

Feasibility analysis of As(III) removal in a continuous flow fixed bed system by modified calcined bauxite (MCB)

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Abstract

This study examines the feasibility of As(III) removal from aqueous environment by an adsorbent, modified calcined bauxite (MCB) in a continuous flow fixed bed system. MCB exhibited excellent adsorption capacity of 520.2 mg/L (0.39 mg/g) with an adsorption rate constant 0.7658 L/mg h for an influent As(III) concentration of 1 mg/L. In a 2 cm diameter continuous flow fixed MCB bed, a depth of only 1.765 cm was found necessary to produce effluent As(III) concentration of 0.01 mg/L, from an influent of 1 mg/L at a flow rate of 8 mL/min. Also, bed heights of 10, 20, and 30 cm could treat 427.85, 473.88 and 489.17 bed volumes of water, respectively, to breakthrough. A reduction in adsorption capacity of MCB was observed with increase in flow rates. The theoretical service times evaluated from bed depth service time (BDST) approach for different flow rates and influent As(III) concentrations had shown good correlation with the corresponding experimental values. The theoretical breakthrough curve developed from constantly mixed batch reactor (CMBR) isotherm data also correlated well with experimental breakthrough curve.

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1. Introduction

The ‘natural poisoning’ of drinking water sources with arsenic, has become one of the most critical health hazards of this century as it induces intense impact on human health including cancers in skin, liver, lungs, kidney and bladder in acute proportions [1]. It was estimated that around 35–77 million out of 130 million inhabitants of Bangladesh were potentially affected by excess arsenic concentration in drinking water [2] to the tune of nearly 180 times higher than the prescribed World Health Organization limit of 0.01 mg/L [3], ensuing 2–2.7 lakhs death from cancer alone [1]. In West Bengal, India, seven districts (with more than 34 million inhabitants) out of 16 were potentially poised by high level of arsenic in drinking water [4] with 40% of the affected having visible symptoms of arsenic poisoning [5,6]. It was reported that more than 14.6 million people of Inner Mongolia, Guizhou and Xinjiang provinces of China, and 13 million from the Western States, were affected by arsenic rich drinking water. Arsenic concentrations up

to 15–20 times the maximum permissible limit were also reported from countries like Greece, Serbia and Montenegro [7–9].

In the water environment, arsenic is mainly found in inorganic forms with oxidation states of +III and +V. Arsenates [As(V)] are found in oxidizing environment, while arsenites [As(III)], which are more toxic and mobile in anoxic and reducing environment [10–13]. The As(III) species, which exists predominantly as non-ionic H_3AsO_3 in natural waters, is more difficult to remove compared to As(V) which exists predominantly as deprotonated oxyanions H_2AsO_4^- or HASO_4^{2-} [14]. Traditional treatment technologies for arsenic removal include co-precipitation, coagulation and filtration, reverse osmosis, electro dialysis, ion exchange, lime softening, membrane filtration and adsorption/ion exchange. The cost effectiveness and viability for installation at the end-use (both in domestic and community level), makes adsorption/ion exchange process practically more acceptable and appropriate for the point-of-use (POU) level especially in rural endemic habitations. However, most of the reported studies on As(III) removal [15–21] were centered mainly on constantly mixed batch reactors (CMBR) and only few of them focused on performance evaluation of the adsorbent by continuous flow fixed bed reactors.

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The objective of the present study is to examine the potential of a newly developed adsorbent, MCB for the removal of As(III) from aqueous environment in a continuous flow fixed bed system. Since the adsorbent column systems are receiving increasing importance for arsenic removal in small scale treatment units, fixed bed column studies were carried out to evaluate the performance of MCB under different operating conditions of flow rate, bed depth and influent concentration. The adsorption parameters essential for analyzing and characterizing the performance of MCB in a continuous flow fixed bed system were also evaluated.

2. Materials and methods

2.1. Preparation of adsorbent (MCB)

The calcined bauxite used in this experimental study was procured from M/s Refcom (India) Pvt. Ltd, West Bengal, India. This material was first sieved to obtain granules having geometrical mean size 0.212 mm and then washed thoroughly with distilled water. The washed material was oven dried for 24 h at $100 \pm 5^\circ\text{C}$. Ferric nitrate non-hydrate [$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, (Merck)] was used for coating of calcined bauxite. The iron oxide coating was done as described earlier [22], the material was further dried at room temperature, and kept in airtight container for use.

2.2. Reagents and stock solutions

All chemicals and reagents used in this study were of analytical grade and used without further purification. As(III) stock solution (100 mg/L) was prepared, by dissolving NaAsO_2 (LOBA Chemie) in double distilled water. Solutions of various As(III) concentrations were prepared prior to the experimental study from stock solutions.

2.3. Instrumental

A peristaltic pump (Miclins, India) was used to charge As(III) spiked water through the MCB packed fixed bed in an up flow mode at desired flow rates. The quantitative determination of As(III) was done by spectrophotometer (GENESYS 20, thermo spectronic model no. 4001/4, USA) and pH by Cyber Scan 510 (Oakton Instruments, USA) pH meter. The chemical composition of MCB was determined by energy dispersive X-ray (EDX) analysis (Oxford ISIS-300 model) and X-ray diffraction analysis (XRD) by Miniflex diffractometer (30 kV, 10 Maq; Rigaku Corp., Tokyo, Japan) with Cu $\text{K}\alpha$ source and a scan rate of $2^\circ/\text{min}$ at room temperature.

2.4. Analytical determination

Quantitative determination of arsenic was done by the silver dithiodiethylcarbamate method (minimum detectable quantity is 1 μg), commonly known as SDDC method as mentioned in the standard methods for the examination of water and wastewater

[23]. The calibration curve was drawn for absorbance at 0, 1, 2, 5, 10, and 20 μg As in 70 mL sample.

The iron content of MCB was determined by acid digestion using the procedure described in AWWARF [24]. One gram of MCB was added to 50 mL of 10% HNO_3 , and the solution was heated to boiling point. After 2 h, the iron oxide in the medium was completely dissolved and the acid solution turned yellow. The digestion was discontinued at this point and the solution was made up to 1 L with deionized water. It was then filtered through Whatman No. 42 filter paper, and the iron content was determined as per the standard methods [23].

2.5. Experimental setup

The MCB adsorbent was packed inside borosilicate glass columns with internal diameter of 20 mm and length of 550 mm. Glass wool was provided at top of the adsorbent bed to prevent floating of adsorbent particles and at bottom for uniform distribution of flow.

2.6. Column studies

In column study, all the tests were conducted in the up flow mode at $\text{pH } 6.8 \pm 0.4$. The As(III) spiked water was pumped through the packed bed of MCB with a peristaltic pump. The effect of process parameters such as inlet flow rate, initial As(III) concentration and bed height at various throughout volumes were studied and analyzed. The effluent samples were collected at definite interval and analyzed for As(III) concentration. The As(III) spiked water was allowed to pass through MCB bed in up flow mode at a volumetric flow rate of 8 mL/min ($\sim 1.53 \text{ m}^3/\text{m}^2/\text{h}$). The bed depths of 10, 20 and 30 cm and initial As(III) concentration of 1 mg/L were selected for experimental evaluation of column parameters. The effect of flow rate on As(III) removal was studied at 5 and 12 mL/min for a fixed bed depth of 10 cm and As(III) concentration of 1 mg/L. The performance of MCB at a bed depth of 10 cm was also evaluated at a higher As(III) concentration of 2 mg/L at 8 mL/min. The evaluation of column performance and analysis of breakthrough curves were done by the modified BDST approach [25] and mass transfer model [26]. The BDST approach was further used for prediction of breakthrough time and exhaust time of adsorbent bed under different flow rates and influent concentrations. All experiments were performed at room temperature ($27 \pm 2^\circ\text{C}$).

3. Results and discussion

3.1. Composition of MCB and its characterization after As(III) uptake

The physical characteristics and elemental composition of MCB combined with oxygen obtained from energy dispersive X-ray (EDX) analysis are shown in Table 1. The iron (Fe) content in MCB was found to be 23.42 mg/g. The possible compound formation of As(III) with elements of MCB as revealed by XRD analysis were aluminum arsenate (AlAsO_4), iron arse-

Table 1
Physical properties and elemental composition of the MCB media

Properties	Quantitative value
Geometric mean size (mm)	0.212
Bulk density (g/cm ³)	1.34
Specific gravity	2.63
Na ₂ O (%)	0.77
Al ₂ O ₃ (%)	63.31
SiO ₂ (%)	7.64
K ₂ O (%)	0.67
CaO (%)	0.19
TiO ₂ (%)	3.41
Fe ₂ O ₃ (%)	24.01
pH of ZPC	6.15

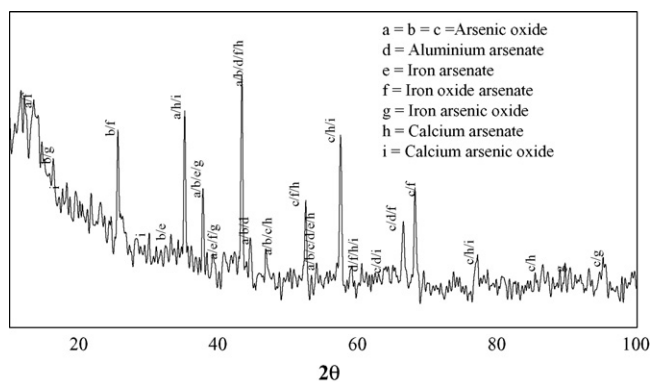


Fig. 1. X-ray diffractogram of MCB after As(III) uptake.

nate (FeAsO₄), iron oxide arsenate (Fe₄As₂O₁₁), iron arsenic oxide (Fe₄As₅O₁₃), calcium arsenic oxide (Ca₄As₂O), calcium arsenate (CaAs₂O₆), various oxides of arsenic As₂O₃, As₂O₅, As₄O₆ and other various trace compounds (Fig. 1). The different arsenic compounds and its oxide formation with MCB indicated that the mechanism of As(III) removal by MCB may be due to chemisorption.

3.2. Adsorption column behavior

The plots of exit concentrations of arsenic as a function of lapse time or volume of water treated (breakthrough curves) for an initial As(III) concentration of 1 mg/L are shown in Fig. 2 for three different bed depths of 10, 20 and 30 cm at a flow rate of 8 mL/min. The point on the breakthrough curve at which arsenic concentration reaches 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 90% of the influent concentration as 'point of exhaustion'. The time correspond-

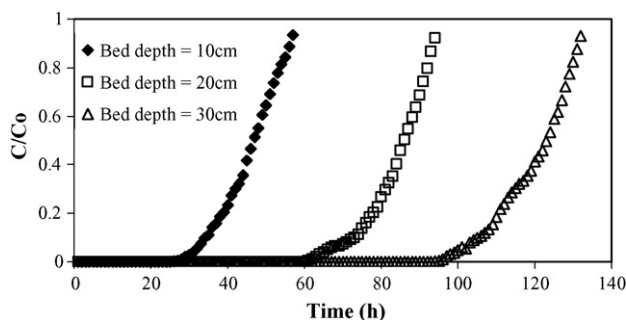


Fig. 2. Breakthrough curves of As(III) adsorption on MCB for different bed depths (initial As(III) conc. = 1 mg/L, flow rate = 8 mL/min).

ing to these points with respective volumes of water treated are shown in Table 2.

3.3. Effects of various column parameter for As(III) adsorption on MCB bed

3.3.1. Effects of bed height

As expected, the increase in column depth increased the volume of treated water (Table 2), due to the availability of more adsorbent binding sites for sorption resulting in a broadened mass transfer zone. At relatively low bed depth, the breakthrough curves become steeper (Fig. 2) showing faster saturation resulting early exhaustion of the bed. A reduction in adsorption capacity of MCB was observed with increased bed heights, as few sites of the adsorbent may be remaining inaccessible for adsorption of As(III) ions.

3.3.2. Effect of initial As(III) concentration

The performance of MCB bed was tested for influent As(III) concentrations of 1 and 2 mg/L for the same bed depth of 10 cm at 8 mL/min and the corresponding breakthrough curves are shown in Fig. 3. The breakthrough time and time of exhaustion for 1 mg/L As(III) concentration were obtained as 28 and 56 h, respectively. The corresponding values were 13 and 28 h for 2 mg/L. The quantities of treated water were 13440 mL (428.02 bed volumes) and 6240 mL (198.72 bed volumes) at breakthrough for 1 and 2 mg/L concentrations, respectively. The adsorption capacities obtained by the integration of the area above breakthrough curve were 0.459 and 0.463 mg/g for these concentrations. A decrease in breakthrough as well as time of exhaustion at higher initial concentration may be due to the rapid exhaustion of the sorption sites. Though, the breakthrough curve is dispersed and breakthrough came late at lower As(III) concentrations, saturation of the bed appeared faster at higher concentrations. Thus higher As(III) concentrations resulted in

Table 2
The bed volumes of As(III) treated water corresponding to different bed depths for an initial concentration of 1 mg/L and flow rate of 8 mL/min

Bed depth (cm)	Breakthrough time (h)	Time of exhaustion (h)	Volume of treated water before breakthrough (mL)	Volume of treated water before exhaust (ml)	Adsorption capacity (mg/g)
10	28	56	13440	26880	0.459
20	62	92	29760	44160	0.426
30	96	126	46080	60480	0.392

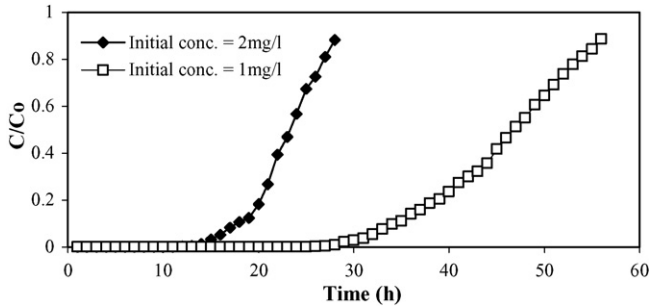


Fig. 3. Effect of initial concentrations on the breakthrough curves for As(III) adsorption on MCB (bed depth = 10 cm, flow rate = 8 mL/min).

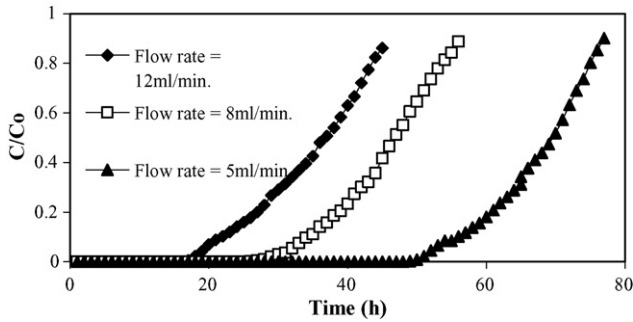


Fig. 4. Effect of flow rates on the breakthrough curve of As(III) adsorption on MCB (bed depth = 10 cm, initial As(III) conc. = 1 mg/L).

quick exhaustion of sorption sites, making the uptake less effective. At influent As(III) concentrations of 1 and 2 mg/L, the value of q/C_0 are 0.459 and 0.2315 L/g (q/C_0 represents the ratio of As(III) adsorbed on MCB in (mg/g) to the initial arsenic concentration (mg/L)). The higher breakthrough times at lower initial As(III) concentrations may also be due to the high q/C_0 values and vice versa.

3.3.3. Effect of flow rate

The effect of flow rate was investigated at 5, 8 and 12 mL/min for an influent As(III) concentration of 1 mg/L (bed depth of 10 cm and column diameter of 2 cm) and the corresponding breakthrough curves are shown in Fig. 4. The quantity of water treated at breakthrough point and exhaust point are shown in Table 3. There is a reduction in the adsorption capacity of MCB with increase in flow rate. This may be possibly due to relatively low contact time between the adsorbate and adsorbent thereby reducing the diffusion of As(III) ions into pores of MCB. Also, at higher flow rates, the movement of adsorption zone along the bed is faster reducing the time for sorption of As(III) ions on MCB bed.

Table 3

The total quantity of water treated in terms of bed volume before breakthrough and exhaust times for different flow rates

Flow rate (mL/min)	Time for breakthrough (h)	Time of exhaustion (h)	Quantity of water treated before breakthrough (mL)	Quantity of water treated before exhaust (ml)	Adsorption capacity (mg/g)
5	50	77	15000	23100	0.490
8	28	56	13440	26880	0.459
12	17.5	45	12600	32400	0.436

3.4. Evaluation of basic design parameters of adsorption column

The time required for the exchange zone to move the length of its own height up/down the column (t_z) once it has become established is [27]:

$$t_z = \frac{V_s}{Q_w} \tag{1}$$

where V_s is the initial volume of As(III) spiked water treated between breakthrough and exhaustion (L) and Q_w is the influent flow rate (L/h).

The time required for the exchange zone to become established and move completely out of the bed (t_E) is:

$$t_E = \frac{V_E}{Q_w} \tag{2}$$

where V_E is the total volume of As(III) spiked water treated to the point of exhaustion (L).

The rate at which the adsorption zone is moving up and down through the bed is:

$$U_z = \frac{h_z}{t_z} = \frac{h}{t_E - t_f} \tag{3}$$

where h_z is the height of exchange zone (cm); h the total bed depth (cm); t_f is the time (h) required for the adsorption zone to form initially.

The expression for the height of the exchange zone (h_z) is:

$$h_z = \frac{h(t_z)}{t_E - t_f} \tag{4}$$

The value of t_f can be calculated as

$$t_f = (1 - F)t_z \tag{5}$$

At breakthrough, the remaining fraction of the MCB (F) present in the adsorption zone still able to remove As(III) is:

$$F = \frac{S_z}{S_{max}} = \frac{\int_{V_B}^{V_E} (C_0 - C)dV}{C_0(V_E - V_B)} \tag{6}$$

where C_0 is the initial concentration of As(III) in water (mg/L); C the concentration of solute As(III) at any instant in the effluent (mg/L); V_B the total volume of As(III) spiked water treated to the point of breakthrough (L); S_z the amount of As(III) that has been removed by the adsorption zone from breakthrough to exhaustion (mg) and S_{max} is the amount of As(III) removed by adsorption zone if completely exhausted (mg). At breakthrough an adsorption column will not be completely saturated and will be composed of the partially exhausted zone and the

Table 4
Parameters for the fixed bed MCB column

Parameter	Bed depth 10 cm	Bed depth 20 cm	Bed depth 30 cm	Average value of the parameter
t_z (h)	28	30	30	29.33
h_z (cm)	6.5	7.42	7.98	7.33
U_z (cm/h)	0.232	0.247	0.266	0.248
Bed saturation (%)	70.01	86.27	82.22	79.5

totally exhausted material located above the adsorption zone. The percentage of total column bed saturated at breakthrough is:

$$\% \text{ saturation} = \frac{h + (F - 1)h_z}{h} \times 100 \quad (7)$$

The values of the important design parameters t_z , h_z , U_z and % saturation of MCB bed of depths of 10, 20 and 30 cm after As(III) uptake are shown in Table 4.

3.5. Design of MCB adsorption column for As(III) removal

3.5.1. Analysis and design based on mass transfer model

The isotherm data of constantly mixed batch reactor (CMBR) can be used for the generation of theoretical breakthrough curves using the concept of Michaels [26]. The Freundlich isotherm data were used for preparing theoretical breakthrough curves as it showed better fit ($R^2 = 0.9915$) in batch isotherm study. The detailed calculation for initial As(III) concentration of 1 mg/L and breakthrough concentration of 0.01 mg/L are as follows:

1. The equilibrium line was prepared (figure not shown) assuming various values for C_e and calculating the corresponding values of q_e using Freundlich isotherm equation (obtained from CMBR study):

$$q_e = 1.362C_e^{0.3046} \quad (8)$$

where q_e is the amount of As(III) (mg) adsorbed per unit weight of MCB (g) and C_e is the equilibrium concentration of As(III) remaining in the solution (mg/L).

2. An operating line was drawn which passes through the origin and the point (C_0, q_e) , where $C_0 = 1$ mg/L and q_e is the value corresponding to C_0 as per Eq. (8). The significance of this operating line is that the CMBR data and the data of the fixed bed reactor (FBR) are identical at these two points, first at the initiation and other at the exhaustion of the reaction.
3. According to Weber [28], the height of adsorption zone is:

$$h_z = \frac{F_w}{K_a} \int_{C_B}^{C_E} \frac{dC}{C - C^*} \quad (9)$$

where F_w is the flow rate; K_a the overall mass transfer coefficient, which includes the resistance offered by film diffusion and pore diffusion; C^* is the equilibrium concentration of solute in solution corresponding to an adsorbed concentration q_e . The term $(C - C^*)$ is the driving force for adsorption and is equal to the distance between the operating line and equilibrium curve at any given value of q_e . In the plot of

$(C - C^*)^{-1}$ versus C , (figure not shown) the area under the curve represents the value of the above integration for any value of $h < h_z$, corresponding to a concentration C between C_B and C_E . From this value the depth of adsorption zone can be evaluated.

Eq. (9) can now be written as

$$h = \frac{F_w}{K_a} \int_{C_B}^C \frac{dC}{(C - C^*)} \quad (10)$$

Dividing Eq. (10) by Eq. (9) results in:

$$\frac{h}{h_z} = \frac{\int_{C_B}^C dC/(C - C^*)}{\int_{C_B}^{C_E} dC/(C - C^*)} = \frac{V - V_B}{V_E - V_B} \quad (11)$$

where V_B and V_E are the total volume of water treated till breakthrough and up to the exhaust point, respectively and V is the volume of water treated at any time (t) for effluent concentration C . Dividing the values of $\int_{C_B}^C (dC/(C - C^*))$ by the values of $\int_{C_B}^{C_E} (dC/(C - C^*))$, the term $(V - V_B)/(V_E - V_B)$ was evaluated.

4. Now the plot of C/C_0 versus $(V - V_B)/(V_E - V_B)$ represents the theoretical breakthrough curves. From the area above theoretical breakthrough curves, the fractional capacity F and the % saturation, can be calculated. Based on an influent flow rate, % saturation, and the maximum adsorption capacity (obtained from CMBR), the required amount of MCB (to bring down As(III) to the permissible limit of 0.01 mg/L) and the bed run time can be calculated for any initial As(III) concentration. The reported advantage of the mass transfer design approach is that the necessary data can be collected by CMBR studies which are less time consuming and less expensive than that of continuous flow studies. The developed theoretical breakthrough curve from batch isotherm data, and the experimental breakthrough curve obtained (for 10 cm bed depth, feed flow rate of 8 mL/min, and initial As(III) concentration of 1 mg/L) shows good correlation (Fig. 5).

3.5.2. Analysis and design based on bed depth/service time approach

The modified form of Bohart–Adams equation by Hutchins [25], known as bed depth service time approach (BDST) need only three column test to collect the necessary data required for

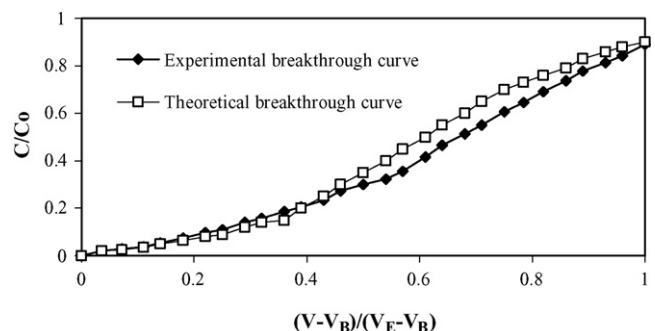


Fig. 5. Plot of experimental and theoretical breakthrough curves.

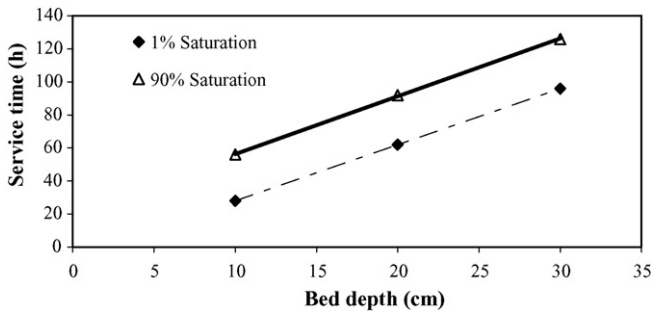


Fig. 6. Bed depths versus service time plot at 1% and 90% saturation of MCB fixed bed.

adsorption column design and can be expressed as

$$t = ax + b \tag{12}$$

where

$$a = \text{slope} = \frac{N_0}{C_0 V} \tag{13}$$

$$b = \text{intercept} = \frac{1}{K C_0} \ln \left(\frac{C_0}{C_B} - 1 \right) \tag{14}$$

From the breakthrough times (corresponding to $C/C_0 = 0.01$) and the exhaust times (corresponding to $C/C_0 = 0.9$) for bed depths of 10, 20 and 30 cm, a plot of service time versus bed depth (for 1% and 90% saturation of the MCB bed) was made as in Fig. 6. The equations of these lines are:

$$t = 3.5x + 21.333 \text{ (for 90\% saturation)} \tag{15}$$

$$t = 3.4x - 6 \text{ (for 1\% saturation)} \tag{16}$$

These two straight lines represented above are nearly parallel and the horizontal distance between these lines were found as 7.85 cm. This horizontal distance is referred as ‘height of exchange zone’. Theoretically this value was calculated as 7.30 cm (Table 4). Using the slope and intercept of the 1% saturation line (Eq. (16)), design parameters N_0 and K could be found out using Eqs. (13) and (14), respectively. The minimum bed depth (x_0) necessary to produce an effluent concentration C_B was calculated as [29]

$$x_0 = \frac{V}{K N_0} \ln \left(\frac{C_0}{C_B} - 1 \right) \tag{17}$$

The values of K , N_0 and x_0 were found to be 0.7658 L/mg h, 520.2 mg/L (0.39 mg/g) and 1.765 cm, respectively. The value of the important characteristic parameters N_0 and K indicates excellent As(III) removal capacity of MCB indicative of its potential in field application.

3.5.3. Prediction of service times of columns under various operating conditions using BDST approach and its comparison with the experimentally obtained service times

The design parameters obtained from experimental observations for fixed studies can be used for the design of an adsorption column for practical use. According to BDST approach, if the value of ‘ a ’ is determined for one flow rate, values for the other

Table 5

Comparison of the experimental service times with theoretical service times predicted using BDST model

Flow rates (mL/min)	Breakthrough time (h)		Time of exhaustion (h)	
	Experimental	Theoretical	Experimental	Theoretical
5	50	49.2	77	76.53
12	17.5	17	45	44.33

flow rates can be calculated by multiplying the original slope (here it is 3.45, the average of two slopes was taken from BDST equation) by the ratio of the original and the new flow rates. Since the value of ‘ b ’ is not affected significantly with flow rates, it is not necessary to adjust. For flow rates of 5 and 12 mL/min, the revised values ‘ a ’, calculated from the flow rate ratio are 5.52 and 2.3, respectively. With these values the equation of service time/bed depth can be modified.

For flow rate of 5 mL/min:

$$t = 5.52x + 21.333 \text{ (for 90\% saturation)} \tag{18}$$

$$t = 5.52x - 6 \text{ (for 1\% saturation)} \tag{19}$$

and for flow rate of 12 mL/min:

$$t = 2.3x + 21.333 \text{ (for 90\% saturation)} \tag{20}$$

$$t = 2.3x - 6 \text{ (for 1\% saturation)} \tag{21}$$

From Eqs. (17)–(21), the breakthrough and exhaust times for 10 cm bed depth column are presented in Table 5 indicating that the experimental and theoretical values are well comparable. Also, by BDST approach, using the data of a solute concentration C_1 it is possible to predict the equation for another concentration C_2 as [25]

$$a_2 = a_1 \frac{C_1}{C_2} \tag{22}$$

$$b_2 = b_1 \left(\frac{C_1}{C_2} \right) \frac{\ln((C_2/C_F) - 1)}{\ln((C_1/C_B) - 1)} \tag{23}$$

where a_1 is the slope at concentration C_1 ; a_2 the slope at concentration C_2 ; b_1 the intercept at concentration C_1 ; b_2 the intercept at concentration C_2 ; C_F the effluent concentration at influent concentration C_2 and C_B is the effluent concentration at influent concentration C_1 .

For As(III) concentration of 2 mg/L, the values of a_2 and b_2 calculated from Eqs. (22) and (23) at breakthrough are 1.725 and -3.456 and for exhaust are 1.725 and 10.666, respectively, and with these values the equation of service time/bed depth can be written as

$$t = 1.725x - 3.456 \text{ (for 1\% saturation)} \tag{24}$$

$$t = 1.725x + 10.666 \text{ (for 90\% saturation)} \tag{25}$$

The theoretical breakthrough and exhaust time calculated from Eqs. (24) and (25) are 13.79 and 27.91 h, respectively, whereas the corresponding experimental values were 13 and

28 h. Hence these equations can be used for prediction of service times for different As(III) influent concentrations with a fair degree of accuracy.

4. Conclusion

The adsorption of As(III) on MCB in a fixed bed, was observed strongly depending on the influent flow rate, initial As(III) concentration and depth of adsorbent bed. The increase in bed depth was followed by increase in the quantity of treated water, but with a slight reduction in adsorption capacity. At lower flow rates, the quantity of treated water and adsorption capacity were found increasing. At higher influent concentrations, better adsorption capacity was observed (0.459 mg/g at 1 mg/L and 0.463 mg/g at 2 mg/L). The minimum depth of MCB bed required to produce effluent As(III) concentration within permissible limit was 1.765 cm at an influent concentration of 1 mg/L for a flow rate of 8 mL/min. The theoretical break through curve developed by mass transfer model and experimental break through curve exhibited identical trends. The various design parameters obtained from fixed bed experimental studies showed good correlation with corresponding theoretical values, under different operating conditions. The observations of fixed bed studies, suggests the practical applicability of MCB in As(III) mitigation by sorptive removal in fixed bed adsorption columns.

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