Dynamic Study and Modelling of Arsenic Removal from Groundwater Using Ferromagnetic Carbon as Fixed Bed Adsorbent in Column.

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This study investigated the performance of Ferromagnetic Carbon (FC) as an effective natural adsorbent for arsenic removal from groundwater in Dong Thap Province (Vietnam). To do this, leaching fixed-bed column experiments have been carried out. The influence of operating variables affecting the process was studied, under varying operating conditions and experimental data were modelled using bed depth service time (BDST) and mass transfer approaches. Speciation studies showed that the groundwater contained 48.5% of particulate arsenic and 51.5% of soluble arsenic. Indeed, As (III) and As (V) forms represented respectively 41.9% and 58.1% in the dissolved arsenic. As removal was parametric depending such as pH, flow rate, initial As and adsorbent mass, requiring an optimization for optimum conditions When the pH increased from 3 to 11, removal of As(V) decreased from 96.5% to 5% while As(III) removal increased from 40% to 69%. The increase of initial arsenic has caused an increase in removal efficiency of different forms of arsenic. The easy regeneration of FC using a molar sodium hydroxide solution suggests that is an efficient and low-cost material to reduce the contamination of arsenic in drinking groundwater.

Introduction

In Vietnam and some parts of the world, arsenic contamination in groundwater has become a major environmental concern [1, 26]. Arsenic toxicity mostly reported by two inorganic forms are As (III)-arsenite and As (V) – arsenate [12]. As (III) species are more toxic and more difficult to remove from water than arsenate [27] while As (V) species are less toxic and strongly adsorbed on different kind of mineral surfaces [8]. According to a previous study [31], arsenic contamination in groundwater from Mekong Delta is naturally occurring and caused by chemical and microbial induced reductive dissolution of iron-oxides from the alluvial sediments in the delta. Previous studies

[1, 31] conducted in this region suggested that arsenic released from the delta sediments is due to the reductive dissolution of the iron bearing minerals and arsenic concentrations in the region can achieve 1300 ppb. Arsenic concentration in ground waters was ranged from 0.5 to 977.7 µg/L in Dong Thap Province [14]. In Dong Thap Province, it has been demonstrated that As(V) form is predominant in dissolved arsenic and 49.9% particulate arsenic from groundwater containing 427µg/L of total As [17].

Various technologies have been developed for the treatment of enriched arsenic water, among them, there is adsorption in batch or column mode [16, 23]. Adsorption is one of the most popular processes for arsenic removal from water because of its cost-effective, high affinity of dissolved arsenic and can also be used in small scale household units [29]. Moreover, lot of reports indicated that cheap natural adsorbents such as clay, ferric hydroxide, laterite, and carbons could remove successfully arsenic from water [9, 11, 24, 25].

In Burkina Faso, preliminary study showed the efficiency of ferromagnetic carbon as adsorbent in As(V) removal from aqueous solutions with high removal percentages up to 97% [24]. In the literature, only a few studies on arsenic removal were conducted using column experiments and most of works have been carried out in batch mode [6, 9, 12]. This work aims to use ferromagnetic carbon as adsorbent of arsenic in column adsorption for the treatment of natural groundwater.

The objectives of this study were (i) to assess the effects of operating parameters under various conditions (pH, initial arsenic concentrations, and hydrological regimes in the column on breakthrough curves) and (ii) to model the dynamics of adsorption process using bed depth service time (BDST) and mass transfer approaches.

Material and methods

Materials

Ferromagnetic Carbon (FC) was prepared and characterized in previous work [24]. Characterization revealed that this material contained 63% of Carbon confirming its carbonaceous structure and microporous structure. In addition, this FC presented an arsenic removal capacity of 153 µg/g at pH 7 and 60 min of contact time [24].

Sampling and analysis of groundwater

Groundwater samples were collected on September 29th, 2016, in Dong Thap, a Mekong Delta Province located in the South of Vietnam and water samples were shipped the same day to the Institute for Environment and Resources' Laboratory (IER's lab) and stored at 4°C. Measurements of groundwater composition were carried out at 28°C from September to October 2016. Parameters such as temperature, pH, Electric conductivity (EC) and total dissolved

solids (TDS) were measured using the pH meter Inolab serial WTW 730 and Handy Lab 2000. Chemical oxygen demand (COD) was determined using standard method as described elsewhere [22]. All measurements were repeated three times and the average values are given in **Table 1**.

Arsenic speciation studies were conducted using the protocol described by Edwards et al. [3], modified by [28] and used by [17]. In the process of speciation, total As, soluble As and As (III) were analyzed directly from the groundwater sample using Hydride Generation - Atomic Absorption Spectrophotometer (HG-AAS). Afterby, Particulate As was obtained by deducting soluble As from total As and As (V) by deducting As (III) from soluble arsenic. All chemicals used were of analytical grade.

Leaching fixed-bed column experiments

A leaching fixed-bed column system was set-up for the investigation of arsenic removal efficiency from groundwater using FC particles. The column was designed with the internal diameter of 28 mm and the length of 225 mm (**Figure 1**). At first, different weights of FC were packed in columns corresponding to different bed depths. Double distilled water was used to wash the FC materials for 5 times before the experiment starts. Enriched arsenic groundwater was loaded on the top of the column and the effluent water was collected in order to analyze arsenic concentration. Glass wools and glass beads were putted to secure the bottom of column.

Arsenic removal experiments have been realized from October to December 2016. Fixed bed column experiments were conducted from 0 to 420 min, under various conditions in order to evaluate the influence of initial pH values, initial arsenic concentrations, and the column hydrological regimes on arsenic removal efficiency.

The efficiency of arsenic removal (%As) was calculated as follows:

$$\%As = \frac{C_0 - C_e}{C_0} \times 100 \qquad (1)$$

Where C_0 and Ce represent the concentration of arsenic in influent water and effluent water (µg/L), respectively.

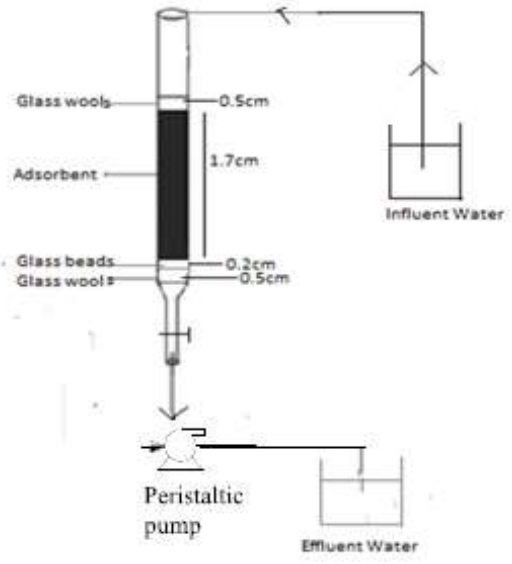


Figure 1. Experimental setup of fixed bed column

Effect of pH values

At first, columns were packed with 20 g of FC and the flow rate was fixed to 5 mL/min using natural groundwater containing an initial arsenic concentration of 0.511 mg/L. The value of pH in influent water was fixed to 3, 5, 7, 9 and 11, and adjusted with stock solutions 1.0 M NaOH or 1.0 M HNO_3. After loading of each solution into the columns during 60 min, effluents waters were collected at the bottom for the determination of residual total arsenic.

Effect of initial arsenic concentrations

In this study, columns were also packed with laterite 20 g corresponding to 4.5 cm of bed depth. Arsenic concentration in groundwater was adjusted using dilution and 1000 mg/L As (V) solution to various initial concentrations between 0.153, and 0.853 mg/L. Flow rate was fixed to 5 mL/min for all the experiments. These water samples were loaded on the top of the columns during 60 min and the concentrations of total arsenic was determined in the effluent water.

Effect of flow rates

Two values of flow rate (3.84 and 7 mL/min) were used to treat a water sample containing 0.511 mg/L and pH 7 in the whole of each experiment during 60 min. A weight of 20 g of FC was used at room temperature.

Effect of adsorbent masses or bed depths in column

Enriched arsenic groundwater with initial As concentration of 0.511 mg/L was loaded in the column with arsenic-spiked groundwater in the up-flow mode with a volumetric flow rate of 5.67 mL/min. The initial concentration of arsenic in groundwater sample was fixed to 0.511 mg/L.

Fixed bed column studies were conducted using the column packed with FC at 2.5, 3.5 and 4.5 cm of bed depth, corresponding to 10 g, 15 g and 20 g of FC, respectively.

Results and discussion

Physical-chemical characteristics of groundwater sample

The characteristics of groundwater are provided in **Table 1** where we can remark the presence of total iron, and high values of COD, Hardness and dissolved solids (TDS). It was observed a strong presence of some competitors' anions such as phosphate, sulfate, chloride, bicarbonate and fluoride that can affect the removal of arsenates and arsenites through a competitive adsorption [23, 13]. Ammonium was not competing with arsenic species for occupation of adsorption sites because of charge incompatibility. The value of pH of groundwater sample between 5.5 and 9 indicates that likely arsenic species could be H_3AsO_3, $H_2AsO_4^-$ and $HAsO_4^{2-}$ according to the equilibrium diagram of arsenic speciation [10]. These results are in agreement with conclusions of previous works in

this region [14, 17, 31] indicating that the main forms of arsenic are probably As (III), As (V) and particulate form coated in total suspended solids from sediments.

Table 1. Physical-chemical properties of groundwater sample

Parameter	pH	T (°C)	EC (µS/cm)	TSS (mg/L)	TDS (mg/L)	TS (mg/L)	TH ($mgCaCO_3$/L)	TA ($mgCaCO_3$/L)
Value	6.93	27.2	1112	61	591	652	214	40

Parameter	F^- (mg/L)	COD (mg/L)	Fe (mg/L)	NH_4^+ (mg/L)	PO_4^{3-} (mg/L)	SO_4^{2-} (mg /L)	Cl^- (mg/L)	HCO_3^- (mg/L)	Total As (µg/L)
Value	1.6	28	13.54	29.4	1.87	15.5	15	48.8	511

Arsenic speciation studies

Ferromagnetic carbon was used to prepare a resin in the acetate form and this resin was used as fixed bed in the column to specify As (V) and As (III) quantities in the dissolved arsenic. This resin removed totally As (V) form by anion exchange between As (V) species and hydroxyl ions. The concentration of As(III) is analyzed in effluent water and As(V) amount was deducted from dissolved As and As (III) quantities. Calculations showed that groundwater contains 48.5% of particulate arsenic and 51.05% of soluble arsenic. In the soluble arsenic, As (III) represented 41.9% while 58.1% for As (V). The presence of As (III) and As (V) in the groundwater sample with predominance of As (V) is in agreement with literature data [14, 17]. So, groundwater contains more of As (V) easily removable compared to As (III).

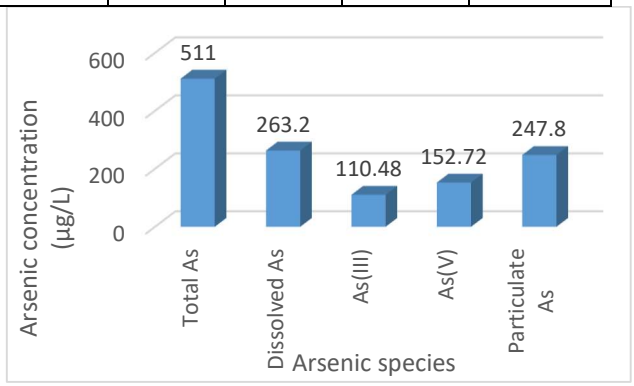


Figure 2. Arsenic speciation in groundwater from Dong Thap Province

Effect of initial pH on arsenic removal percentage

The value of pH is known to be an important parameter which considerably affects the arsenic species using column adsorption experiments [5]. The increase of pH values in water from 3 to 11 caused a decrease of removal percentage for total arsenic and As(V) according to two steps (**Figure 3**). Slow step between pH 3 and 9 was due the positive surface charge (pH) on FC and the rate of particulate arsenic. The rapid step after pH 9 would be due to the negative surface charge of FC and the electrostatic repulsion between arsenates and hydroxyl ions

which are more mobile [4]. Indeed, total arsenic was removed from 84 to 63.68% while As(V) removal decreased from 96.5% to 5% in the same range of pH from 3 to 11. The decrease of total arsenic and As(V) removal with pH increasing can be attributed to the decreasing of electrostatic interactions between the surface charge of adsorbents and multipotent anionic species such as $HAsO_4^{2-}$ and $H_2AsO_4^-$ [18]. According to the literature, the removal efficiency of As (V) should decrease with pH increasing [11, 17, 23, 24, 25] . While when the pH was increased, As(III) removal increased from 40% to 69% according to two steps: first step (slow) between pH 3 and 7 was due to neutral As(III) form (H_3AsO_3) which can be removed only by surface complexation and second step (quick) between pH 7 and 11 could be explained by the ionization of H_3AsO_3 to give arsenites ($H_2AsO_3^-$ and $HAsO_3^{2-}$) easily to remove by other mechanisms such as anion exchange and competitive adsorption [21]. The increase in As(III) removal can be attributable to coulomb interactions and the formation of chelator complexes between arsenites and charged surface functions on FC [20]. Optimum percentages in arsenic removal were achieved at pH=3 for As(V) and pH=11 for As(III) . Arsenate and arsenite ions are involved in the formation of external sphere complexes with iron ions on the surface of FC through the chemisorption process [24].

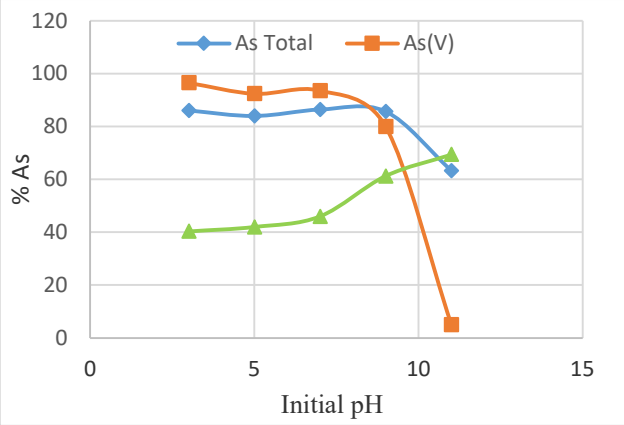


Figure 3. Effect of initial pH on arsenic removal using FC with m = 20 g, C_0 = 0.511 mg/L, Flow rate = 5 mL/min and T=25°C.

Effect of initial Arsenic concentration on arsenic removal percentage

The behavior of arsenic species was studies by varying the initial arsenic concentration in water. When initial total arsenic concentration was increased from 0.153 to 0.853 mg/L, arsenic removal percentage increased for all arsenic species (**Figure 4**). Indeed, the removal of total arsenic was easily comparatively to As(V) and As(III) as indicated by high removal rates in **Figure 3**. In addition, As(V) was highly removed compared to As(III). This increase in arsenic removal can be explained as the result of the occupation of free sites, inaccessible at low concentrations of adsorbate [16, 29] . Maximum removals of total arsenic, As(V) and As(III) were respectively 85.72%, 88.48%, and 67.54% at high arsenic concentration (0.853 mg/L).

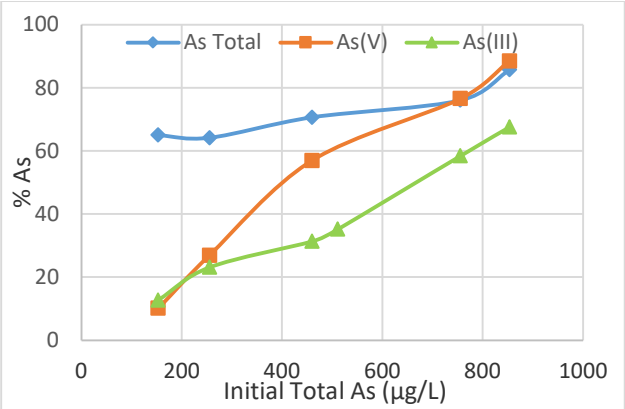


Figure 4. Effect of influent concentration on arsenic removal using FC with m = 20 g, pH=7, Flow rate = 5 mL/min and T=25°C.

Effect of flow rate on breakthrough curves

Flow rate is known to have a quick effect on arsenic removal in column experiments. To do this, two values of flow rate (3.84 and 7 mL/min) were used with groundwater containing 0.511 mgAs/L. As seen in **Figure 5**, the breakthrough (corresponding to 1% of influent concentration), was occurred about 10 and 5 min with flow rates 3.84 and 7 mL/min, respectively. The exhaustion (corresponding to 100% of influent concentration) was achieved around 420 and 240 min with flow rates 3.84 and 7 mL/min, respectively. Analysis of these results showed a decrease of service time of the column using high flow rate (7 mL/min). Indeed, an increase of flow rate causes a decrease of contact time involving a decrease of the removal efficiency [9]. With lower flow rate, the removal efficiency increases with empty bed contact time (EBCT) increasing.

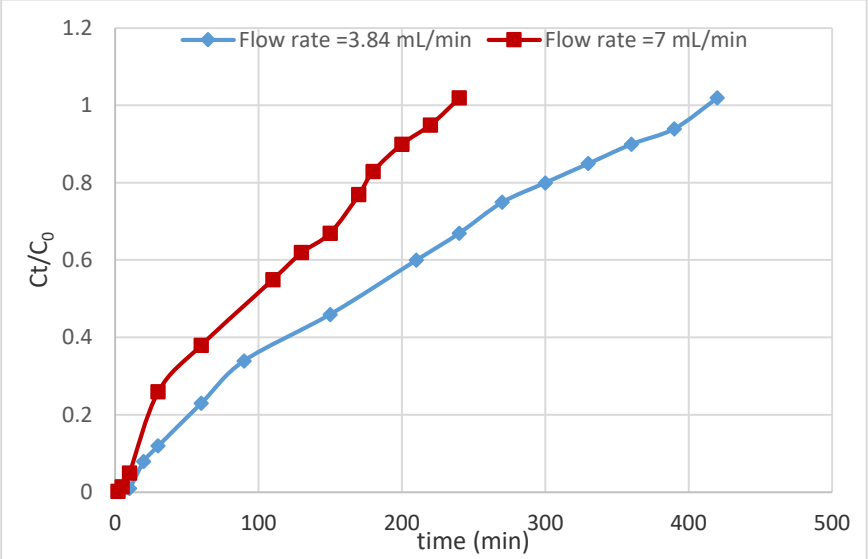


Figure 5. Effect of flow rate on breakthrough curves using FC with m = 20 g, pH = 7, C_0 = 0.511 mg/L and T=25°C.

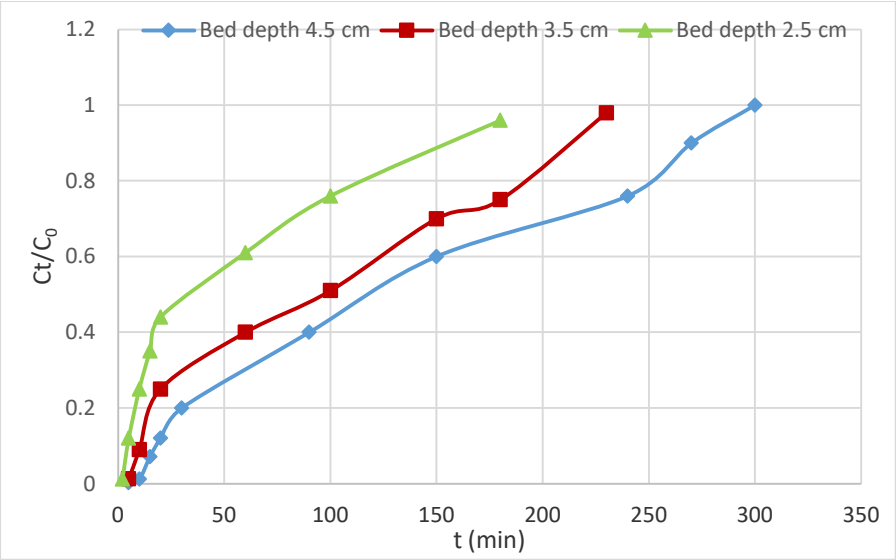


Figure 6. Effect of bed depth on breakthrough curves in arsenic removal using FC packed columns with C_0 = 0.47 mg/L, flow rate = 11.4 mL/min and T=25°C.

Effect of bed depths on breakthrough curves

The breakthrough curves were obtained by plotting the effluent arsenic concentrations as a function of lapse time using different bed depths (2.5 cm, 3.5 cm and 4.5 cm) or equivalent FC mass of 10 g, 15 g and 20 g. Points on the breakthrough curves at which As concentration reached its maximum allowable value of 0.01 mg/L (corresponding to C/C_0 = 0.01) was taken as "breakthrough point" and that corresponding to 100% of the influent concentration as "point of exhaustion" (**Figure 6**).

From **Figure 5**, the breakthrough times were obtained around 2, 5 and 10 min for bed depth of 2.5 cm, 3.5 cm and 4.5 cm respectively corresponding to 11.34 mL, 28.35 mL and 56.7 mL of treated water. The exhaustion was occurred at 180, 230 and 330 min, respectively corresponding to 1020 mL, 1304 mL and 1871 mL of treated water. We noticed the increase of service time of columns when the bed depth or FC mass increased inside of column.

Assessment of operational column behavior

The behavior of column was evaluated from different parameters of column such as time required for the exchange zone to move its own height (*tz*), height of the adsorption zone (*hz*), rate at which the adsorption zone is moving up or down through the bed (*Uz*) and bed saturation. Those parameters have been calculated following the concepts of Michaels [15], reported by Kundu and Gupta [9] and used by Nugyen [17]. In **Table 2**, are listed the obtained values.

Table 2. *Important column behavior parameters*

Parameter	Bed depth = 2.5 cm	Bed depth = 3.5 cm	Bed depth = 4.5 cm	Average value
tz (min)	178	225	290	231
hz (cm)	3	4	5	4
Uz (cm/min)	0.017	0.017	0.017	0.017
% saturation	78.88	81.71	85.22	82

From **Table 2**, it was observed that adsorption was occurred on 4cm of bed depth in the column at 82% of saturation. In addition, the low speed of adsorption area moving (0.017 cm/min) could be explained by the duration of the adsorption area moving on its own height during 231 minutes.

Operational column regimes and modelling of column data

Data modeling was done using two approaches: BDST and mass transfer. The BDST model is optimized according to the equation of Bohart and Adams while the mass transfer is based on the Wolborska equation and optimized through the Langmuir isotherm ($R^2 = 0.99$) which proved to be more suitable than that of Freundlich ($R^2 = 0.58$).

BDST approach

The modelling of parameters for adsorption column design was based on bed depth-service time approach and mass transfer approach. Design of full-scale adsorption columns can be done from the data collected during laboratory and pilot plant tests (**Figure 6**).

Among the mathematical models developed in order to study the column design, the model proposed by [2] is widely used [9, 12, 16, 17]. The simplified equation of this model based on surface reaction rate theory and the service time is presented as follows:

$$t = \frac{N_0}{C_0 V} x - \frac{1}{C_0 K} \ln\left(\frac{C_0}{C_B} - 1\right) \qquad (2)$$

Where C_0 = initial solute concentration (mg/L); C_B = desired solute concentration at breakthrough (mg/L); K = adsorption rate constant (L/mg. h); N_0 = adsorption capacity (mg /L); x = bed depth (cm); V = linear flow velocity of feed to bed (m^3/h. m^2) and t = service time of column under above conditions (h).

The form of Bohart-Adams equation, shown in Eq. (2) can be used to determine the service time (t) of a column of bed depth (x) given the values of N_0, C_0 and K which must be determined for laboratory columns operated over a range of velocity values V.

Setting $t = 0$ and solving Eq. (2) for x yields

$$x_0 = \frac{V}{K N_0} \ln\left(\frac{C_0}{C_B} - 1\right) \qquad (3)$$

Where x_0 is the minimum column height necessary to produce an effluent concentration C_B.

In addition, Hutchins [7] presented a modification of Bohart–Adams equation, which inquires to collect only the necessary data from three column tests. This technique called the bed depth service time (BDST) approach, is expressed as follows:

$$t = ax + b \quad (4)$$

$$\text{Where } a = \text{Slope} = \frac{N_0}{C_0 V} \quad (5)$$

$$b = \text{Intercept} = \frac{1}{KC_0} \ln\left(\frac{C_0}{C_B} - 1\right) \quad (6)$$

From the breakthrough times (corresponding to $C/C_0 = 0.01$) and the exhaust times (corresponding to $C/C_0 = 1$) for bed depth 2.5, 3.5, and 4.5 cm mentioned previously. The graphs were plotted, as shown in **Figure 7**, which showed the bed depth vs service time for 1 and 100% saturation of columns. The equations of these lines are given as follows:

$$t = 0.067x - 0.1402 \quad \text{for 1\% saturation} \quad (7)$$

$$t = x + 0.4433 \quad \text{for 100\% saturation} \quad (8)$$

From the slope and intercept of 1 % saturation line (Eq. (7)), design parameters K and N_0 were found using Eqs. (5) and (6). The minimum column height (x_0) required to produce an effluent concentration of C_B was calculated using Eq. (3). The values of K, N_0, and x_0 were found to be 60.52 L/mg. h; 0.6 mg/L, and 2 cm, respectively. The value of N_0 shows a mass capacity of 0.004 mg/g for each adsorbent.

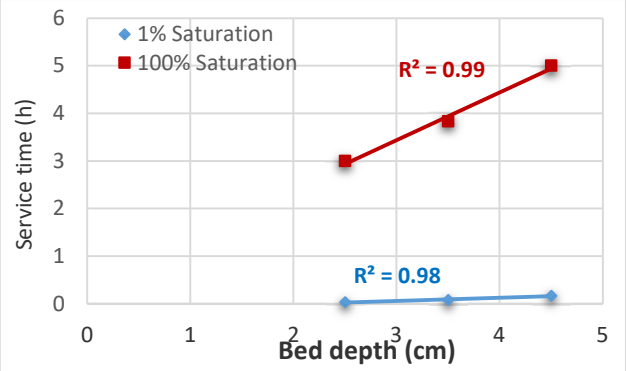


Figure 7. Bed depth service time (BDST) lines in arsenic removal

According to the BDST approach, if a value is determined for one flow rate, values for the other flow rates can be calculated by multiplying the original slope by the ratio of the original and the new flow rates. It is not necessary to adjust the b value, since this term is assumed to be insignificantly affected by changing flow rates. But the values of a were calculated separately for breakthrough and exhaustion times. The breakthrough and exhaustion times for a bed depth 4.5 cm column were calculated and given in **Table 5**.

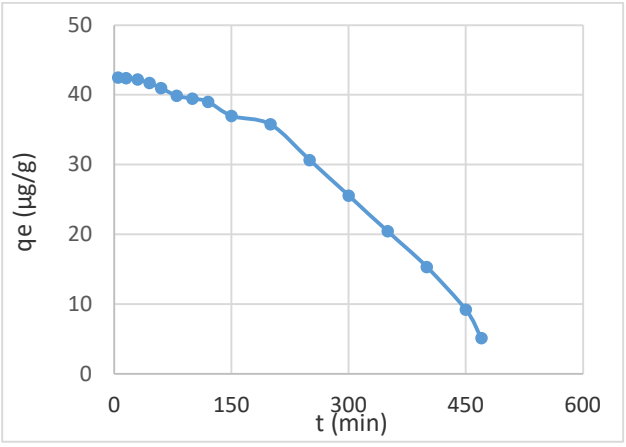
Data reported in **Table 5** shows that the theoretical and experimental values are comparable at breakthrough and exhaustion of columns. However, a time tag observed could be due to the adjustment or control of flow rate at the beginning of experiment and the porosity of FC particles. This approach indicates the possibility to predict the column service times before the dynamic experiments.

Table 5. Comparison of the theoretical service times with the experimental times

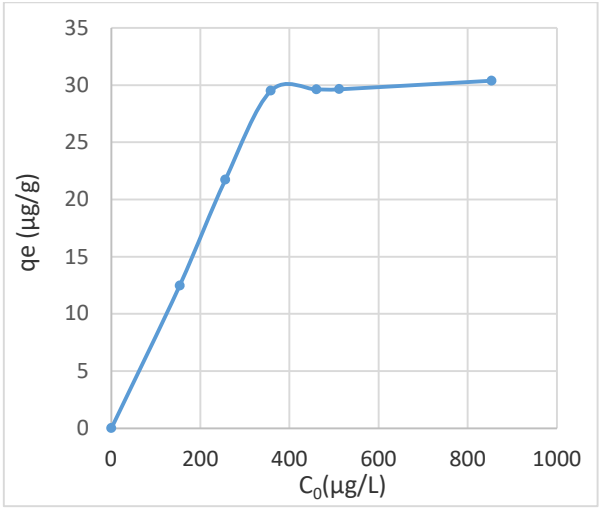
Flow rate	Breakthrough (h)		Exhaustion (h)	
	Experimental	Theoretical	Experimental	Theoretical
7 mL/min	0.08	0.1	4	4.08
3.84 mL/min	0.16	0.3	7	7.08

Mass transfer approach

To study mass transfer, the kinetic-based Langmuir isotherm in a static reactor was used. Indeed, the influence of the contact time was evaluated by varying the contact between 5 and 470 min. This showed a decrease in the adsorption capacity of carbon when time increases (Fig 8a). In addition, the effect of the initial concentration was studied to serve for the application of Langmuir's isotherm. The results showed an increase in adsorption capacity with the initial arsenic concentration in two stages: fast step from 0 to 357 µg/L and slow step between 357 and 853 µg/L indicating the achievement of equilibrium in batch studies (**Figure 8b**).



(a) Effect of contact time



(b) Effect of initial arsenic concentration

Figure 8. Kinetic study of arsenic removal in static mode.

By using the obtained data in batch study, it is theoretically possible to predict the breakthrough curve which must be compared to experimental curve obtained in dynamic experiment. The operating line (black) is drawn from Langmuir's equation for initial arsenic of 0 and 0.511 mg/L (**Figure 9**). It translates the equality between the data in batch study and those in dynamic study at these two points, namely the beginning and the end of the reaction.

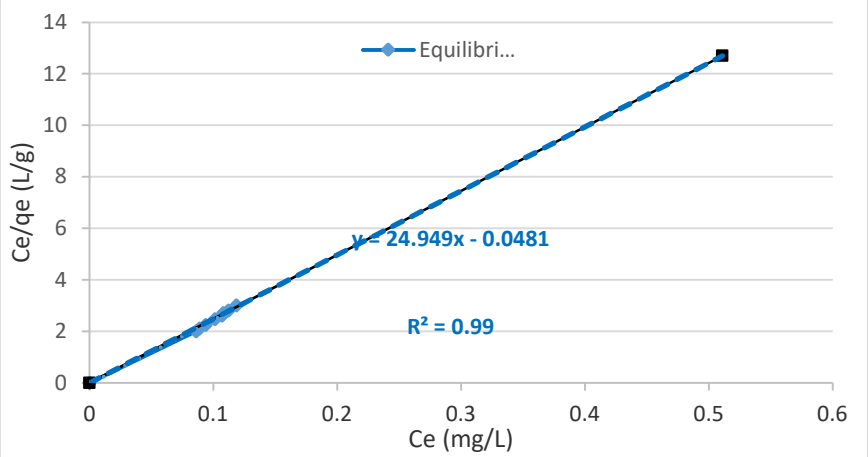


Figure 9. Langmuir isotherm for the determination of theoretical breakthrough curve.

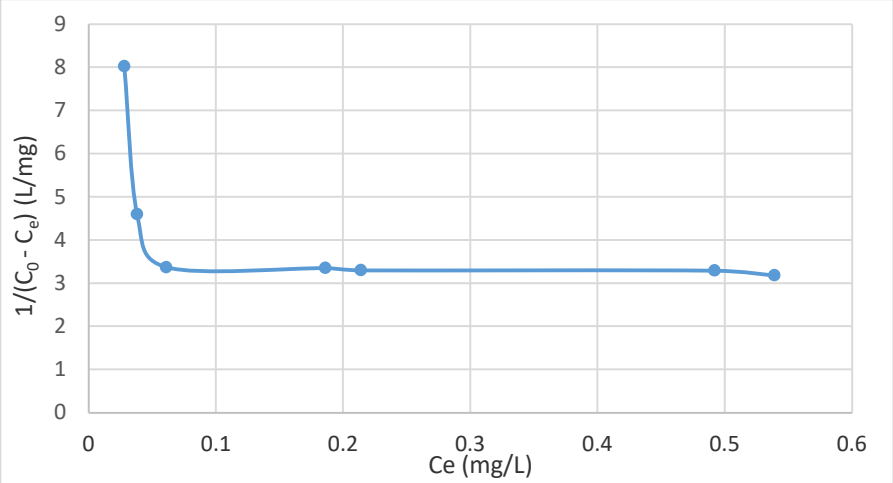


Figure 10. Curve for assessment of theoretical breakthrough curve.

According to Weber [30], the rate of solute transfer from solution over a differential bed height (*dh*) is given by equation 9:

$$FdC = Ka\ (C0 - Ce)dh \qquad (9)$$

With F: water flow, K_a: global mass transfer coefficient including the diffusion resistance of the pore and that of the liquid film.

The term $C0 - Ce$ is the driving force and corresponds to the distance between the operating line (theory) and the equilibrium curve (Langmuir) at a given value of adsorption capacity (qe). By integration and resolution of Eq. (9) for a height *hz* of adsorption zone, Eq. (10) is obtained:

$$h_z = \frac{F}{K_a}\int_{C_B}^{C_E}\frac{dC}{C_0 - C_e} \qquad (10)$$

The curve $1/(C0 - Ce) = f(Ce)$ is drawn (**Figure 10**), the part under the curve represents the value of the integral above.

For any value of $h < hz$, corresponding to a concentration between C_B and C_E, Eq. (10) becomes:

$$h = \frac{F}{K_a}\int_{C_B}^{C}\frac{dC}{C_0 - C_e} \qquad (11)$$

By dividing the Equations (10) by (11), Equation (12) presented as follows is obtained:

$$\frac{h}{h_z} = \frac{\int_{C_B}^{C} dC/(C_0 - C_e)}{\int_{C_B}^{C_E} dC/(C_0 - C_e)} = \frac{V - V_B}{V_E - V_B} \qquad (12)$$

V_B and V_E: volumes of water treated up to the point of breakthrough and saturation, respectively. V is the volume of water treated at any time for a concentration C between C_B and C_E.

The breakthrough curve corresponding to a mass of 20 g of FC (4.5 cm of bed depth) was drawn in the same benchmark Ct/C_0 *vs* $V\text{-}V_B/V_E\text{-}V_B$ as indicated in **Figure 11**. Two curves (experimental and theoretical) revealed a good correlation for arsenic removal in dynamic study. This concludes that the kinetic study and the models of isotherms in static mode (batch) can be used well to predict the breakthrough curve in dynamic mode.

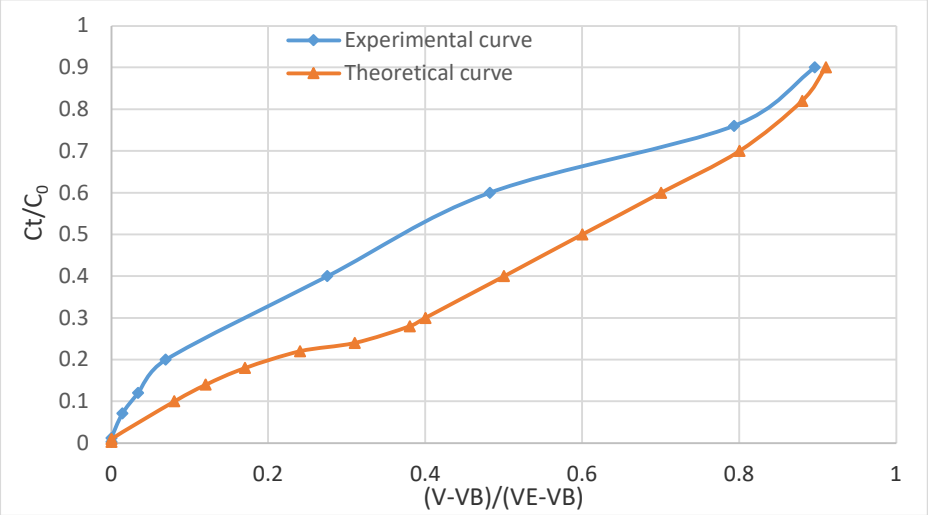


Figure 11. Theoretical and experimental breakthrough curves for arsenic removal.

To determine the kinetic coefficient of mass transfer (βa), the moving speed of the adsorption front (V) and the maximum adsorption capacity (N_0), Wolborska's equation was applied with a flow rate of 3.84 mL/min. The straight line $lnCt/C0 = f(t)$ was drawn and its slope and ordinate at the origin make it possible to deduce βa, N_0, D and the speed of displacement of the adsorption front V. High flow rate (7 mL/min) was used in the save operation to prevent the diffusion of the solute through the liquid film is not the limiting step of the arsenic adsorption process, and to determine the axial diffusion coefficient (D).

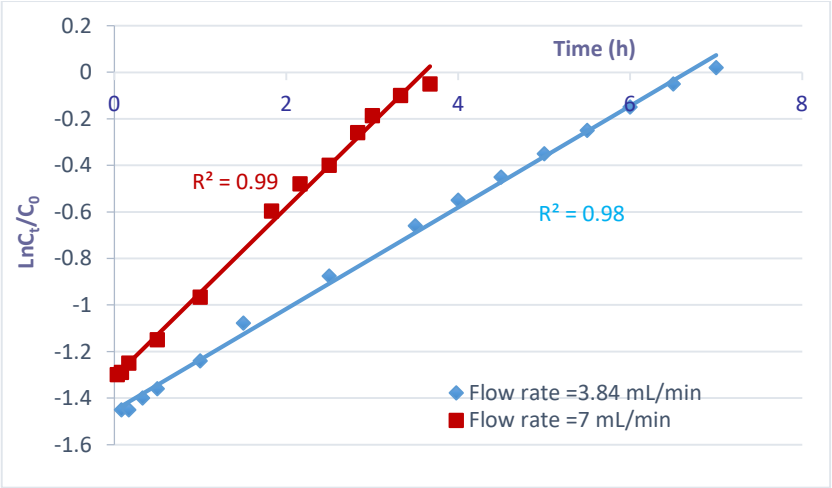


Figure 12. Curves for the determination of mass transfer constants

Table 6. Constants of Wolborska's isotherm for mass transfer

Flow rate (mL/min)	N_0 (mg/L)	βa (h^{-1})	V (cm/h)
3.84	8.05	3.81	0.70
7	6.21	4.42	1.27

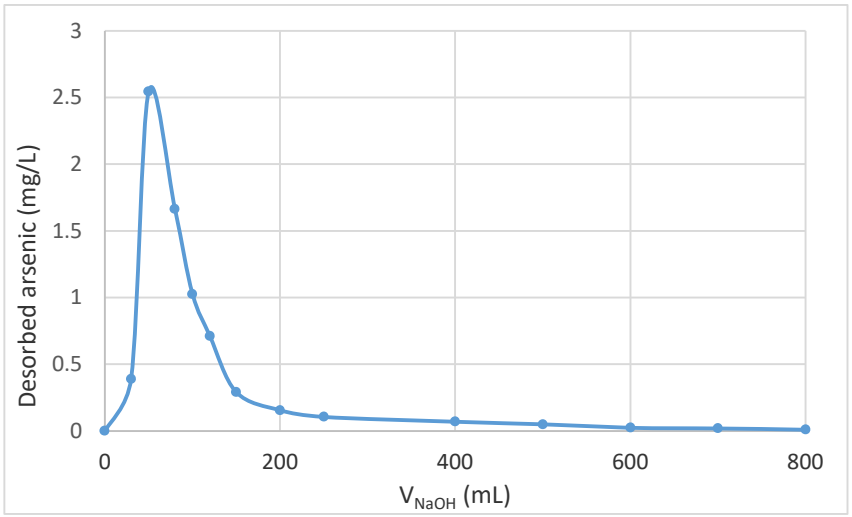


Figure 13. Arsenic recovery profile during the regeneration of FC

The mass transfer coefficient at 3.84 mL/min corresponds to the diffusion coefficient of arsenates and arsenites through the liquid film while at 7 mL/min, this coefficient represents the diffusion coefficient at the surface or in the pore of FC particles. Since, the kinetic coefficient **βa** is greater at 7 mL/min, the diffusion of the arsenic ions on the surface or in pore of FC could be the limiting step of the adsorption of arsenic. The axial diffusion coefficient (**D**) has a value of 112.6 cm^2/h calculated by a combination of **βa** for flow rates 3.84 mL/min and 7 mL/min. This

high value clearly confirms the diffusion of the pore or on the surface as a determining step during the process of arsenic removal by adsorption.

Arsenic desorption study

For the sorption process to be viable, an efficient regeneration of worn out adsorbent is necessary. To do this, 20 g of exhausted FC with 5.65 mg of arsenic fixed was used to desorb arsenic using 1 NaOH solution and 2 mL/min of flow rate. The **Figure 13** shows *t*he profile of arsenic recovery during desorption process. We notice a decrease of desorbed arsenic when the volume of NaOH solution was increased. Calculations revealed that 200 mL of 1 M NaOH solutions could desorb 93% of fixed arsenic and 99% of arsenic was recovered using 600 mL of molar NaOH. The rest of arsenic (1%) not desorbed was due to the fact that arsenates and arsenites are linked on surface FC by chemisorption and anion exchange using covalent bonds.

Conclusions

This study showed that Ferromagnetic Carbon is an effective adsorbent for arsenic removal from groundwater. From speciation studies, groundwater sample did contain As (V), As (III) and the particulate form with a predominance of As (V) in the dissolved form of arsenic. Some competing anions including phosphates, sulfates and bicarbonates were present in groundwater and those anions strongly decrease the arsenic removal efficiency through a competitive adsorption. In the removal process, breakthrough times were strongly influenced by the flow rate and bed depth or adsorbent mass while the removal efficiency was affected by initial pH and arsenic concentrations. Bed Depth-Service Time approach could allow to predict the service times of columns and the mass transfer approach to drawn the theoretical breakthrough curve from data obtained in batch reactor. 600 mL of 1 M NaOH solution could desorb 99% of adsorbed arsenic on FC.

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