volume (cm <sup>3</sup> )	Seepage velocity (m/day)
5	10.00	2.50	1.57	0.31	15.27	1.6±0.03
6	10.00	2.50	1.56	0.32	15.66	1.6±0.01
7	10.00	2.50	1.57	0.31	15.12	1.6±0.02
8	10.00	2.50	1.56	0.31	15.17	1.6±0.02

**Table 4.7** - Properties for Cd-bearing kaolinite suspensions at solution IS of 0.0, 0.225, 0.45 and 0.9 mM. used in co-transport experiments.

Column No.	Dissolved Cd (ppm)	Total Cd (ppm)	Facilitated Cd (ppm)	Kaolinite colloids (ppm)	IS (mM)	pH	Size (um) <sup>ϕ</sup>	Zeta potential (mV) <sup>ϕ</sup>
5	8.30	9.29	0.99	103.87	0.0	5.59±0.02	0.923±0.024	-26.3±2.0
6	8.60	9.40	0.80	100.00	0.225	5.60±0.02	1.848±0.180	-24.4±0.7
7	8.54	9.27	0.73	99.33	0.45	5.60±0.01	2.494±0.032	-22.4±1.1
8	8.66	8.99	0.33	112.80	0.9	5.61±0.02	2.691±0.084	-20.7±0.7

<sup>ϕ</sup> Size and surface charge of Cd bearing kaolinite colloid were measured before performing the transport test.



**Figure 4.7** - Effect of solution IS to breakthrough curves of Cd-bearing kaolinite colloid through saturated sand column

The data (Table 4.8) show that the percentage recovery of Cd-bearing kaolinite colloid was decreased from 20.4 to 3.4 when solution IS was increased, but the sorption capacity of Cd-bearing kaolinite colloid onto sand was increased as the increasing in IS, indicating that the increase in IS can promote Cd-bearing kaolinite colloid retention in saturated sand column because the repulsive forces between kaolinite colloid and sand are decreased due to compressing the diffuse double layer by divalent ions (Akbour et al., 2002). The results of this study demonstrated the same effect found in the study of co-transport of hydroxyapatite nanoparticle (nHAP) and Cu in saturated sand column (Wang et al., 2011). In addition, Magal et al. (2011) have studied the impact of hyper-saline solutions on colloid transport in porous media. They reported that colloid transport was decreased with increase in IS which was diluted solutions of hyper-saline.



**Table 4.8** - Percentage recovery and sorption capacity of Cd-bearing kaolinite colloid transport through saturated sand column

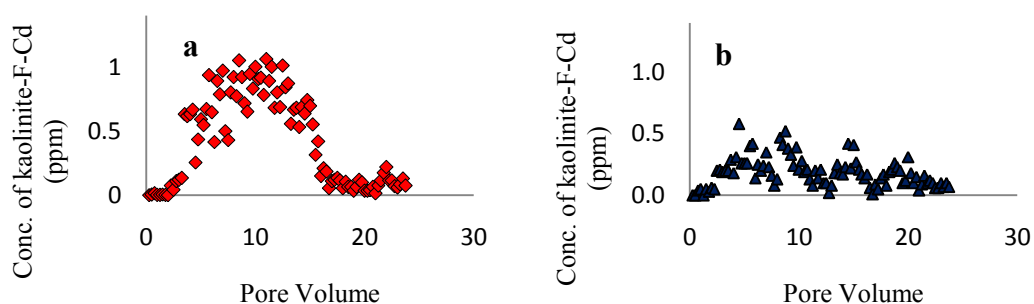
Column (No.)	IS (mM)	Kaolinite* (Influent) (mg)	Kaolinite* (Effluent) (mg)	% recovery	Sorbed Kaolinite colloid (mg)	Sand (g)	Sorption capacity (mg/g)
5	0.0	21.72	4.44	20.4	17.28	77.0666	0.2242
6	0.225	21.42	1.96	9.15	19.46	76.5758	0.2541
7	0.45	20.54	1.22	5.93	19.33	77.0666	0.2507
8	0.9	23.43	0.81	3.4	22.62	76.5757	0.2954

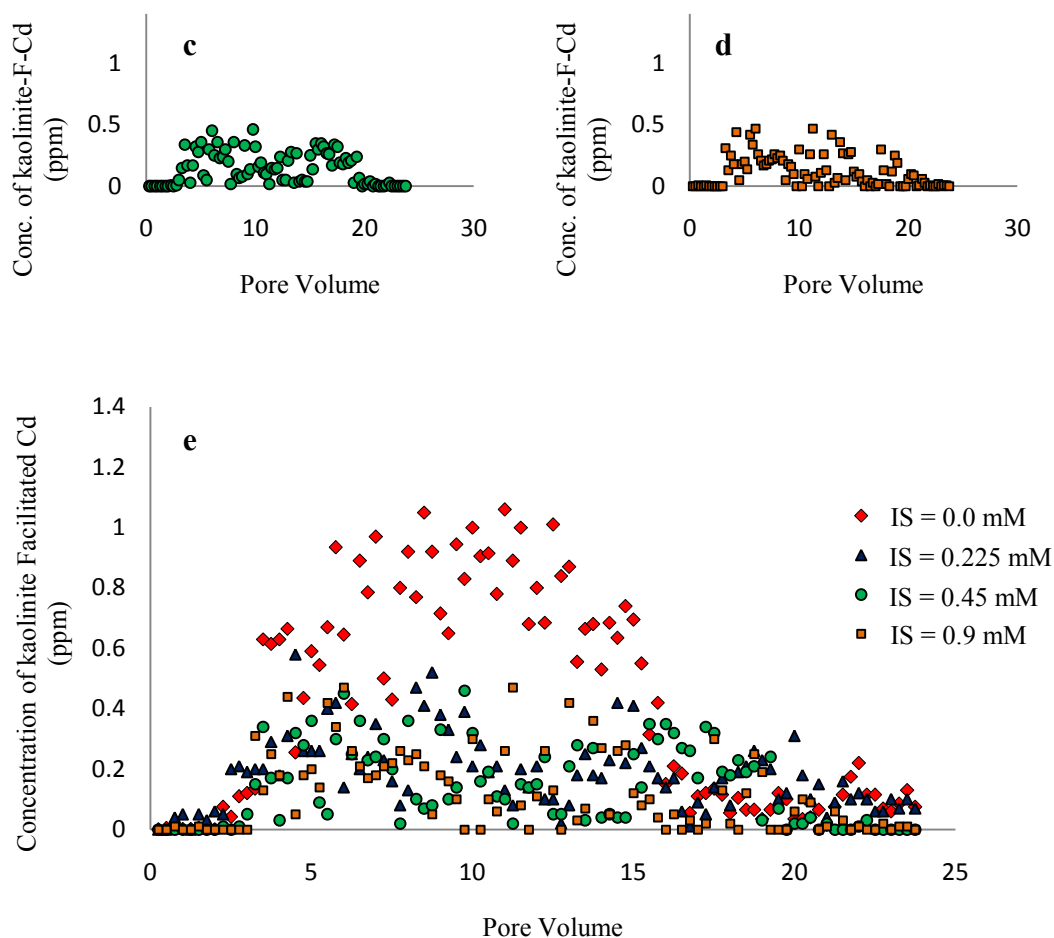
\*Calculated from complete breakthrough curves

According to the zeta potential and size of Cd-bearing kaolinite colloid shown in Table 4.7, it can be described that increasing in solution IS can reduce electrostatic repulsion and trigger to colloid retention on media surface and colloid aggregation. (Wang et al., 2011; Kretzschmar et al., 1998)

#### 4.5.2 Kaolinite-Facilitated Cd transport

The concentration of total Cd and dissolved Cd were measured before performing the co-transport test. Table 4.7 represents that concentration of total Cd and dissolved Cd was varied from 8.99 to 9.40 ppm. and 8.30 to 8.66 ppm., respectively. However, the concentration of kaolinite-facilitated Cd was decreased from 0.99 to 0.33 ppm. when the solution IS was increased from 0.0 mM to 0.9 mM. The results shows the similar results of batch experiment that the amount of Cd sorbed onto kaolinite clay was decreased as the increasing in solution IS.





**Figure 4.8** - Breakthrough curve for kaolinite-facilitated Cd as a function of pore volume under different solution IS: 0.0 mM (a), 0.225 mM (b), 0.45 (c), 0.9 mM (d) and a compilation of all kaolinite-facilitated Cd breakthrough curves (e)

Figure 4.8 displays the breakthrough curves for kaolinite-facilitated Cd under the different solution IS conditions. The concentration of kaolinite-facilitated Cd in effluent under every IS conditions was fluctuated. The observation suggested that increasing in solution IS decreased the concentration of kaolinite-facilitated Cd in the effluent (Table 4.9). The same results about the relationship between IS and colloid facilitated contaminants were reported by Walshe *et al.* (2010). As mentioned before cations ion solution can compete with metal ion for vacant sites on kaolinite colloid, this moreover leads to decline concentration of kaolinite-facilitated Cd. Therefore, the increase in retention of Cd-bearing kaolinite colloid and decrease in amount of Cd sorbed onto kaolinite colloid accounted for the decrease in kaolinite-facilitated Cd

mobilization with increasing in solution IS. However, dissolved Cd should not be ruled out because dissolved Cd accounted for a higher percentage of total Cd in the solution than kaolinite-facilitated Cd.

**Table 4.9** – Amount of kaolinite-facilitated Cd in effluents under different IS conditions

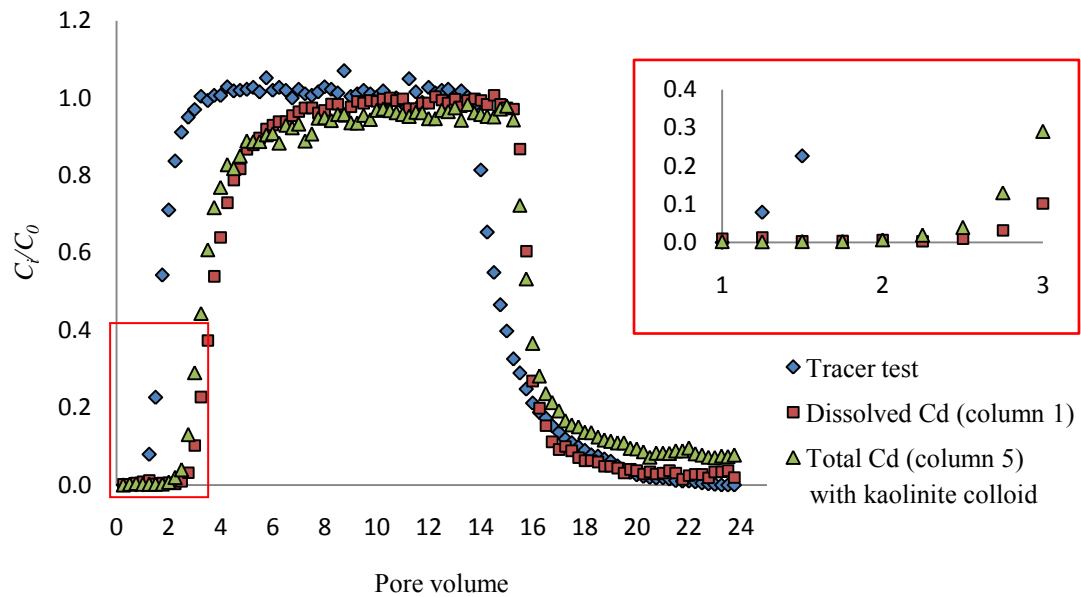
Column (No.)	IS (mM)	Kaolinite-facilitated Cd* (Effluent) (mg)
5	0.0	0.15
6	0.225	0.07
7	0.45	0.06
8	0.9	0.04

\*Calculated from complete breakthrough curves

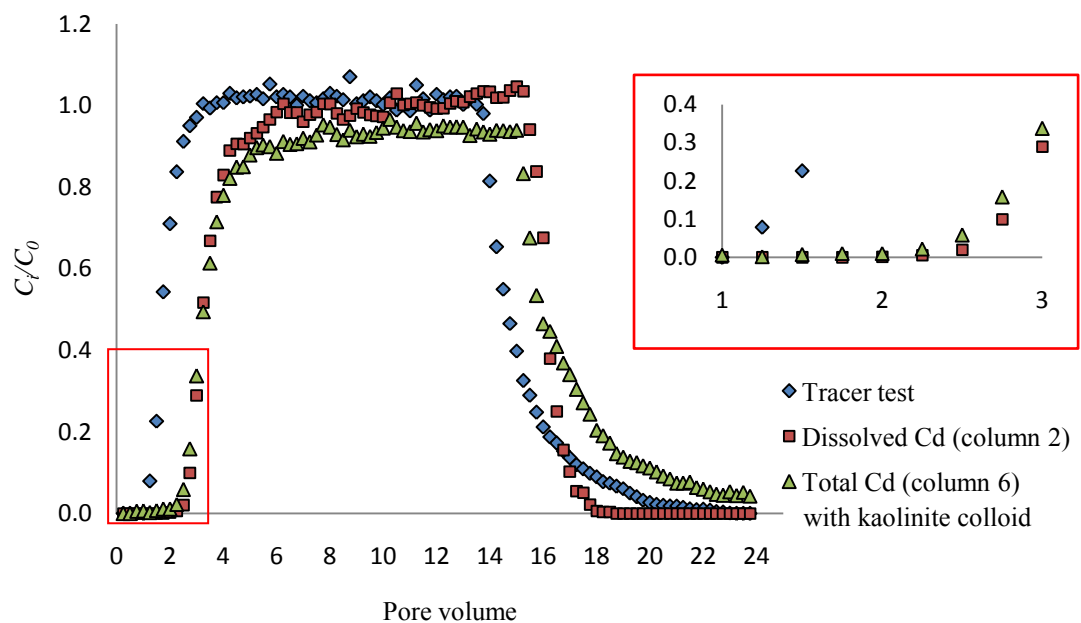
#### 4.6 Effect of kaolinite colloid to Cd transport through saturated sand column.

The breakthrough curves of total Cd in co-transport test were compared to breakthrough curves of Cd in Cd transport test to illustrate the effect of kaolinite colloid on Cd transport.

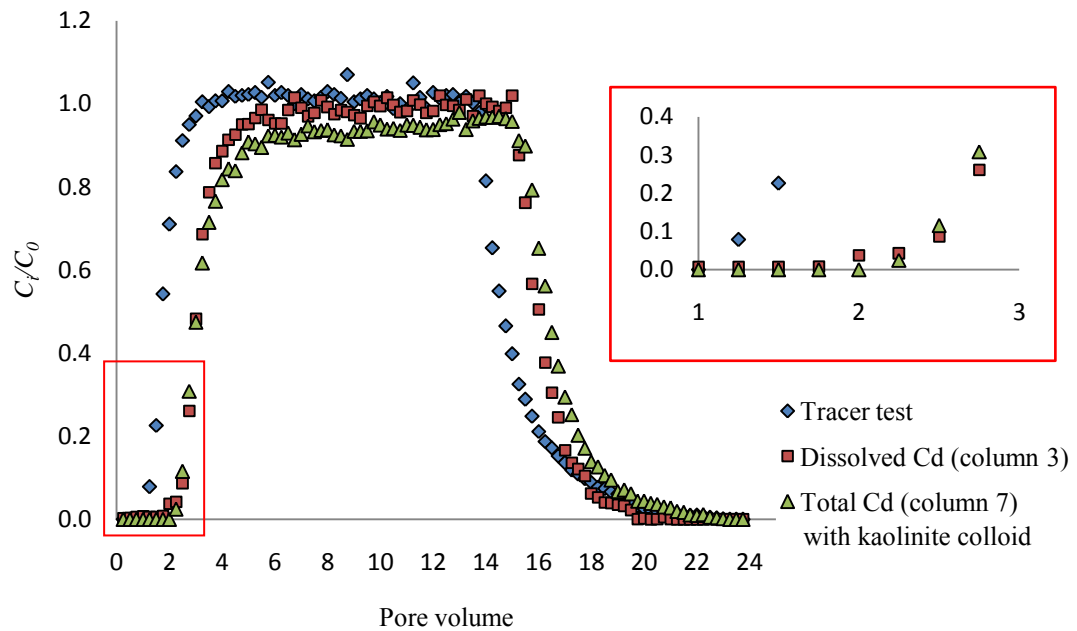
Figure 4.9 shows that the breakthrough time of total Cd co-injected with kaolinite colloid (Column No. 5) was a little bit faster than Cd transport (Column No. 1) at solution IS at 0.0 mM. On the other hand, when the solution IS was increased the breakthrough time of dissolved Cd was decreased. For example, the breakthrough time of dissolved Cd almost equaled the breakthrough time of total Cd at the solution IS of 0.225 (Figure 4.10) and 0.45 mM (Figure 4.11). In addition, Figure 4.12 represents that the breakthrough time of total Cd (Column No. 8) is greater than the breakthrough time of dissolve Cd (Column No. 4).



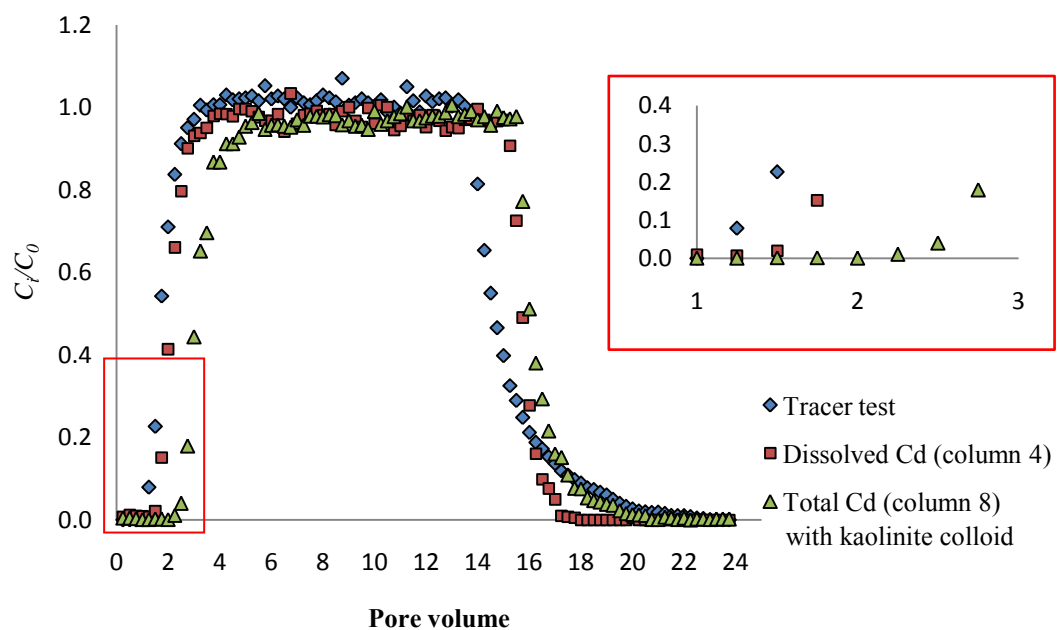
**Figure 4.9** – Comparison between breakthrough curve of Cd without kaolinite colloid (Column No. 1) and breakthrough curve of total Cd with kaolinite colloid (Column No. 5) at solution IS of 0.0 mM.



**Figure 4.10** – Comparison between breakthrough curve of Cd without kaolinite colloid (Column No. 2) and breakthrough curve of total Cd with kaolinite colloid (Column No. 6) at solution IS of 0.225 mM.



**Figure 4.11** – Comparison between breakthrough curve of Cd without kaolinite colloid (Column No. 3) and breakthrough curve of total Cd with kaolinite colloid (Column No. 7) at solution IS of 0.45 mM.



**Figure 4.12** – Comparison between breakthrough curve of Cd without kaolinite colloid (Column No. 4) and breakthrough curve of total Cd with kaolinite colloid (Column No. 8) at solution IS of 0.9 mM.

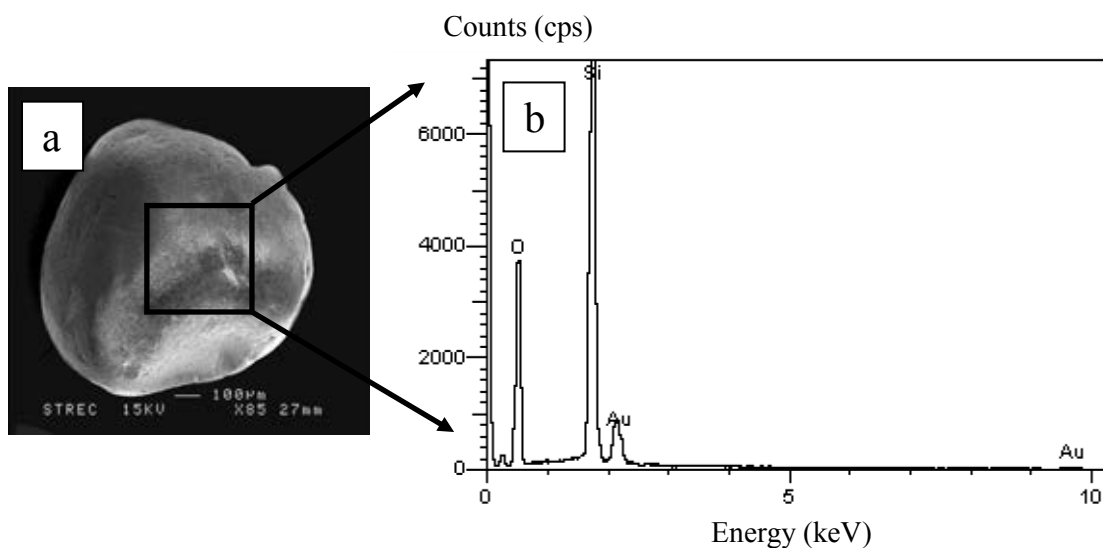
**Table 4.10** - Retardation factors of Cd transport with kaolinite colloid and without kaolinite colloid through saturated sand column

Solution IS (mM)	Column (No.)	Retardation factor of Cd.	% recovery
0.0	1	4.04	89.3
	5	3.93	92.3
0.225	2	3.46	93.8
	6	3.71	93.9
0.45	3	3.16	95.0
	7	3.38	94.2
0.9	4	2.23	97.2
	8	3.33	94.1

Table 4.10 represents retardation factors of Cd transport through saturated sand. The data shows that both retardation factors of Cd transport and Cd transport along with kaolinite colloid were decreased when solution IS was increased. In addition, the retardation factors of Cd transport with kaolinite colloid (column 6, 7 and 8) were higher than retardation factors of Cd in Cd transport without kaolinite colloid (column 2, 3 and 4) under IS of 0.225, 0.45 and 0.9 mM. Similarly, Zhu et al. (2012) have studied about the interaction of kaolinite colloid and mercury (Hg) transport in saturated sand. The results showed that kaolinite colloid reduced Hg's mobility and from the breakthrough curve of Hg in co-transport of 100 ppm Hg and 100 ppm kaolinite colloid and Hg transport, the maximum  $C_i/C_0$  of Hg was found at 6.6 PV in co-transport test was later than 100 ppm Hg transport at 1.2 PV.

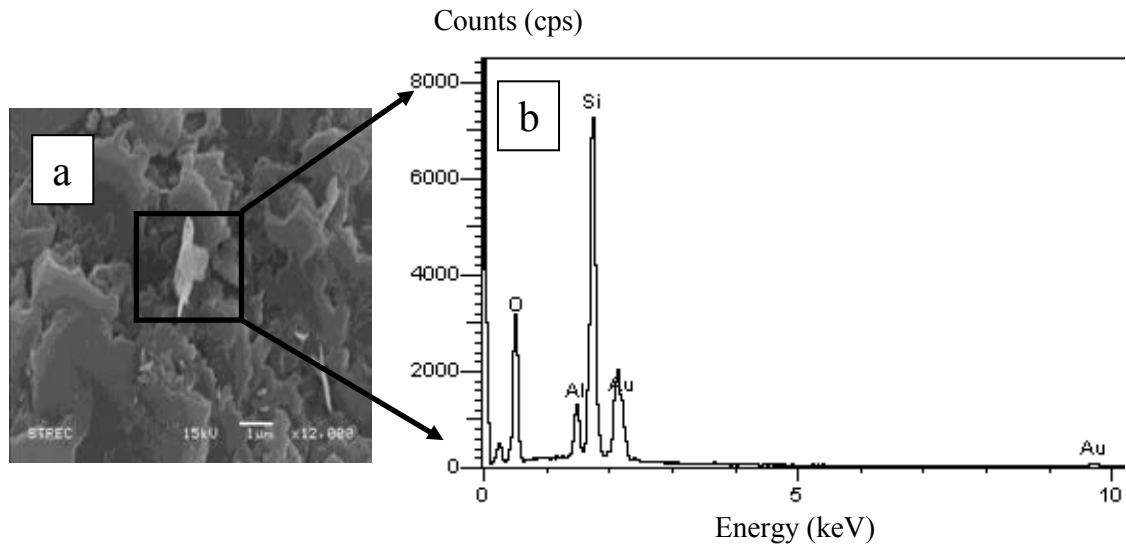
According to the results of transport experiment of Cd without kaolinite colloid and Cd with kaolinite colloid, under higher solution IS conditions kaolinite colloid tended to decrease Cd's mobility. This observation indicates that kaolinite colloid retards Cd transport due to retention of kaolinite-facilitated Cd although kaolinite colloid tends to facilitate Cd transport at very low solution IS.

The SEM-EDX was used to determine the structure and identify the major elements. Figure 4.13(a) shows the surface of a granular sand grain has surface roughness. The surface roughness can probably create regions that favorable for kaolinite colloid retention. Besides, the result of EDX chemical analysis of sand represents the basis elements of quartz sand which is O and Si (Figure 4.13(b)).

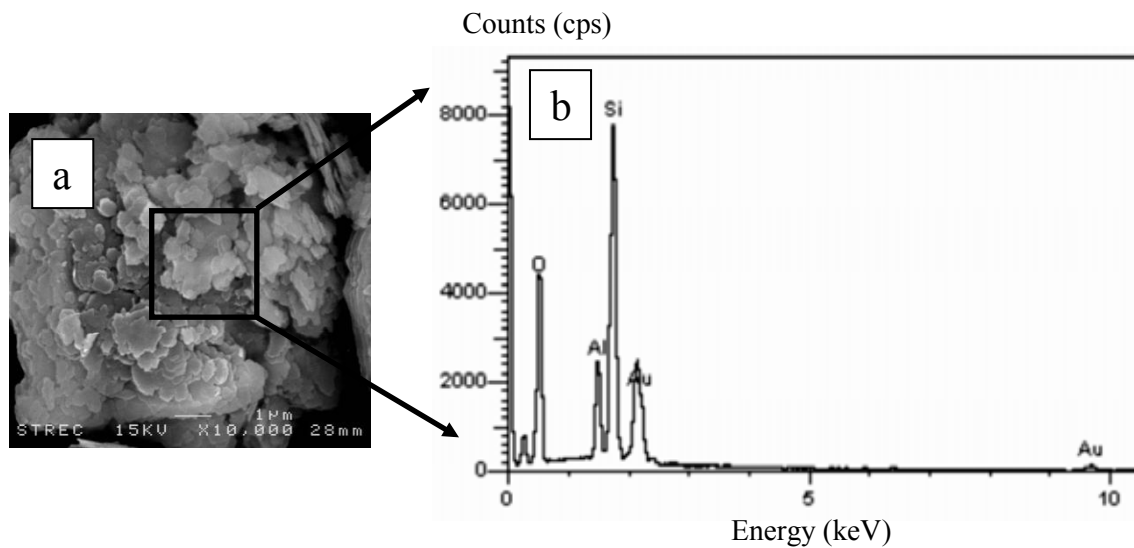


**Figure 4.13** - SEM image of cleaned sand (a) and the corresponding EDX spectrum of sand (b).

Figure 4.14 shows a SEM image of sand excavated from column after finishing of the transport test at solution IS of 0.3 mM. Moreover, figure 4.14(a) demonstrates that kaolinite plates were retained at grain surface. The results of EDX chemical analysis of the kaolinite plate is presented in figure 4.14(b) confirmed that this plate was kaolinite colloid because of the presence of Si, Al and O elements which are basis elements of kaolinite colloid (Figure 4.15).



**Figure 4.14** - SEM image of kaolinite retained on grain surface (a) and the corresponding EDX spectrum of retained kaolinite (b).



**Figure 4.15** - SEM image of kaolinite clay (a) and the corresponding EDX spectrum of kaolinite clay (b).



## **CHAPTER V**

### **CONCLUSIONS AND RECOMMENDATIONS**

#### **5.1 Conclusions**

The effect of solution IS on Cd sorption onto kaolinite clay and sand, Cd transport, and co-transport of Cd and kaolinite colloid was studied in this research. The results were summarized as following.

##### **5.1.1 Kinetic sorption experiment**

- The amount of Cd sorbed onto kaolinite clay was 30 times greater than sand. Moreover, the equilibrium for using kaolinite clay was reached within 120 minutes; on the other hand, sand was reached within 1080 minutes.

##### **5.1.2 Equilibrium sorption experiment**

- Sorption capacities of kaolinite clay and sand were decreased as the increasing in solution IS because of ion competition between metal ions and cations in solution.
- Sorption isotherms studies for Cd sorbed onto kaolinite clay, Freundlich equation described the data more suitable than Langmuir equation when the IS was higher. In addition, the experimental data of Cd sorbed onto sand for isotherm studies was not fitted to Langmuir equation model on the other hand Freundlich equation described the data better.

### **5.1.3 Cd transport experiment**

- The increase of solution IS can promote the transport of Cd through saturated sand column because of the decrease in sorption capacity of Cd onto sand by competition with cations for sorption sites and complexation of Cd with anions.

### **5.1.4 Co-transport of Cd with kaolinite colloid experiment**

- Concentration of Cd-bearing kaolinite colloid in the effluent was decreased when the solution IS was increased. On the other word, increasing in solution IS can promote the retention of Cd-bearing kaolinite colloid on sand surface due to decreasing in electrostatic repulsive forces between Cd-bearing kaolinite colloid and sand.
- The solution IS has strong effect on kaolinite facilitated transport of Cd through sand column saturated with water and the concentration of kaolinite facilitated Cd was declined when solution IS was increased because the sorption capacity of Cd onto kaolinite colloid was decreased as the increasing in solution IS, and the retention of Cd-bearing kaolinite colloids increased when the solution IS was increased.
- Kaolinite colloid can promote mobility of Cd in water saturated sand column under extremely low IS; on the other hand kaolonite colloid can inhibit mobility of Cd under higher IS.

## 5.2 Recommendations

1. The further study should establish the mathematical model to describe the colloid facilitated contaminant transport and provide understanding for the colloid facilitated contaminant transport.
2. This study only focuses on kaolinite colloid and Cd the further study should investigate other colloids like hydroxyapatite nanoparticle, carbon nanotube and montmorillonite or another heavy metal such as Pb and As.
3. In the real situation, there are many other contributing factors that can affect the colloid facilitated heavy metal transport. Thus the studies of those others factor such as pH, water flow and cations should be persued.

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*Appendices*

*Appendix A*

*Batch sorption experimental data: Kinetic sorption experiment*

**Table A.1** - Observed data of concentration of Cd (ppm) at time (t) for effect of contact time to amount of Cd sorbed onto kaolinite clay

Time (Min)	Concentration of Cd (ppm) at time (t)			Average (ppm)	SD ( $\pm$ ppm)	Initial conc. of Cd (ppm)
	Replication 1	Replication 2	Replication 3			
0.5	0.73	0.50	0.60	0.610	0.0115	7.75
1	0.39	0.34	0.26	0.330	0.0656	7.70
2	0.34	0.34	0.22	0.300	0.0693	7.86
3	0.49	0.25	0.28	0.340	0.1308	7.80
4	0.42	0.35	0.28	0.350	0.0700	7.85
5	0.42	0.25	0.17	0.280	0.1277	7.47
10	0.46	0.31	0.16	0.310	0.1500	7.61
20	0.26	0.38	0.31	0.317	0.0603	7.63
30	0.35	0.25	0.34	0.313	0.0551	7.77
45	0.42	0.33	0.14	0.297	0.1429	7.65
60	0.49	0.28	0.23	0.333	0.1380	7.68
120	0.36	0.29	0.43	0.360	0.0700	7.70
180	0.38	0.30	0.33	0.337	0.0404	7.62
360	0.26	0.29	0.38	0.310	0.0624	7.84
1080	0.23	0.33	0.38	0.313	0.0764	7.82
1440	0.46	0.32	0.44	0.407	0.0757	8.00

**Table A.2** - Observed data of concentration of Cd (ppm) at time (t) for effect of contact time to amount of Cd sorbed onto sand

Time (Min)	Concentration of Cd at time (t)			Average (ppm)	SD ( $\pm$ ppm)	Initial conc. of Cd (ppm)
	Replication 1	Replication 2	Replication 3			
0.5	8.34	8.39	8.52	8.417	0.0929	8.54
1	8.21	7.99	8.31	8.170	0.1637	8.40
2	7.78	8.12	8.32	8.073	0.2730	8.50
3	7.84	8.19	8.18	8.070	0.1992	8.53
4	7.82	8.12	8.30	8.080	0.2425	8.40
5	8.16	8.29	8.37	8.273	0.1060	8.52
10	7.75	8.12	8.66	8.177	0.4576	8.51
20	7.83	8.11	8.24	8.060	0.2095	8.47
30	7.72	8.05	8.07	7.947	0.1965	8.44
45	8.21	8.12	8.24	8.190	0.0624	8.53
60	7.90	8.05	8.33	8.093	0.2182	8.48
120	8.09	8.09	8.38	8.187	0.1674	8.49
180	7.96	8.06	8.11	8.043	0.0763	8.50
360	7.96	7.86	7.91	7.910	0.0500	8.44
1080	7.70	7.46	7.54	7.567	0.1222	8.50
1440	7.58	7.50	7.50	7.527	0.0046	8.45

**Table A.3** - Observed data of amount of Cd sorbed onto kaolinite clay

Time (Min)	Amount of Cd sorbed onto kaolinite clay (mg/g)			Average (ppm)	SD (±ppm)
	Replication 1	Replication 2	Replication 3		
0.5	0.2808	0.2900	0.2860	0.2856	0.0046
1	0.2924	0.2944	0.2976	0.2948	0.0026
2	0.3008	0.3008	0.3056	0.3024	0.0028
3	0.2924	0.3020	0.3008	0.2984	0.0052
4	0.2972	0.3000	0.3028	0.3000	0.0028
5	0.2820	0.2888	0.2920	0.2876	0.0051
10	0.2860	0.2920	0.2980	0.2920	0.0060
20	0.2948	0.2900	0.2928	0.2925	0.0024
30	0.2968	0.3008	0.2972	0.2983	0.0022
45	0.2892	0.2928	0.3004	0.2941	0.0057
60	0.2876	0.2960	0.2980	0.2939	0.0055
120	0.2936	0.2964	0.2908	0.2936	0.0028
180	0.2896	0.2928	0.2916	0.2913	0.0016
360	0.3032	0.3020	0.2984	0.3012	0.0025
1080	0.3036	0.2996	0.2976	0.3003	0.0031
1440	0.3016	0.3072	0.3024	0.3037	0.0030

**Table A.4** - Observed data of amount of Cd sorbed onto sand

Time (Min)	Amount of Cd sorbed onto sand (mg/g)			Average (ppm)	SD (±ppm)
	Replication 1	Replication 2	Replication 3		
0.5	0.0040	0.0030	0.0004	0.0025	0.0019
1	0.0038	0.0082	0.0018	0.0046	0.0033
2	0.0144	0.0076	0.0036	0.0085	0.0055
3	0.0138	0.0068	0.0070	0.0092	0.0040
4	0.0116	0.0056	0.0020	0.0064	0.0048
5	0.0072	0.0046	0.0030	0.0049	0.0021
10	0.0152	0.0078	-0.0030	0.0067	0.0092
20	0.0128	0.0072	0.0046	0.0082	0.0042
30	0.0144	0.0078	0.0074	0.0099	0.0039
45	0.0064	0.0082	0.0058	0.0068	0.0012
60	0.0116	0.0086	0.0030	0.0077	0.0044
120	0.0080	0.0080	0.0022	0.0061	0.0033
180	0.0108	0.0088	0.0078	0.0091	0.0015
360	0.0096	0.0116	0.0106	0.0106	0.0010
1080	0.0160	0.0208	0.0192	0.0187	0.0024
1440	0.0174	0.0190	0.0190	0.0185	0.0009



*Appendix B*

*Batch sorption experimental data: Equilibrium sorption experiment*

**Table B.1** - Observed and fitted data of amount of Cd sorbed onto kaolinite clay at solution IS of 0.0, 0.9, 1.8, 2.7 and 3.6 mM.

Solution IS (mM)	$C_e$ (mg/L)	$Q_e$ (observed) (mg/g)	SD (observed) ( $\pm$ mg/g)	Langmuir $Q_e$ (fitted) (mg/g)	Freundlich $Q_e$ (fitted) (mg/g)
0.0	0.3200	0.3508	0.0021	0.3297	0.5682
	0.6667	0.9323	0.0064	0.6000	0.7072
	2.7900	1.4670	0.0174	1.4155	1.0834
	11.8200	1.9512	0.0236	2.1001	1.6659
	24.4800	2.0384	0.0493	2.2760	2.0695
	38.1267	2.1495	0.0440	2.3416	2.3616
	41.2467	2.5683	0.0972	2.3508	2.4176
	52.4160	2.6354	0.0805	2.3750	2.5966
	78.5000	2.3380	0.1816	2.4055	2.9287
0.9	0.5333	0.3439	0.0016	0.2611	0.3707
	3.9667	0.8183	0.0015	1.2894	0.7727
	10.3200	1.2036	0.0354	2.0687	1.0965
	24.2800	1.4480	0.0246	2.6418	1.4997
	34.0000	1.7024	0.0401	2.8061	1.6963
	46.1383	1.9089	0.1324	2.9257	1.8969
	55.2767	2.0577	0.0744	2.9846	2.0266
	65.1560	2.2610	0.2594	3.0313	2.1523
	89.4500	2.1460	0.1724	3.1052	2.4170
1.8	1.1367	0.3189	0.0061	0.1519	0.3249
	6.9833	0.6877	0.0255	0.6788	0.6827
	16.3650	0.9420	0.0322	1.1064	0.9671
	30.3800	1.1872	0.0798	1.4118	1.2456
	40.5333	1.5883	0.0441	1.5358	1.4015
	53.1367	1.6175	0.0022	1.6379	1.5656
	62.5217	1.7265	0.0731	1.6922	1.6733
	73.7620	1.8990	0.2336	1.7420	1.7904
	97.2500	1.8000	0.0476	1.8138	2.0047
2.7	1.8633	0.2935	0.0036	0.1548	0.2947
	8.3833	0.6127	0.0076	0.5540	0.5885
	19.0350	0.7992	0.0312	0.9427	0.8582
	32.0000	1.0888	0.0903	1.2144	1.0899
	45.3333	1.3291	0.0297	1.3870	1.2792
	56.9233	1.4471	0.1198	1.4906	1.4205
	66.5083	1.5073	0.0553	1.5561	1.5259
	82.3940	1.8054	0.4288	1.6385	1.6839
	103.0500	1.8000	0.0476	1.7147	1.8664

**Table B.1** - Observed and fitted data of amount of Cd sorbed onto kaolinite clay at solution IS of 0.0, 0.9, 1.8, 2.7 and 3.6 mM. (Continue)

Solution IS (mM)	$C_e$ (mg/L)	$Q_e$ (observed) (mg/g)	SD (observed) ( $\pm$ mg/g)	Langmuir $Q_e$ (fitted) (mg/g)	Freundlich $Q_e$ (fitted) (mg/g)
3.6	2.3200	0.2760	0.0056	0.1638	0.2848
	10.0333	0.5767	0.0168	0.5429	0.5529
	21.3900	0.7536	0.0442	0.8611	0.7791
	33.8000	1.0336	0.0736	1.0632	0.9585
	50.4267	1.0805	0.0375	1.2269	1.1490
	64.0933	1.1945	0.0316	1.3146	1.2808
	70.5717	1.4873	0.1079	1.3473	1.3379
	85.5920	1.5267	0.2903	1.4079	1.4602
	107.2500	1.5060	0.0924	1.4708	1.6173

**Table B.2** - Observed and fitted data of amount of Cd sorbed onto sand at solution IS of 0.0, 0.9, 1.8, 2.7 and 3.6 mM.

Solution IS (mM)	$C_e$ (mg/L)	$Q_e$ (observed) (mg/g)	SD observed ( $\pm$ mg/g)	Langmuir $Q_e$ (fitted) (mg/g)	Freundlich $Q_e$ (fitted) (mg/g)
0.0	8.7233	0.0073	0.0047	0.0053	0.0058
	23.4583	0.0103	0.0043	0.0154	0.0189
	38.5350	0.0186	0.0126	0.0276	0.0344
	56.4200	0.0716	0.0082	0.0454	0.0543
	75.1200	0.0720	0.0334	0.0695	0.0766
	82.7133	0.0766	0.0364	0.0815	0.0860
	98.0567	0.0721	0.0206	0.1112	0.1055
	113.9233	0.1525	0.0746	0.1530	0.1263
	133.9000	0.1960	0.0420	0.2342	0.1533
	0.9	9.0533	0.0015	0.0006	0.0020
23.9417		0.0097	0.0053	0.0059	0.0082
39.5117		0.0180	0.0127	0.0109	0.0174
57.3800		0.0140	0.0159	0.0184	0.0304
75.2533		0.0293	0.0079	0.0288	0.0457
88.2867		0.0488	0.0639	0.0394	0.0581
99.7817		0.0468	0.0288	0.0522	0.0698
118.9933		0.1031	0.0411	0.0873	0.0909
131.7000		0.1530	0.0150	0.1318	0.1058

**Table B.2** - Observed and fitted data of amount of Cd sorbed onto sand at solution IS of 0.0, 0.9, 1.8, 2.7 and 3.6 mM. (Continue)

Solution IS (mM)	$C_e$ (mg/L)	$Q_e$ (observed) (mg/g)	SD observed ( $\pm$ mg/g)	Langmuir $Q_e$ (fitted) (mg/g)	Freundlich $Q_e$ (fitted) (mg/g)
1.8	9.0367	0.0015	0.0006	0.0022	0.0017
	23.6500	0.0105	0.0054	0.0063	0.0070
	39.0117	0.0181	0.0109	0.0116	0.0148
	56.8600	0.0208	0.0120	0.0196	0.0259
	75.3600	0.0288	0.0388	0.0313	0.0395
	85.4050	0.0475	0.0352	0.0398	0.0476
	98.7083	0.0452	0.0281	0.0550	0.0591
	118.1267	0.1101	0.0202	0.0922	0.0773
	130.7000	0.1100	0.0407	0.1377	0.0899
2.7	9.1300	0.0014	0.0002	0.0021	0.0016
	23.3167	0.0077	0.0060	0.0059	0.0063
	38.4267	0.0118	0.0039	0.0109	0.0133
	57.0000	0.0264	0.0107	0.0189	0.0238
	72.2667	0.0299	0.0357	0.0278	0.0338
	86.5767	0.0184	0.0171	0.0392	0.0442
	99.2450	0.0368	0.0061	0.0534	0.0541
	117.3033	0.1213	0.0157	0.0863	0.0693
	132.0000	0.0960	0.0454	0.1382	0.0825
3.6	9.1500	0.0014	0.0016	0.0018	0.0014
	24.1417	0.0062	0.0045	0.0054	0.0057
	39.5783	0.0130	0.0110	0.0099	0.0119
	57.3000	0.0228	0.0187	0.0167	0.0207
	72.0800	0.0224	0.0167	0.0243	0.0292
	87.4317	0.0241	0.0227	0.0352	0.0389
	101.7367	0.0422	0.0291	0.0499	0.0488
	116.3500	0.1196	0.0300	0.0737	0.0595
	133.3500	0.0900	0.0246	0.1277	0.0730

*Appendix C*

*Column experimental data: Effect of solution IS to Cd transport through  
saturated sand column*

**Table C.1** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.0 mM.

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
1	0.25	0.02	8.98	0.0022
2	0.50	0.02	8.98	0.0022
3	0.75	0.04	8.98	0.0045
4	1.00	0.08	8.98	0.0089
5	1.25	0.11	8.98	0.0122
6	1.50	0.03	8.98	0.0033
7	1.75	0.04	8.98	0.0045
8	2.00	0.06	8.98	0.0067
9	2.25	0.03	8.98	0.0033
10	2.50	0.09	8.98	0.0100
11	2.75	0.29	8.98	0.0323
12	3.00	0.92	8.98	0.1024
13	3.25	2.04	8.98	0.2272
14	3.50	3.36	8.98	0.3742
15	3.75	4.84	8.98	0.5390
16	4.00	5.75	8.98	0.6403
17	4.25	6.55	8.98	0.7294
18	4.50	7.08	8.98	0.7884
19	4.75	7.34	8.98	0.8174
20	5.00	7.79	8.98	0.8675
21	5.25	7.90	8.98	0.8797
22	5.50	8.06	8.98	0.8976
23	5.75	8.27	8.98	0.9209
24	6.00	8.36	8.98	0.9310
25	6.25	8.43	8.98	0.9388
26	6.50	8.44	8.98	0.9399
27	6.75	8.57	8.98	0.9543
28	7.00	8.67	8.98	0.9655
29	7.25	8.75	8.98	0.9744
30	7.50	8.75	8.98	0.9744
31	7.75	8.63	8.98	0.9610
32	8.00	8.70	8.98	0.9688
33	8.25	8.85	8.98	0.9855
34	8.50	8.84	8.98	0.9844
35	8.75	8.56	8.98	0.9532
36	9.00	8.78	8.98	0.9777
37	9.25	8.91	8.98	0.9922
38	9.50	8.86	8.98	0.9866
39	9.75	8.92	8.98	0.9933
40	10.00	8.91	8.98	0.9922
41	10.25	8.96	8.98	0.9978

**Table C.1** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.0 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
42	10.50	8.98	8.98	1.0000
43	10.75	8.92	8.98	0.9933
44	11.00	8.97	8.98	0.9989
45	11.25	8.74	8.98	0.9733
46	11.50	8.74	8.98	0.9733
47	11.75	8.86	8.98	0.9866
48	12.00	8.86	8.98	0.9866
49	12.25	9.01	8.98	1.0033
50	12.50	8.94	8.98	0.9955
51	12.75	8.86	8.98	0.9866
52	13.00	8.95	8.98	0.9967
53	13.25	8.78	8.98	0.9777
54	13.50	8.92	8.98	0.9933
55	13.75	8.97	8.98	0.9989
56	14.00	8.93	8.98	0.9944
57	14.25	8.83	8.98	0.9833
58	14.50	9.05	8.98	1.0078
59	14.75	8.83	8.98	0.9833
60	15.00	8.75	8.98	0.9744
61	15.25	8.73	8.98	0.9722
62	15.50	7.80	8.98	0.8686
63	15.75	5.43	8.98	0.6047
64	16.00	2.41	8.98	0.2684
65	16.25	1.78	8.98	0.1982
66	16.50	1.38	8.98	0.1537
67	16.75	1.00	8.98	0.1114
68	17.00	0.82	8.98	0.0913
69	17.25	0.90	8.98	0.1002
70	17.50	0.79	8.98	0.0880
71	17.75	0.64	8.98	0.0713
72	18.00	0.56	8.98	0.0624
73	18.25	0.57	8.98	0.0635
74	18.50	0.53	8.98	0.0590
75	18.75	0.44	8.98	0.0490
76	19.00	0.44	8.98	0.0490
77	19.25	0.39	8.98	0.0434
78	19.50	0.28	8.98	0.0312
79	19.75	0.36	8.98	0.0401
80	20.00	0.33	8.98	0.0367
81	20.25	0.26	8.98	0.0290
82	20.50	0.30	8.98	0.0334

**Table C.1** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.0 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
83	20.75	0.26	8.98	0.0290
84	21.00	0.28	8.98	0.0312
85	21.25	0.33	8.98	0.0367
86	21.50	0.28	8.98	0.0312
87	21.75	0.13	8.98	0.0145
88	22.00	0.22	8.98	0.0245
89	22.25	0.25	8.98	0.0278
90	22.50	0.24	8.98	0.0267
91	22.75	0.17	8.98	0.0189
92	23.00	0.30	8.98	0.0334
93	23.25	0.31	8.98	0.0345
94	23.50	0.33	8.98	0.0367
95	23.75	0.18	8.98	0.0200

**Table C.2** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.225 mM.

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
1	0.25	0.00	9.42	0.0000
2	0.50	0.00	9.42	0.0000
3	0.75	0.00	9.42	0.0000
4	1.00	0.00	9.42	0.0000
5	1.25	0.00	9.42	0.0000
6	1.50	0.00	9.42	0.0000
7	1.75	0.00	9.42	0.0021
8	2.00	0.02	9.42	0.0064
9	2.25	0.06	9.42	0.0202
10	2.50	0.19	9.42	0.0998
11	2.75	0.94	9.42	0.2898
12	3.00	2.73	9.42	0.5170
13	3.25	4.87	9.42	0.6688
14	3.50	6.30	9.42	0.7749
15	3.75	7.30	9.42	0.8291
16	4.00	7.81	9.42	0.8896
17	4.25	8.38	9.42	0.9066
18	4.50	8.54	9.42	0.9055
19	4.75	8.53	9.42	0.9204



**Table C.2** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.225 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
20	5.00	8.67	9.42	0.9321
21	5.25	8.78	9.42	0.9469
22	5.50	8.92	9.42	0.9660
23	5.75	9.10	9.42	0.9841
24	6.00	9.27	9.42	1.0042
25	6.25	9.46	9.42	0.9820
26	6.50	9.25	9.42	0.9820
27	6.75	9.25	9.42	0.9607
28	7.00	9.05	9.42	0.9777
29	7.25	9.21	9.42	0.9841
30	7.50	9.27	9.42	1.0042
31	7.75	9.46	9.42	1.0032
32	8.00	9.45	9.42	0.9809
33	8.25	9.24	9.42	0.9660
34	8.50	9.10	9.42	0.9756
35	8.75	9.19	9.42	0.9926
36	9.00	9.35	9.42	0.9830
37	9.25	9.26	9.42	0.9766
38	9.50	9.20	9.42	0.9745
39	9.75	9.18	9.42	0.9724
40	10.00	9.16	9.42	1.0064
41	10.25	9.48	9.42	1.0297
42	10.50	9.70	9.42	1.0011
43	10.75	9.43	9.42	1.0042
44	11.00	9.46	9.42	1.0074
45	11.25	9.49	9.42	1.0000
46	11.50	9.42	9.42	0.9958
47	11.75	9.38	9.42	0.9926
48	12.00	9.35	9.42	0.9936
49	12.25	9.36	9.42	1.0053
50	12.50	9.47	9.42	1.0106
51	12.75	9.52	9.42	1.0085
52	13.00	9.50	9.42	1.0212
53	13.25	9.62	9.42	1.0297
54	13.50	9.70	9.42	1.0350
55	13.75	9.75	9.42	1.0329
56	14.00	9.73	9.42	1.0191
57	14.25	9.60	9.42	1.0202
58	14.50	9.61	9.42	1.0361
59	14.75	9.76	9.42	1.0456
60	15.00	9.85	9.42	1.0350

**Table C.2** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.225 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_o$ (ppm)	$C_i/C_o$
61	15.25	9.75	9.42	0.9406
62	15.50	8.86	9.42	0.8376
63	15.75	7.89	9.42	0.6752
64	16.00	6.36	9.42	0.3800
65	16.25	3.58	9.42	0.2505
66	16.50	2.36	9.42	0.1550
67	16.75	1.46	9.42	0.1030
68	17.00	0.97	9.42	0.0552
69	17.25	0.52	9.42	0.0510
70	17.50	0.48	9.42	0.0223
71	17.75	0.21	9.42	0.0064
72	18.00	0.06	9.42	0.0042
73	18.25	0.04	9.42	0.0042
74	18.50	0.04	9.42	0.0000
75	18.75	0.00	9.42	0.0000
76	19.00	0.00	9.42	0.0000
77	19.25	0.00	9.42	0.0000
78	19.50	0.00	9.42	0.0000
79	19.75	0.00	9.42	0.0000
80	20.00	0.00	9.42	0.0000
81	20.25	0.00	9.42	0.0000
82	20.50	0.00	9.42	0.0000
83	20.75	0.00	9.42	0.0000
84	21.00	0.00	9.42	0.0000
85	21.25	0.00	9.42	0.0000
86	21.50	0.00	9.42	0.0000
87	21.75	0.00	9.42	0.0000
88	22.00	0.00	9.42	0.0000
89	22.25	0.00	9.42	0.0000
90	22.50	0.00	9.42	0.0000
91	22.75	0.00	9.42	0.0000
92	23.00	0.00	9.42	0.0000
93	23.25	0.00	9.42	0.0000
94	23.50	0.00	9.42	0.0000
95	23.75	0.00	9.42	0.0000

**Table C.3** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.45 mM.

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_o$ (ppm)	$C_i/C_o$
1	0.25	0.03	8.94	0.0034
2	0.50	0.04	8.94	0.0045
3	0.75	0.06	8.94	0.0067
4	1.00	0.07	8.94	0.0078
5	1.25	0.06	8.94	0.0067
6	1.50	0.06	8.94	0.0067
7	1.75	0.08	8.94	0.0089
8	2.00	0.34	8.94	0.0380
9	2.25	0.38	8.94	0.0425
10	2.50	0.78	8.94	0.0872
11	2.75	2.34	8.94	0.2617
12	3.00	4.31	8.94	0.4821
13	3.25	6.14	8.94	0.6868
14	3.50	7.04	8.94	0.7875
15	3.75	7.67	8.94	0.8579
16	4.00	7.92	8.94	0.8859
17	4.25	8.17	8.94	0.9139
18	4.50	8.28	8.94	0.9262
19	4.75	8.50	8.94	0.9508
20	5.00	8.51	8.94	0.9519
21	5.25	8.64	8.94	0.9664
22	5.50	8.82	8.94	0.9866
23	5.75	8.60	8.94	0.9620
24	6.00	8.52	8.94	0.9530
25	6.25	8.52	8.94	0.9530
26	6.50	8.81	8.94	0.9855
27	6.75	9.07	8.94	1.0145
28	7.00	8.86	8.94	0.9911
29	7.25	8.67	8.94	0.9698
30	7.50	8.75	8.94	0.9787
31	7.75	9.02	8.94	1.0089
32	8.00	8.87	8.94	0.9922
33	8.25	8.72	8.94	0.9754
34	8.50	8.80	8.94	0.9843
35	8.75	8.77	8.94	0.9810
36	9.00	8.70	8.94	0.9732
37	9.25	8.63	8.94	0.9653
38	9.50	8.90	8.94	0.9955
39	9.75	8.98	8.94	1.0045
40	10.00	8.89	8.94	0.9944
41	10.25	9.07	8.94	1.0145

**Table C.3** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.45 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_o$ (ppm)	$C_i/C_o$
42	10.50	8.92	8.94	0.9978
43	10.75	8.76	8.94	0.9799
44	11.00	8.79	8.94	0.9832
45	11.25	9.02	8.94	1.0089
46	11.50	8.93	8.94	0.9989
47	11.75	8.75	8.94	0.9787
48	12.00	8.79	8.94	0.9832
49	12.25	9.12	8.94	1.0201
50	12.50	8.92	8.94	0.9978
51	12.75	8.90	8.94	0.9955
52	13.00	8.80	8.94	0.9843
53	13.25	9.04	8.94	1.0112
54	13.50	8.68	8.94	0.9709
55	13.75	9.11	8.94	1.0190
56	14.00	8.95	8.94	1.0011
57	14.25	8.88	8.94	0.9933
58	14.50	8.78	8.94	0.9821
59	14.75	8.86	8.94	0.9911
60	15.00	9.12	8.94	1.0201
61	15.25	7.84	8.94	0.8770
62	15.50	6.81	8.94	0.7617
63	15.75	5.07	8.94	0.5671
64	16.00	4.52	8.94	0.5056
65	16.25	3.38	8.94	0.3781
66	16.50	2.73	8.94	0.3054
67	16.75	2.20	8.94	0.2461
68	17.00	1.49	8.94	0.1667
69	17.25	1.22	8.94	0.1365
70	17.50	1.08	8.94	0.1208
71	17.75	0.94	8.94	0.1051
72	18.00	0.56	8.94	0.0626
73	18.25	0.48	8.94	0.0537
74	18.50	0.37	8.94	0.0414
75	18.75	0.35	8.94	0.0391
76	19.00	0.32	8.94	0.0358
77	19.25	0.29	8.94	0.0324
78	19.50	0.20	8.94	0.0224
79	19.75	0.01	8.94	0.0011
80	20.00	0.02	8.94	0.0022
81	20.25	0.00	8.94	0.0000
82	20.50	0.01	8.94	0.0011

**Table C.3** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.45 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
83	20.75	0.05	8.94	0.0056
84	21.00	0.01	8.94	0.0011
85	21.25	0.00	8.94	0.0000
86	21.50	0.00	8.94	0.0000
87	21.75	0.00	8.94	0.0000
88	22.00	0.00	8.94	0.0000
89	22.25	0.00	8.94	0.0000
90	22.50	0.01	8.94	0.0011
91	22.75	0.00	8.94	0.0000
92	23.00	0.00	8.94	0.0000
93	23.25	0.01	8.94	0.0011
94	23.50	0.00	8.94	0.0000
95	23.75	0.00	8.94	0.0000

**Table C.4** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.9 mM.

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
1	0.25	0.07	8.71	0.0080
2	0.50	0.11	8.71	0.0126
3	0.75	0.09	8.71	0.0103
4	1.00	0.08	8.71	0.0092
5	1.25	0.07	8.71	0.0080
6	1.50	0.18	8.71	0.0207
7	1.75	1.32	8.71	0.1515
8	2.00	3.60	8.71	0.4133
9	2.25	5.75	8.71	0.6602
10	2.50	6.94	8.71	0.7968
11	2.75	7.85	8.71	0.9013
12	3.00	8.11	8.71	0.9311
13	3.25	8.17	8.71	0.9380
14	3.50	8.28	8.71	0.9506
15	3.75	8.53	8.71	0.9793
16	4.00	8.58	8.71	0.9851
17	4.25	8.57	8.71	0.9839
18	4.50	8.52	8.71	0.9782
19	4.75	8.68	8.71	0.9966

**Table C.4** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.9 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
20	5.00	8.67	8.71	0.9954
21	5.25	8.63	8.71	0.9908
22	5.50	8.50	8.71	0.9759
23	5.75	8.43	8.71	0.9679
24	6.00	8.42	8.71	0.9667
25	6.25	8.57	8.71	0.9839
26	6.50	8.20	8.71	0.9414
27	6.75	9.00	8.71	1.0333
28	7.00	8.37	8.71	0.9610
29	7.25	8.54	8.71	0.9805
30	7.50	8.58	8.71	0.9851
31	7.75	8.64	8.71	0.9920
32	8.00	8.55	8.71	0.9816
33	8.25	8.56	8.71	0.9828
34	8.50	8.34	8.71	0.9575
35	8.75	8.63	8.71	0.9908
36	9.00	8.71	8.71	1.0000
37	9.25	8.43	8.71	0.9679
38	9.50	8.29	8.71	0.9518
39	9.75	8.70	8.71	0.9989
40	10.00	8.37	8.71	0.9610
41	10.25	8.76	8.71	1.0057
42	10.50	8.72	8.71	1.0011
43	10.75	8.23	8.71	0.9449
44	11.00	8.32	8.71	0.9552
45	11.25	8.55	8.71	0.9816
46	11.50	8.42	8.71	0.9667
47	11.75	8.55	8.71	0.9816
48	12.00	8.29	8.71	0.9518
49	12.25	8.55	8.71	0.9816
50	12.50	8.43	8.71	0.9679
51	12.75	8.22	8.71	0.9437
52	13.00	8.29	8.71	0.9518
53	13.25	8.27	8.71	0.9495
54	13.50	8.45	8.71	0.9701
55	13.75	8.47	8.71	0.9724
56	14.00	8.67	8.71	0.9954
57	14.25	8.44	8.71	0.9690
58	14.50	8.39	8.71	0.9633
59	14.75	8.42	8.71	0.9667
60	15.00	8.44	8.71	0.9690

**Table C.4** - Observed breakthrough curve of Cd through saturated sand at solution IS of 0.9 mM. (Continue)

Sample (No.)	Pore volume (PV)	$C_i$ (ppm)	$C_0$ (ppm)	$C_i/C_0$
61	15.25	7.90	8.71	0.9070
62	15.50	6.32	8.71	0.7256
63	15.75	4.27	8.71	0.4902
64	16.00	2.42	8.71	0.2778
65	16.25	1.40	8.71	0.1607
66	16.50	0.86	8.71	0.0987
67	16.75	0.66	8.71	0.0758
68	17.00	0.43	8.71	0.0494
69	17.25	0.09	8.71	0.0103
70	17.50	0.07	8.71	0.0080
71	17.75	0.05	8.71	0.0057
72	18.00	0.00	8.71	0.0000
73	18.25	0.00	8.71	0.0000
74	18.50	0.00	8.71	0.0000
75	18.75	0.00	8.71	0.0000
76	19.00	0.00	8.71	0.0000
77	19.25	0.00	8.71	0.0000
78	19.50	0.00	8.71	0.0000
79	19.75	0.00	8.71	0.0000
80	20.00	0.05	8.71	0.0057
81	20.25	0.00	8.71	0.0000
82	20.50	0.00	8.71	0.0000
83	20.75	0.00	8.71	0.0000
84	21.00	0.00	8.71	0.0000
85	21.25	0.00	8.71	0.0000
86	21.50	0.00	8.71	0.0000
87	21.75	0.00	8.71	0.0000
88	22.00	0.00	8.71	0.0000
89	22.25	0.00	8.71	0.0000
90	22.50	0.00	8.71	0.0000
91	22.75	0.00	8.71	0.0000
92	23.00	0.00	8.71	0.0000
93	23.25	0.00	8.71	0.0000
94	23.50	0.00	8.71	0.0000
95	23.75	0.00	8.71	0.0000

*Appendix D*

*Column experimental data: Co-transport test of Cd and kaolinite colloid  
through saturated sand column*



**Table D.1** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.0 mM.

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
1	0.25	4.0	0.0385	0.00	0.0001	0.00	0.0000	0.00	0.0010
2	0.50	1.6	0.0154	0.02	0.0022	0.02	0.0018	0.01	0.0050
3	0.75	3.6	0.0347	0.04	0.0043	0.03	0.0030	0.02	0.0151
4	1.00	3.2	0.0308	0.02	0.0024	0.02	0.0024	0.00	0.0020
5	1.25	5.6	0.0539	0.02	0.0022	0.02	0.0022	0.00	0.0020
6	1.50	10.6	0.1021	0.02	0.0024	0.02	0.0019	0.01	0.0060
7	1.75	11.8	0.1136	0.02	0.0025	0.02	0.0024	0.00	0.0030
8	2.00	17.6	0.1694	0.07	0.0071	0.07	0.0078	0.00	0.0010
9	2.25	13.8	0.1329	0.18	0.0194	0.11	0.0127	0.08	0.0754
10	2.50	17.4	0.1675	0.37	0.0395	0.33	0.0392	0.04	0.0422
11	2.75	15.2	0.1463	1.21	0.1302	1.10	0.1326	0.11	0.1106
12	3.00	13.0	0.1252	2.70	0.2906	2.58	0.3110	0.12	0.1206
13	3.25	16.0	0.1540	4.12	0.4435	3.99	0.4804	0.14	0.1357
14	3.50	17.8	0.1714	5.65	0.6082	5.02	0.6052	0.63	0.6332
15	3.75	20.8	0.2003	6.66	0.7169	6.05	0.7288	0.62	0.6181
16	4.00	18.0	0.1733	7.15	0.7696	6.52	0.7860	0.63	0.6332
17	4.25	22.6	0.2176	7.69	0.8278	7.03	0.8469	0.67	0.6683
18	4.50	18.2	0.1752	7.60	0.8181	7.35	0.8855	0.25	0.2563
19	4.75	18.6	0.1791	7.90	0.8504	7.47	0.8999	0.44	0.4372
20	5.00	19.4	0.1868	8.26	0.8891	7.67	0.9247	0.59	0.5930
21	5.25	20.2	0.1945	8.25	0.8881	7.71	0.9289	0.55	0.5477
22	5.50	19.2	0.1849	8.25	0.8881	7.58	0.9138	0.67	0.6734
23	5.75	19.6	0.1887	8.41	0.9053	7.48	0.9011	0.94	0.9397

**Table D.1** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.0 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
24	6.00	16.8	0.1617	8.44	0.9085	7.80	0.9397	0.65	0.6482
25	6.25	21.4	0.2060	8.21	0.8837	7.80	0.9397	0.42	0.4171
26	6.50	19.2	0.1849	8.64	0.9300	7.75	0.9343	0.89	0.8945
27	6.75	22.2	0.2137	8.58	0.9236	7.80	0.9397	0.79	0.7889
28	7.00	20.2	0.1945	8.67	0.9333	7.70	0.9283	0.97	0.9749
29	7.25	21.0	0.2022	8.26	0.8891	7.76	0.9355	0.50	0.5025
30	7.50	20.8	0.2003	8.43	0.9074	8.00	0.9644	0.43	0.4322
31	7.75	21.8	0.2099	8.81	0.9483	8.01	0.9656	0.80	0.8040
32	8.00	21.0	0.2022	8.82	0.9494	7.90	0.9524	0.92	0.9246
33	8.25	24.4	0.2349	8.75	0.9419	7.98	0.9620	0.77	0.7739
34	8.50	22.8	0.2195	8.90	0.9580	7.85	0.9464	1.05	1.0553
35	8.75	20.0	0.1926	8.90	0.9580	7.98	0.9620	0.92	0.9246
36	9.00	23.0	0.2214	8.70	0.9365	7.99	0.9626	0.72	0.7186
37	9.25	23.6	0.2272	8.69	0.9354	8.04	0.9693	0.65	0.6533
38	9.50	20.6	0.1983	8.88	0.9559	7.94	0.9566	0.95	0.9497
39	9.75	22.2	0.2137	8.78	0.9451	7.95	0.9584	0.83	0.8342
40	10.00	21.4	0.2060	9.00	0.9688	8.00	0.9644	1.00	1.0050
41	10.25	24.0	0.2311	9.03	0.9720	8.13	0.9795	0.91	0.9095
42	10.50	25.6	0.2465	8.99	0.9677	8.08	0.9735	0.92	0.9196
43	10.75	24.2	0.2330	8.94	0.9623	8.16	0.9837	0.78	0.7839
44	11.00	24.8	0.2388	8.90	0.9580	7.84	0.9451	1.06	1.0653
45	11.25	19.6	0.1887	8.85	0.9526	7.96	0.9596	0.89	0.8945
46	11.50	22.6	0.2176	8.95	0.9634	7.95	0.9584	1.00	1.0050

**Table D.1** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.0 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
47	11.75	22.0	0.2118	8.94	0.9623	8.26	0.9958	0.68	0.6834
48	12.00	23.2	0.2234	8.80	0.9473	8.00	0.9644	0.80	0.8040
49	12.25	22.6	0.2176	8.80	0.9473	8.12	0.9783	0.69	0.6884
50	12.50	22.0	0.2118	9.00	0.9688	7.99	0.9632	1.01	1.0151
51	12.75	22.6	0.2176	8.97	0.9656	8.13	0.9801	0.84	0.8442
52	13.00	20.8	0.2003	9.06	0.9752	8.19	0.9873	0.87	0.8744
53	13.25	20.6	0.1983	8.76	0.9429	8.21	0.9892	0.56	0.5578
54	13.50	16.6	0.1598	9.14	0.9839	8.48	1.0217	0.67	0.6683
55	13.75	20.2	0.1945	8.94	0.9623	8.26	0.9958	0.68	0.6834
56	14.00	14.6	0.1406	8.90	0.9580	8.37	1.0090	0.53	0.5327
57	14.25	16.4	0.1579	8.85	0.9526	8.17	0.9843	0.69	0.6884
58	14.50	15.0	0.1444	8.84	0.9516	8.21	0.9892	0.64	0.6382
59	14.75	12.0	0.1155	9.03	0.9720	8.29	0.9994	0.74	0.7437
60	15.00	3.6	0.0347	9.10	0.9795	8.41	1.0133	0.69	0.6985
61	15.25	2.2	0.0212	8.77	0.9440	8.22	0.9910	0.55	0.5528
62	15.50	3.2	0.0308	6.72	0.7234	6.41	0.7722	0.32	0.3166
63	15.75	3.8	0.0366	4.95	0.5328	4.53	0.5461	0.42	0.4221
64	16.00	1.6	0.0154	3.40	0.3660	3.25	0.3918	0.15	0.1508
65	16.25	2.6	0.0250	2.62	0.2820	2.41	0.2905	0.21	0.2111
66	16.50	2.2	0.0212	2.20	0.2363	2.01	0.2423	0.19	0.1859
67	16.75	1.8	0.0173	1.98	0.2131	1.93	0.2321	0.05	0.0553
68	17.00	2.2	0.0212	1.78	0.1916	1.67	0.2013	0.11	0.1106
69	17.25	2.4	0.0231	1.54	0.1658	1.42	0.1712	0.12	0.1206

**Table D.1** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.0 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
70	17.50	1.4	0.0135	1.45	0.1555	1.31	0.1579	0.14	0.1357
71	17.75	2.2	0.0212	1.40	0.1507	1.29	0.1549	0.12	0.1156
72	18.00	0.0	0.0000	1.27	0.1362	1.21	0.1459	0.05	0.0553
73	18.25	1.2	0.0116	1.26	0.1356	1.16	0.1392	0.11	0.1055
74	18.50	1.8	0.0173	1.16	0.1243	1.09	0.1314	0.06	0.0653
75	18.75	1.4	0.0135	1.08	0.1163	1.02	0.1224	0.06	0.0653
76	19.00	2.2	0.0212	1.05	0.1130	1.02	0.1224	0.03	0.0352
77	19.25	1.6	0.0154	1.01	0.1087	0.95	0.1139	0.06	0.0653
78	19.50	1.4	0.0135	1.01	0.1087	0.89	0.1073	0.12	0.1206
79	19.75	1.4	0.0135	0.88	0.0947	0.78	0.0940	0.10	0.1005
80	20.00	2.2	0.0212	0.87	0.0936	0.84	0.1007	0.03	0.0352
81	20.25	1.8	0.0173	0.80	0.0861	0.77	0.0922	0.04	0.0352
82	20.50	1.8	0.0173	0.67	0.0721	0.63	0.0759	0.04	0.0402
83	20.75	1.6	0.0154	0.77	0.0823	0.70	0.0844	0.07	0.0653
84	21.00	1.6	0.0154	0.77	0.0829	0.76	0.0910	0.02	0.0151
85	21.25	1.8	0.0173	0.76	0.0818	0.69	0.0826	0.08	0.0754
86	21.50	1.4	0.0135	0.82	0.0883	0.71	0.0850	0.12	0.1156
87	21.75	1.6	0.0154	0.82	0.0883	0.65	0.0778	0.18	0.1759
88	22.00	1.8	0.0173	0.89	0.0958	0.67	0.0808	0.22	0.2211
89	22.25	2.0	0.0193	0.75	0.0807	0.64	0.0766	0.12	0.1156
90	22.50	1.0	0.0096	0.72	0.0775	0.61	0.0729	0.12	0.1156
91	22.75	1.4	0.0135	0.67	0.0721	0.60	0.0723	0.07	0.0704
92	23.00	1.6	0.0154	0.66	0.0710	0.60	0.0723	0.06	0.0603

**Table D.1** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.0 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
93	23.25	2.0	0.0193	0.70	0.0753	0.62	0.0741	0.09	0.0854
94	23.50	1.2	0.0116	0.68	0.0732	0.55	0.0663	0.13	0.1307
95	23.75	1.2	0.0116	0.72	0.0775	0.65	0.0778	0.08	0.0754

**Table D.2** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.225 mM.

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
1	0.25	3.0	0.0300	0.00	0.0000	0.00	0.0000	0.00	0.0000
2	0.50	3.6	0.0360	0.00	0.0000	0.00	0.0000	0.00	0.0000
3	0.75	4.6	0.0460	0.05	0.0053	0.01	0.0012	0.04	0.0500
4	1.00	6.8	0.0680	0.06	0.0064	0.01	0.0012	0.05	0.0625
5	1.25	8.0	0.0800	0.02	0.0021	0.02	0.0023	0.00	0.0000
6	1.50	7.8	0.0780	0.07	0.0074	0.02	0.0023	0.05	0.0625
7	1.75	8.0	0.0800	0.10	0.0106	0.07	0.0081	0.03	0.0375
8	2.00	8.6	0.0860	0.10	0.0106	0.04	0.0047	0.06	0.0750
9	2.25	6.6	0.0660	0.21	0.0223	0.16	0.0186	0.05	0.0625
10	2.50	7.2	0.0720	0.55	0.0585	0.35	0.0407	0.20	0.2500

**Table D.2** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.225 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
11	2.75	6.4	0.0640	1.49	0.1585	1.28	0.1488	0.21	0.2625
12	3.00	6.4	0.0640	3.17	0.3372	2.98	0.3465	0.19	0.2375
13	3.25	6.8	0.0680	4.65	0.4947	4.45	0.5174	0.20	0.2500
14	3.50	8.2	0.0820	5.77	0.6138	5.57	0.6477	0.20	0.2500
15	3.75	6.4	0.0640	6.72	0.7149	6.43	0.7477	0.29	0.3625
16	4.00	6.2	0.0620	7.33	0.7798	7.15	0.8314	0.18	0.2250
17	4.25	6.6	0.0660	7.72	0.8213	7.41	0.8616	0.31	0.3875
18	4.50	7.6	0.0760	7.98	0.8489	7.40	0.8605	0.58	0.7250
19	4.75	7.2	0.0720	7.99	0.8500	7.73	0.8988	0.26	0.3250
20	5.00	6.8	0.0680	8.26	0.8787	8.00	0.9302	0.26	0.3250
21	5.25	6.6	0.0660	8.43	0.8968	8.17	0.9500	0.26	0.3250
22	5.50	8.0	0.0800	8.49	0.9032	8.09	0.9407	0.40	0.5000
23	5.75	7.6	0.0760	8.45	0.8989	8.03	0.9337	0.42	0.5250
24	6.00	7.6	0.0760	8.30	0.8830	8.16	0.9488	0.14	0.1750
25	6.25	7.2	0.0720	8.57	0.9117	8.32	0.9674	0.25	0.3125
26	6.50	7.0	0.0700	8.50	0.9043	8.30	0.9651	0.20	0.2500
27	6.75	6.6	0.0660	8.52	0.9064	8.28	0.9628	0.24	0.3000
28	7.00	6.8	0.0680	8.64	0.9191	8.29	0.9640	0.35	0.4375
29	7.25	6.4	0.0640	8.56	0.9106	8.33	0.9686	0.23	0.2875
30	7.50	7.8	0.0780	8.72	0.9277	8.56	0.9953	0.16	0.2000
31	7.75	8.0	0.0800	8.95	0.9521	8.87	1.0314	0.08	0.1000
32	8.00	7.0	0.0700	8.90	0.9468	8.77	1.0198	0.13	0.1625
33	8.25	6.4	0.0640	8.73	0.9287	8.26	0.9605	0.47	0.5875

**Table D.2** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.225 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
34	8.50	6.2	0.0620	8.61	0.9160	8.20	0.9535	0.41	0.5125
35	8.75	6.6	0.0660	8.83	0.9394	8.31	0.9663	0.52	0.6500
36	9.00	5.4	0.0540	8.68	0.9234	8.30	0.9651	0.38	0.4750
37	9.25	6.2	0.0620	8.74	0.9298	8.41	0.9779	0.33	0.4125
38	9.50	6.6	0.0660	8.69	0.9245	8.45	0.9826	0.24	0.3000
39	9.75	6.8	0.0680	8.78	0.9340	8.39	0.9756	0.39	0.4875
40	10.00	6.6	0.0660	8.88	0.9447	8.67	1.0081	0.21	0.2625
41	10.25	7.0	0.0700	9.08	0.9660	8.80	1.0233	0.28	0.3500
42	10.50	6.8	0.0680	8.90	0.9468	8.71	1.0128	0.19	0.2375
43	10.75	6.2	0.0620	8.82	0.9383	8.61	1.0012	0.21	0.2625
44	11.00	7.2	0.0720	8.80	0.9362	8.67	1.0081	0.13	0.1625
45	11.25	6.6	0.0660	8.99	0.9564	8.91	1.0360	0.08	0.1000
46	11.50	5.2	0.0520	8.79	0.9351	8.59	0.9988	0.20	0.2500
47	11.75	5.8	0.0580	8.84	0.9404	8.70	1.0116	0.14	0.1750
48	12.00	6.4	0.0640	8.82	0.9383	8.61	1.0012	0.21	0.2625
49	12.25	7.0	0.0700	8.93	0.9500	8.83	1.0267	0.10	0.1250
50	12.50	7.8	0.0780	8.90	0.9468	8.80	1.0233	0.10	0.1250
51	12.75	7.6	0.0760	8.91	0.9479	8.89	1.0337	0.02	0.0250
52	13.00	7.0	0.0700	8.90	0.9468	8.82	1.0256	0.08	0.1000
53	13.25	5.2	0.0520	8.71	0.9266	8.53	0.9919	0.18	0.2250
54	13.50	5.8	0.0580	8.86	0.9426	8.61	1.0012	0.25	0.3125
55	13.75	5.2	0.0520	8.79	0.9351	8.61	1.0012	0.18	0.2250
56	14.00	4.4	0.0440	8.74	0.9298	8.57	0.9965	0.17	0.2125

**Table D.2** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.225 mM. (Continue)

Sample (No.)	PV	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
57	14.25	6.0	0.0600	8.83	0.9394	8.60	1.0000	0.23	0.2875
58	14.50	5.8	0.0580	8.82	0.9383	8.40	0.9767	0.42	0.5250
59	14.75	5.0	0.0500	8.80	0.9362	8.58	0.9977	0.22	0.2750
60	15.00	3.8	0.0380	8.83	0.9394	8.42	0.9791	0.41	0.5125
61	15.25	3.8	0.0380	7.83	0.8330	7.56	0.8791	0.27	0.3375
62	15.50	3.2	0.0320	6.35	0.6755	6.14	0.7140	0.21	0.2625
63	15.75	3.4	0.0340	5.02	0.5340	4.85	0.5640	0.17	0.2125
64	16.00	2.4	0.0240	4.37	0.4649	4.23	0.4919	0.14	0.1750
65	16.25	3.6	0.0360	4.20	0.4468	4.03	0.4686	0.17	0.2125
66	16.50	4.0	0.0400	3.85	0.4096	3.79	0.4407	0.06	0.0750
67	16.75	3.4	0.0340	3.47	0.3691	3.46	0.4023	0.01	0.0125
68	17.00	2.4	0.0240	3.20	0.3404	3.11	0.3616	0.09	0.1125
69	17.25	2.2	0.0220	2.86	0.3043	2.81	0.3267	0.05	0.0625
70	17.50	3.0	0.0300	2.55	0.2713	2.41	0.2802	0.14	0.1750
71	17.75	3.0	0.0300	2.29	0.2436	2.12	0.2465	0.17	0.2125
72	18.00	3.4	0.0340	1.92	0.2043	1.84	0.2140	0.08	0.1000
73	18.25	3.2	0.0320	1.79	0.1904	1.60	0.1860	0.19	0.2375
74	18.50	3.8	0.0380	1.62	0.1723	1.41	0.1640	0.21	0.2625
75	18.75	2.6	0.0260	1.38	0.1468	1.12	0.1302	0.26	0.3250
76	19.00	3.6	0.0360	1.30	0.1383	1.07	0.1244	0.23	0.2875
77	19.25	4.0	0.0400	1.20	0.1277	1.00	0.1163	0.20	0.2500
78	19.50	2.4	0.0240	1.17	0.1245	1.07	0.1244	0.10	0.1250
79	19.75	3.6	0.0360	1.10	0.1170	0.98	0.1140	0.12	0.1500



**Table D.2** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.225 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
80	20.00	4.0	0.0400	1.05	0.1117	0.74	0.0860	0.31	0.3875
81	20.25	3.4	0.0340	0.96	0.1021	0.78	0.0907	0.18	0.2250
82	20.50	3.2	0.0320	0.86	0.0915	0.76	0.0884	0.10	0.1250
83	20.75	2.6	0.0260	0.80	0.0851	0.65	0.0756	0.15	0.1875
84	21.00	3.4	0.0340	0.70	0.0745	0.66	0.0767	0.04	0.0500
85	21.25	3.8	0.0380	0.70	0.0745	0.61	0.0709	0.09	0.1125
86	21.50	2.8	0.0280	0.72	0.0766	0.56	0.0651	0.16	0.2000
87	21.75	2.2	0.0220	0.60	0.0638	0.50	0.0581	0.10	0.1250
88	22.00	3.2	0.0320	0.56	0.0596	0.44	0.0512	0.12	0.1500
89	22.25	2.8	0.0280	0.50	0.0532	0.40	0.0465	0.10	0.1250
90	22.50	3.6	0.0360	0.44	0.0468	0.38	0.0442	0.06	0.0750
91	22.75	3.8	0.0380	0.42	0.0447	0.36	0.0419	0.06	0.0750
92	23.00	3.0	0.0300	0.50	0.0532	0.40	0.0465	0.10	0.1250
93	23.25	2.2	0.0220	0.41	0.0436	0.34	0.0395	0.07	0.0875
94	23.50	2.4	0.0240	0.49	0.0521	0.39	0.0453	0.10	0.1250
95	23.75	2.0	0.0200	0.40	0.0426	0.33	0.0384	0.07	0.0875

**Table D.3** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.45 mM.

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
1	0.25	0.4	0.0040	0.00	0.0000	0.00	0.0000	0.00	0.0000
2	0.50	1.6	0.0161	0.00	0.0000	0.00	0.0000	0.00	0.0000
3	0.75	2.4	0.0242	0.00	0.0000	0.00	0.0000	0.00	0.0000
4	1.00	1.4	0.0141	0.00	0.0000	0.00	0.0000	0.00	0.0000
5	1.25	2.8	0.0282	0.00	0.0000	0.00	0.0000	0.00	0.0000
6	1.50	1.2	0.0121	0.00	0.0000	0.00	0.0000	0.00	0.0000
7	1.75	1.2	0.0121	0.00	0.0000	0.00	0.0000	0.00	0.0000
8	2.00	5.2	0.0523	0.00	0.0000	0.00	0.0000	0.00	0.0000
9	2.25	3.0	0.0302	0.23	0.0248	0.22	0.0258	0.01	0.0137
10	2.50	4.2	0.0423	1.07	0.1154	1.07	0.1253	0.00	0.0000
11	2.75	4.4	0.0443	2.86	0.3085	2.85	0.3337	0.01	0.0137
12	3.00	5.2	0.0523	4.40	0.4746	4.35	0.5094	0.05	0.0685
13	3.25	6.4	0.0644	5.72	0.6170	5.57	0.6522	0.15	0.2055
14	3.50	3.8	0.0383	6.63	0.7152	6.29	0.7365	0.34	0.4658
15	3.75	2.4	0.0242	7.10	0.7659	6.93	0.8115	0.17	0.2329
16	4.00	4.4	0.0443	7.58	0.8177	7.55	0.8841	0.03	0.0411
17	4.25	4.0	0.0403	7.82	0.8436	7.65	0.8958	0.17	0.2329
18	4.50	4.8	0.0483	7.78	0.8393	7.46	0.8735	0.32	0.4384
19	4.75	7.6	0.0765	8.18	0.8824	7.90	0.9251	0.28	0.3836
20	5.00	5.0	0.0503	8.42	0.9083	8.06	0.9438	0.36	0.4932
21	5.25	6.8	0.0685	8.38	0.9040	8.29	0.9707	0.09	0.1233
22	5.50	3.6	0.0362	8.30	0.8954	8.25	0.9660	0.05	0.0685
23	5.75	6.0	0.0604	8.56	0.9234	8.26	0.9672	0.30	0.4110

**Table D.3** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.45 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
24	6.00	4.2	0.0423	8.57	0.9245	8.12	0.9508	0.45	0.6164
25	6.25	3.6	0.0362	8.53	0.9202	8.28	0.9696	0.25	0.3425
26	6.50	3.8	0.0383	8.62	0.9299	8.26	0.9672	0.36	0.4932
27	6.75	3.2	0.0322	8.47	0.9137	8.24	0.9649	0.23	0.3151
28	7.00	5.2	0.0523	8.59	0.9266	8.35	0.9778	0.24	0.3288
29	7.25	4.0	0.0403	8.78	0.9471	8.48	0.9930	0.30	0.4110
30	7.50	4.8	0.0483	8.65	0.9331	8.45	0.9895	0.20	0.2740
31	7.75	4.4	0.0443	8.68	0.9364	8.66	1.0141	0.02	0.0274
32	8.00	5.0	0.0503	8.69	0.9374	8.33	0.9754	0.36	0.4932
33	8.25	5.2	0.0523	8.58	0.9256	8.48	0.9930	0.10	0.1370
34	8.50	3.0	0.0302	8.56	0.9234	8.49	0.9941	0.07	0.0959
35	8.75	3.6	0.0362	8.48	0.9148	8.40	0.9836	0.08	0.1096
36	9.00	4.2	0.0423	8.66	0.9342	8.33	0.9754	0.33	0.4521
37	9.25	4.0	0.0403	8.66	0.9342	8.56	1.0023	0.10	0.1370
38	9.50	3.0	0.0302	8.67	0.9353	8.53	0.9988	0.14	0.1918
39	9.75	2.8	0.0282	8.87	0.9569	8.41	0.9848	0.46	0.6301
40	10.00	4.8	0.0483	8.80	0.9493	8.48	0.9930	0.32	0.4384
41	10.25	3.0	0.0302	8.71	0.9396	8.55	1.0012	0.16	0.2192
42	10.50	3.2	0.0322	8.72	0.9407	8.53	0.9988	0.19	0.2603
43	10.75	4.6	0.0463	8.68	0.9364	8.57	1.0035	0.11	0.1507
44	11.00	2.6	0.0262	8.80	0.9493	8.70	1.0187	0.10	0.1370
45	11.25	4.0	0.0403	8.79	0.9482	8.77	1.0269	0.02	0.0274
46	11.50	3.0	0.0302	8.75	0.9439	8.60	1.0070	0.15	0.2055

**Table D.3** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.45 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
47	11.75	4.6	0.0463	8.69	0.9374	8.55	1.0012	0.14	0.1918
48	12.00	2.2	0.0221	8.70	0.9385	8.55	1.0012	0.15	0.2055
49	12.25	4.0	0.0403	8.81	0.9504	8.57	1.0035	0.24	0.3288
50	12.50	3.2	0.0322	8.83	0.9525	8.78	1.0281	0.05	0.0685
51	12.75	3.2	0.0322	8.93	0.9633	8.88	1.0398	0.05	0.0685
52	13.00	4.6	0.0463	9.08	0.9795	8.87	1.0386	0.21	0.2877
53	13.25	4.0	0.0403	8.70	0.9385	8.42	0.9859	0.28	0.3836
54	13.50	3.2	0.0322	8.89	0.9590	8.86	1.0375	0.03	0.0411
55	13.75	2.2	0.0221	8.95	0.9655	8.68	1.0164	0.27	0.3699
56	14.00	4.0	0.0403	8.98	0.9687	8.94	1.0468	0.04	0.0548
57	14.25	2.2	0.0221	8.97	0.9676	8.92	1.0445	0.05	0.0685
58	14.50	3.2	0.0322	8.99	0.9698	8.95	1.0480	0.04	0.0548
59	14.75	4.8	0.0483	8.94	0.9644	8.90	1.0422	0.04	0.0548
60	15.00	4.2	0.0423	8.88	0.9579	8.63	1.0105	0.25	0.3425
61	15.25	2.4	0.0242	8.45	0.9115	8.31	0.9731	0.14	0.1918
62	15.50	1.4	0.0141	8.33	0.8986	7.49	0.8770	0.84	1.1507
63	15.75	3.8	0.0383	7.35	0.7929	6.10	0.7143	1.25	1.7123
64	16.00	2.4	0.0242	6.05	0.6526	5.34	0.6253	0.71	0.9726
65	16.25	3.6	0.0362	5.21	0.5620	4.28	0.5012	0.93	1.2740
66	16.50	3.8	0.0383	4.17	0.4498	3.45	0.4040	0.72	0.9863
67	16.75	5.0	0.0503	3.42	0.3689	2.86	0.3349	0.56	0.7671
68	17.00	2.0	0.0201	2.73	0.2945	2.22	0.2600	0.51	0.6986
69	17.25	2.6	0.0262	2.34	0.2524	1.78	0.2084	0.56	0.7671

**Table D.3** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.45 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
70	17.50	3.2	0.0322	1.88	0.2028	1.56	0.1827	0.32	0.4384
71	17.75	4.8	0.0483	1.59	0.1715	1.40	0.1639	0.19	0.2603
72	18.00	2.8	0.0282	1.29	0.1392	1.11	0.1300	0.18	0.2466
73	18.25	2.8	0.0282	1.17	0.1262	0.94	0.1101	0.23	0.3151
74	18.50	4.6	0.0463	0.98	0.1057	0.79	0.0925	0.19	0.2603
75	18.75	3.0	0.0302	0.88	0.0949	0.67	0.0785	0.21	0.2877
76	19.00	3.2	0.0322	0.62	0.0669	0.59	0.0691	0.03	0.0411
77	19.25	2.0	0.0201	0.66	0.0712	0.42	0.0492	0.24	0.3288
78	19.50	2.2	0.0221	0.57	0.0615	0.50	0.0585	0.07	0.0959
79	19.75	3.6	0.0362	0.41	0.0442	0.41	0.0480	0.00	0.0000
80	20.00	2.4	0.0242	0.41	0.0442	0.39	0.0457	0.02	0.0274
81	20.25	1.4	0.0141	0.36	0.0388	0.34	0.0398	0.02	0.0274
82	20.50	2.4	0.0242	0.34	0.0367	0.30	0.0351	0.04	0.0548
83	20.75	0.6	0.0060	0.28	0.0302	0.28	0.0328	0.00	0.0000
84	21.00	2.0	0.0201	0.26	0.0280	0.24	0.0281	0.02	0.0274
85	21.25	3.8	0.0383	0.18	0.0194	0.18	0.0211	0.00	0.0000
86	21.50	2.2	0.0221	0.16	0.0173	0.16	0.0187	0.00	0.0000
87	21.75	1.6	0.0161	0.10	0.0108	0.10	0.0117	0.00	0.0000
88	22.00	2.6	0.0262	0.09	0.0097	0.08	0.0094	0.01	0.0137
89	22.25	2.0	0.0201	0.11	0.0119	0.08	0.0094	0.03	0.0411
90	22.50	3.6	0.0362	0.05	0.0054	0.05	0.0059	0.00	0.0000
91	22.75	2.8	0.0282	0.04	0.0043	0.04	0.0047	0.00	0.0000
92	23.00	2.0	0.0201	0.02	0.0022	0.02	0.0023	0.00	0.0000

**Table D.3** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.45 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
93	23.25	2.0	0.0201	0.00	0.0000	0.00	0.0000	0.00	0.0000
94	23.50	3.0	0.0302	0.00	0.0000	0.00	0.0000	0.00	0.0000
95	23.75	2.2	0.0221	0.00	0.0000	0.00	0.0000	0.00	0.0000

**Table D.4** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.9 mM.

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
1	0.25	0.4	0.0035	0.04	0.0044	0.04	0.0046	0.00	0.0000
2	0.50	1.8	0.0160	0.04	0.0044	0.04	0.0046	0.00	0.0000
3	0.75	1.4	0.0124	0.03	0.0033	0.02	0.0023	0.01	0.0303
4	1.00	0.4	0.0035	0.01	0.0011	0.01	0.0012	0.00	0.0000
5	1.25	0.0	0.0000	0.01	0.0011	0.01	0.0012	0.00	0.0000
6	1.50	0.0	0.0000	0.02	0.0022	0.01	0.0012	0.01	0.0303
7	1.75	0.0	0.0000	0.02	0.0022	0.02	0.0023	0.00	0.0000
8	2.00	0.8	0.0071	0.01	0.0011	0.01	0.0012	0.00	0.0000
9	2.25	0.6	0.0053	0.10	0.0111	0.10	0.0115	0.00	0.0000
10	2.50	1.6	0.0142	0.36	0.0400	0.36	0.0416	0.00	0.0000

**Table D.4** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.9 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
11	2.75	1.0	0.0089	1.61	0.1791	1.61	0.1859	0.00	0.0000
12	3.00	0.8	0.0071	3.99	0.4438	3.99	0.4607	0.00	0.0000
13	3.25	0.4	0.0035	5.86	0.6518	5.55	0.6409	0.31	0.9394
14	3.50	0.6	0.0053	6.26	0.6963	6.13	0.7079	0.13	0.3939
15	3.75	0.2	0.0018	7.80	0.8676	7.55	0.8718	0.25	0.7576
16	4.00	0.2	0.0018	7.80	0.8676	7.62	0.8799	0.18	0.5455
17	4.25	1.6	0.0142	8.20	0.9121	7.76	0.8961	0.44	1.3333
18	4.50	0.0	0.0000	8.20	0.9121	8.15	0.9411	0.05	0.1515
19	4.75	0.2	0.0018	8.34	0.9277	8.16	0.9423	0.18	0.5455
20	5.00	0.4	0.0035	8.58	0.9544	8.38	0.9677	0.20	0.6061
21	5.25	1.2	0.0106	8.66	0.9633	8.52	0.9838	0.14	0.4242
22	5.50	0.6	0.0053	8.86	0.9855	8.44	0.9746	0.42	1.2727
23	5.75	0.0	0.0000	8.51	0.9466	8.17	0.9434	0.34	1.0303
24	6.00	0.8	0.0071	8.60	0.9566	8.13	0.9388	0.47	1.4242
25	6.25	0.4	0.0035	8.61	0.9577	8.35	0.9642	0.26	0.7879
26	6.50	0.0	0.0000	8.58	0.9544	8.37	0.9665	0.21	0.6364
27	6.75	1.8	0.0160	8.56	0.9522	8.39	0.9688	0.17	0.5152
28	7.00	0.0	0.0000	8.72	0.9700	8.54	0.9861	0.18	0.5455
29	7.25	0.0	0.0000	8.60	0.9566	8.39	0.9688	0.21	0.6364
30	7.50	2.4	0.0213	8.80	0.9789	8.58	0.9908	0.22	0.6667
31	7.75	0.0	0.0000	8.80	0.9789	8.54	0.9861	0.26	0.7879
32	8.00	2.4	0.0213	8.78	0.9766	8.55	0.9873	0.23	0.6970
33	8.25	1.2	0.0106	8.83	0.9822	8.58	0.9908	0.25	0.7576

**Table D.4** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.9 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
34	8.50	0.0	0.0000	8.81	0.9800	8.60	0.9931	0.21	0.6364
35	8.75	0.0	0.0000	8.61	0.9577	8.56	0.9885	0.05	0.1515
36	9.00	0.6	0.0053	8.70	0.9677	8.52	0.9838	0.18	0.5455
37	9.25	1.6	0.0142	8.58	0.9544	8.42	0.9723	0.16	0.4848
38	9.50	1.2	0.0106	8.60	0.9566	8.50	0.9815	0.10	0.3030
39	9.75	3.6	0.0319	8.51	0.9466	8.51	0.9827	0.00	0.0000
40	10.00	2.8	0.0248	8.90	0.9900	8.60	0.9931	0.30	0.9091
41	10.25	0.2	0.0018	8.62	0.9588	8.62	0.9954	0.00	0.0000
42	10.50	1.8	0.0160	8.70	0.9677	8.60	0.9931	0.10	0.3030
43	10.75	2.6	0.0230	8.79	0.9778	8.73	1.0081	0.06	0.1818
44	11.00	1.8	0.0160	8.85	0.9844	8.59	0.9919	0.26	0.7879
45	11.25	1.8	0.0160	9.00	1.0011	8.53	0.9850	0.47	1.4242
46	11.50	4.0	0.0355	8.70	0.9677	8.62	0.9954	0.08	0.2424
47	11.75	3.6	0.0319	8.70	0.9677	8.70	1.0046	0.00	0.0000
48	12.00	3.0	0.0266	8.76	0.9744	8.65	0.9988	0.11	0.3333
49	12.25	0.0	0.0000	8.80	0.9789	8.54	0.9861	0.26	0.7879
50	12.50	0.6	0.0053	8.80	0.9789	8.67	1.0012	0.13	0.3939
51	12.75	3.8	0.0337	8.87	0.9867	8.87	1.0242	0.00	0.0000
52	13.00	1.6	0.0142	9.04	1.0056	8.62	0.9954	0.42	1.2727
53	13.25	2.6	0.0230	8.79	0.9778	8.76	1.0115	0.03	0.0909
54	13.50	2.2	0.0195	8.84	0.9833	8.77	1.0127	0.07	0.2121
55	13.75	2.0	0.0177	8.90	0.9900	8.54	0.9861	0.36	1.0909
56	14.00	3.2	0.0284	8.72	0.9700	8.45	0.9758	0.27	0.8182



**Table D.4** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.9 mM. (Continue)

Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
57	14.25	6.2	0.0550	8.79	0.9778	8.74	1.0092	0.05	0.1515
58	14.50	2.6	0.0230	8.60	0.9566	8.34	0.9630	0.26	0.7879
59	14.75	5.8	0.0514	8.91	0.9911	8.63	0.9965	0.28	0.8485
60	15.00	8.2	0.0727	8.77	0.9755	8.65	0.9988	0.12	0.3636
61	15.25	2.6	0.0230	8.74	0.9722	8.66	1.0000	0.08	0.2424
62	15.50	2.2	0.0195	8.79	0.9778	8.69	1.0035	0.10	0.3030
63	15.75	6.8	0.0603	6.94	0.7720	6.90	0.7968	0.04	0.1212
64	16.00	7.4	0.0656	4.60	0.5117	4.60	0.5312	0.00	0.0000
65	16.25	4.6	0.0408	3.42	0.3804	3.37	0.3891	0.05	0.1515
66	16.50	7.0	0.0621	2.64	0.2937	2.64	0.3048	0.00	0.0000
67	16.75	8.2	0.0727	1.94	0.2158	1.91	0.2206	0.03	0.0909
68	17.00	3.0	0.0266	1.44	0.1602	1.44	0.1663	0.00	0.0000
69	17.25	7.0	0.0621	1.36	0.1513	1.34	0.1547	0.02	0.0606
70	17.50	5.8	0.0514	0.98	0.1090	0.68	0.0785	0.30	0.9091
71	17.75	4.6	0.0408	0.69	0.0768	0.56	0.0647	0.13	0.3939
72	18.00	5.4	0.0479	0.68	0.0756	0.66	0.0762	0.02	0.0606
73	18.25	3.6	0.0319	0.48	0.0534	0.48	0.0554	0.00	0.0000
74	18.50	1.6	0.0142	0.42	0.0467	0.30	0.0346	0.12	0.3636
75	18.75	2.2	0.0195	0.39	0.0434	0.14	0.0162	0.25	0.7576
76	19.00	4.8	0.0426	0.34	0.0378	0.15	0.0173	0.19	0.5758
77	19.25	5.2	0.0461	0.32	0.0356	0.32	0.0370	0.00	0.0000
78	19.50	3.8	0.0337	0.20	0.0222	0.20	0.0231	0.00	0.0000
79	19.75	3.6	0.0319	0.14	0.0156	0.14	0.0162	0.00	0.0000

**Table D.4** - Observed breakthrough curve of Cd-bearing kaolinite colloid, total Cd, dissolved Cd and kaolinite-facilitated Cd through saturated sand at solution IS of 0.9 mM. (Continue)

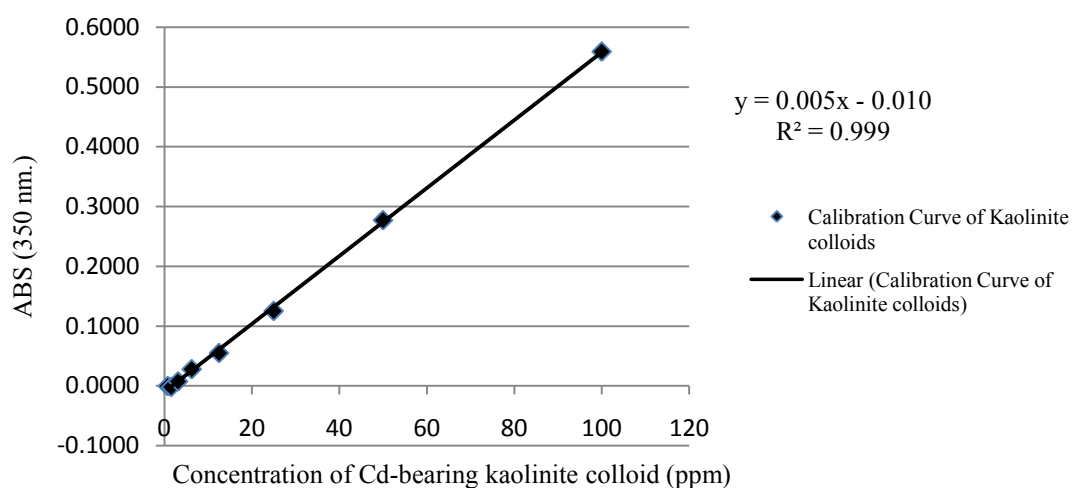
Sample (No.)	<i>PV</i>	Conc. of kaolinite colloid		Conc. of total Cd		Conc. of dissolved Cd		Conc. of kaolinite-F-Cd	
		$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$	$C_i$ (ppm)	$C_i/C_0$
80	20.00	5.0	0.0443	0.12	0.0133	0.06	0.0069	0.06	0.1818
81	20.25	5.0	0.0443	0.11	0.0122	0.01	0.0012	0.10	0.3030
82	20.50	4.8	0.0426	0.10	0.0111	0.01	0.0012	0.09	0.2727
83	20.75	4.0	0.0355	0.01	0.0011	0.01	0.0012	0.00	0.0000
84	21.00	4.6	0.0408	0.01	0.0011	0.00	0.0000	0.01	0.0303
85	21.25	0.0	0.0000	0.06	0.0067	0.00	0.0000	0.06	0.1818
86	21.50	0.0	0.0000	0.04	0.0044	0.01	0.0012	0.03	0.0909
87	21.75	0.0	0.0000	0.01	0.0011	0.01	0.0012	0.00	0.0000
88	22.00	1.6	0.0142	0.04	0.0044	0.03	0.0035	0.01	0.0303
89	22.25	2.0	0.0177	0.00	0.0000	0.00	0.0000	0.00	0.0000
90	22.50	0.2	0.0018	0.02	0.0022	0.02	0.0023	0.00	0.0000
91	22.75	1.0	0.0089	0.02	0.0022	0.00	0.0000	0.02	0.0606
92	23.00	1.4	0.0124	0.01	0.0011	0.01	0.0012	0.00	0.0000
93	23.25	1.6	0.0142	0.02	0.0022	0.01	0.0012	0.01	0.0303
94	23.50	0.6	0.0053	0.02	0.0022	0.01	0.0012	0.01	0.0303
95	23.75	1.8	0.0160	0.02	0.0022	0.02	0.0023	0.00	0.0000

*Appendix E*

*Cd-bearing kaolinite colloid calibration curves*

**Table E.1** Observed data of Cd-bearing kaolinite colloid at solution IS of 0.0 mM measured using UV/vis spectrophotometer at wavelength 350 nm to establish the calibration curve

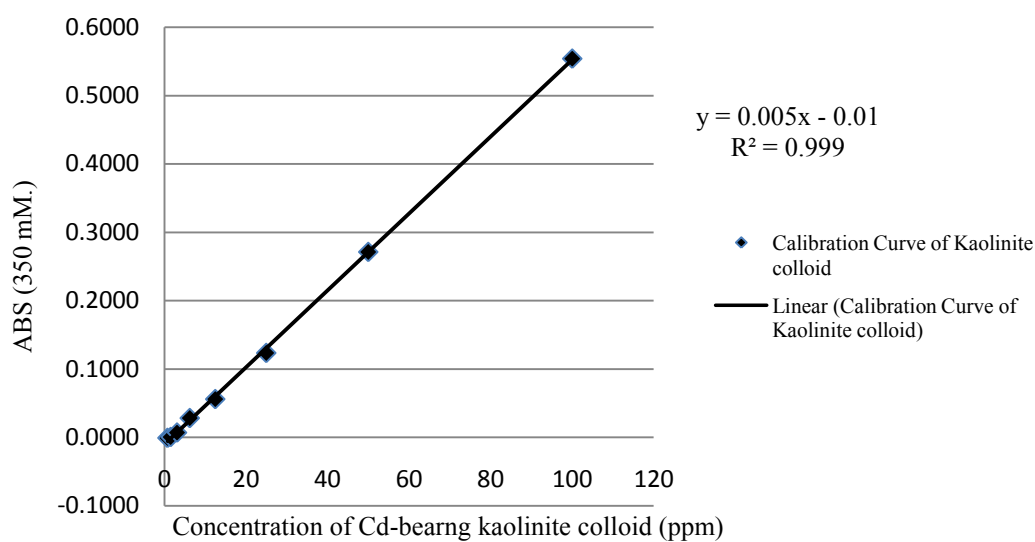
Conc. of Cd-bearing kaolinite colloid (ppm)	ABS				Average	SD ( $\pm$ )
	Replication 1	Replication 2	Replication 3	Replication 4		
0.7815	0.000	0.000	-0.003	0.002	-0.0003	0.0021
1.5625	0.023	-0.011	-0.018	-0.010	-0.0018	0.0179
3.125	0.036	-0.014	0.001	0.007	0.0075	0.0210
6.25	0.036	0.020	0.039	0.017	0.0280	0.0111
12.5	0.065	0.050	0.066	0.039	0.0550	0.0129
25	0.135	0.109	0.136	0.121	0.1253	0.0128
50	0.292	0.282	0.258	0.276	0.2770	0.0143
100	0.569	0.583	0.538	0.545	0.5588	0.0209



**Figure E.1** Calibration curve of Cd-bearing kaolinite colloid at solution IS of 0.0 mM.

**Table E.2** Observed data of Cd-bearing kaolinite colloid at solution IS of 0.225 mM measured using UV/vis spectrophotometer at wavelength 350 nm to establish the calibration curve

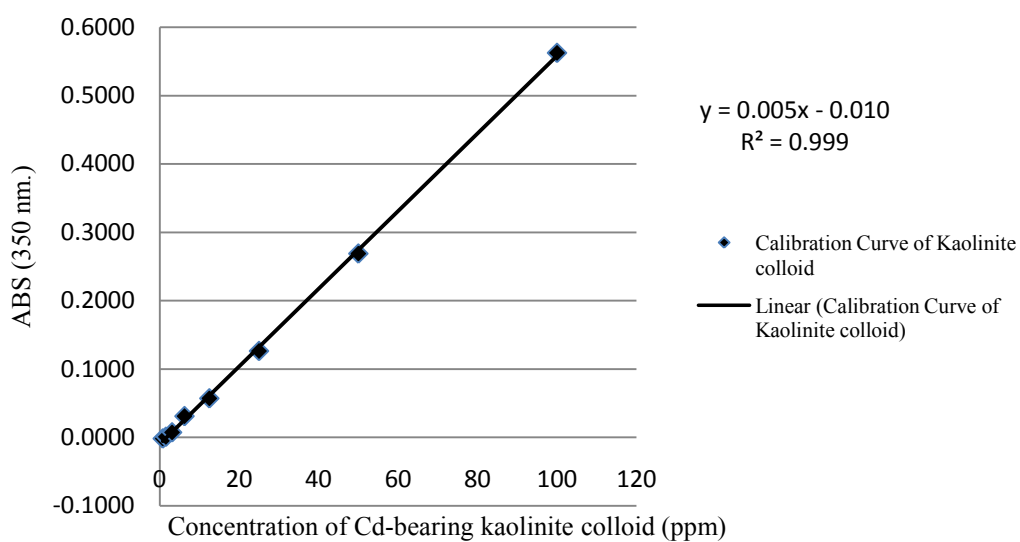
Conc. of Cd-bearing kaolinite colloid (ppm)	ABS Replication 1	ABS Replication 2	ABS Replication 3	ABS Replication 4	Average	SD ( $\pm$ )
0.7815	-0.001	-0.003	0.000	0.001	-0.0008	0.0017
1.5625	-0.005	0.000	0.003	0.004	0.0005	0.0040
3.125	0.007	0.008	0.003	0.010	0.0070	0.0029
6.25	0.031	0.025	0.036	0.021	0.0283	0.0066
12.5	0.065	0.045	0.068	0.046	0.0560	0.0122
25	0.118	0.126	0.122	0.128	0.1235	0.0044
50	0.287	0.270	0.256	0.272	0.2713	0.0127
100	0.559	0.561	0.530	0.566	0.5540	0.0163



**Figure E.2** Calibration curve of Cd-bearing kaolinite colloid at solution IS of 0.225 mM.

**Table E.3** Observed data of Cd-bearing kaolinite colloid at solution IS of 0.45 mM measured using UV/vis spectrophotometer at wavelength 350 nm to establish the calibration curve

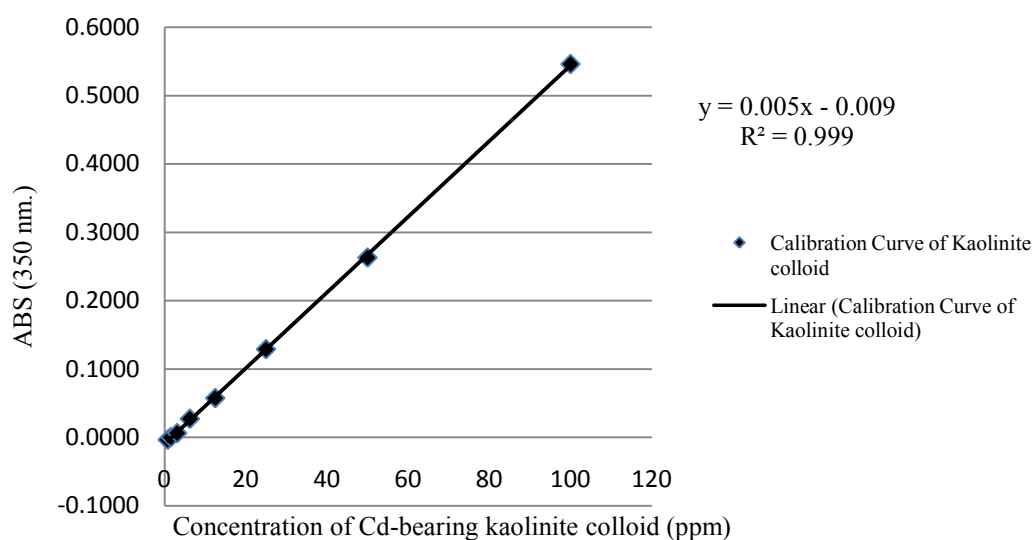
Conc. of Cd-bearing kaolinite colloid (ppm)	ABS	ABS	ABS	ABS	Average	SD ( $\pm$ )
	Replication 1	Replication 2	Replication 3	Replication 4		
0.7815	-0.002	-0.001	-0.004	0.000	-0.0018	0.0017
1.5625	0.000	0.000	0.002	0.001	0.0008	0.0010
3.125	0.005	0.010	0.005	0.009	0.0073	0.0026
6.25	0.029	0.037	0.030	0.022	0.0295	0.0061
12.5	0.055	0.061	0.058	0.054	0.0570	0.0032
25	0.128	0.130	0.126	0.121	0.1263	0.0039
50	0.271	0.266	0.259	0.279	0.2688	0.0084
100	0.589	0.560	0.547	0.553	0.5623	0.0186



**Figure E.3** Calibration curve of Cd-bearing kaolinite colloid at solution IS of 0.45 mM.

**Table E.4** Observed data of Cd-bearing kaolinite colloid at solution IS of 0.9 mM measured using UV/vis spectrophotometer at wavelength 350 nm to establish the calibration curve

Conc. of Cd-bearing kaolinite colloid (ppm)	ABS	ABS	ABS	ABS	Average	SD ( $\pm$ )
	Replication 1	Replication 2	Replication 3	Replication 4		
0.7815	-0.005	0.000	-0.008	-0.001	-0.0035	0.0037
1.5625	-0.001	-0.003	0.005	0.000	0.0003	0.0034
3.125	0.007	0.005	0.006	0.007	0.0063	0.0010
6.25	0.025	0.028	0.029	0.032	0.0285	0.0029
12.5	0.051	0.057	0.062	0.060	0.0575	0.0048
25	0.122	0.128	0.141	0.125	0.1290	0.0084
50	0.257	0.266	0.278	0.251	0.2630	0.0117
100	0.560	0.558	0.556	0.510	0.5460	0.0241



**Figure E.4** Calibration curve of Cd-bearing kaolinite colloid at solution IS of 0.9 mM.

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