

## DESIGN OF HEAVY METALS ADSORPTION COLUMN BASED ON BOHART-ADAMS EQUATION

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### Abstract

Removal of heavy metals from water and wastewater has received a great deal of attention recently. Adsorption technique is one of the technologies being used for the treatment of polluted water, but seeking for low cost adsorbent is the objective of this study. This study records laboratory scale experiments to test the efficiency of washed quarry dust (WQD) in the removal of heavy metals; zinc and copper from wastewater of electroplating industry. Wastewater which was found to have high levels of zinc and copper ions was passed up the adsorption column. The column had a circular cross section with a diameter of 80 millimeters and a height of 1.2 metres. Sampling points were located at 0.50, 0.75 and 1 metre height of the column. A holding (regulating tank), 30 cm diameter and 50 cm height was placed at a height of 1.5 m from the column inlet to enable the wastewater to flow upwards. A gate valve was fixed at the holding tank's outlet to regulate the effluent the flow rate. Leachate samples collected at the outlets of the column were analyzed for concentration of zinc and copper ions using atomic absorption spectrophotometer (AAS). Flow rate and column depths were varied to study their effects on the removal efficiency of heavy metals. This method of heavy metals removal proved highly effective. The mean removal efficiency was 94% and 92% for zinc and copper respectively. Maximum adsorption occurred at a depth of 1 m when wastewater was passed up the column at linear flow rate of 2.4 l/min/m<sup>2</sup> as compared to 0.5 m and 0.75 m column depth. The elemental analyses of quarry dusts were done using X-ray fluorescence (XRF). Bohart-Adams equation was applied in the design of the other adsorption columns using the laboratory results for three columns. The service time predicted using the equation for 0.5, 0.75 and 1 m columns at a linear flow rate of 1.8 l/min/m<sup>2</sup> were similar to those found in the laboratory column experiment.

**Key words:** Heavy metals, industrial effluents, washed quarry dust (WQD), low cost adsorbent

## 1.0 Introduction

Adsorption is a term commonly used for several different processes involving physical as well as chemical interactions between the solid surfaces of a substance and dissolved metal ions. Hence, adsorption can be influenced by changes in hydro-chemical parameters such as pH and flow rates (Abdus-Salam and Adekola, 2005). Treatment of electroplating wastewater is by far the most important environmental problem faced by the steel industry (Yu *et al.*, 2001). This electroplating wastewater is highly polluted in terms of copper (Cu), iron (Fe) and zinc (Zn) (Kaneco *et al.*, 2000) and due to their non-biodegradability and persistence, can accumulate in the environment elements such as food chain and thus pose a significant danger to human health.

Many low-cost adsorbents such as agricultural and waste byproducts have been used, but efficient and easily available adsorbent is the reason why washed quarry dust was tested as an adsorbent. Quarry dusts are produced in large quantities around Nairobi. For this reason, they are cheap and easily available for use in the treatment of industrial effluents.

## 1.1 Literature Review

A number of industrial processes especially metal processing, discharge effluents with high quantities of toxic metals. This leads to contamination of freshwater and the marine environment (Low *et al.*, 1995). Since most heavy metals are non-degradable, their concentrations must be reduced to acceptable levels before discharging wastewater into the environment. According to World Health Organization (WHO) the metals of most immediate concern are chromium, zinc, iron, lead and mercury (WHO, 1995) because they are toxic to human health.

By using efficient and cheaper methods of heavy metal removal, the treated wastewater can be made available for re-use in industries. Adsorption method has been used in the removal of heavy metals from portable water and wastewater. It is an effective purification and separation technique used in industry for the treatment of wastewater (Aksu, 2001). Adsorption is a term commonly used for several different processes involving physical as well as chemical interactions between the solid surfaces of a substance and dissolved metal ions. Thus, adsorption in general can be influenced by changes in hydro-chemical parameters such as pH and flow-rate (Abdus-Salam and Adekola, 2005).

Adsorption of the heavy metals from solution has been studied using naturally occurring minerals. Pyrolusite has been used for adsorption of lead (Pb), zinc (Zn) and magnesium (Mg) from their aqueous solution (Ajmal, 1995). Zeolites have been used for removal of heavy metals from wastewater (Yuan *et al.*, 1999). Other adsorbents that have been used for the removal of heavy metals include

carbonaceous material developed from fertilizer waste slurry (Srivestave *et al.*, 1989).

In recent years, many low-cost adsorbents including agricultural and waste by-products such as soya bean and cottonseed hulls, rice straw, timber sawdust and sugarcane bagasse have also been tested in batch and fixed bed adsorption systems (Yu *et al.*, 2001, Badmus *et al.*, 2007). Other low cost adsorbents that have been used include soils (Campbell and Davies, 1995) and activated carbons from date pits (Girgis and Hendawy, 1997). Some researchers have also reported the adsorption of lead on oxides of silicon, manganese, aluminium (Bilinshi *et al.*, 1977), bentonite (Kozar *et al.*, 1992), hydrated titanium dioxide (Abe *et al.*, 1989), modified silica gel (Mareira *et al.*, 1990), sawdust (Yu *et al.*, 2001), lateritic minerals (Ahmad *et al.*, 2002), and carbon (Qadeer and Akhtar, 2005).

The aim of this study was to find out the effectiveness of washed quarry dust (WQD) in the removal of heavy metals from electroplating wastewater. The WQD has large surface area and is uniform in its physical and chemical properties.

## **2.0 Methodology**

### **2.1 Quarry Dust Characterization and Preparation**

Samples were collected from aggregate and machine cut building stone quarries in Mlolongo, Kitengela and Juja in Kenya. The elemental analysis of the samples was done using the X-ray fluorescence (XRF). Quarry dust of size 0-3 mm sampled from aggregate quarry factory was washed to remove all impurities such as clay and silt. It was then rinsed using distilled water, dried in sunlight and then dried in an oven at 110 °C for 24 hours to reduce the moisture content.

### **2.2 Wastewater Sampling and Analysis**

Industrial effluent from electroplating factory was collected at the point of discharge into the public sewer system. Jerrycan containers used for sample collection were pre-treated by washing them with dilute hydrochloric acid, rinsed with distilled water and allowed to dry. At the point of collection, containers were rinsed with samples twice and then filled with the sample. The samples were preserved by acidifying them with concentrated nitric acid (HNO<sub>3</sub>) to pH less than 2. The containers were then corked tightly and samples taken to the laboratory for treatment and analysis.

The pH meter was used to determine the pH of the wastewater samples. To determine heavy metal concentration, 50 ml of the filtered samples was digested with concentrated HNO<sub>3</sub>. Every time the sample volume was less than 10 ml, HNO<sub>3</sub> was added till white smoke was released. Thereafter, the volume was adjusted to 50 ml with distilled water and the concentration of heavy metals; zinc, copper, cadmium, chromium, arsenic, lead and iron determined using atomic absorption

spectrophotometer: Model Phillip PU 9100 according to standard methods (APHA, 1995). Three sets of samples were analyzed and the mean concentration used.

### **2.3 Effect of Column Depth and Effluent Flow Rate**

Sampling points were located at 0.50, 0.75 and 1.00 m of the column height as shown in Figure 1. The WQD was put in the column up to 1.00 m bed height. Once the WQD was packed inside the column, the columns were fully filled with deionised water for 24 h to 'wet' the column. This was to ensure that all air was expelled between and within the WQD particles in the column. Presence of air inside the column would cause channeling and air entrapment would occur which would lower bed performance. The pH of the wastewater sample was adjusted to  $7 \pm 0.2$  by use of 0.1 N HCl and 0.1 N NaOH. After flushing the column with deionized water, the wastewater was then passed up the column by putting it into the holding tank and passing it through the inlet to the column via a gate valve. This avoided channeling due to gravity and enhanced uniform distribution of solution throughout the column. The gate valve was tuned to give the correct flow rate which was maintained constant during the experiment. Periodic flow rate checks were carried out by physically collecting the effluent at the outlet for a given time and measuring it. The linear flow rates used on each column were varied to 1.2, 1.8 and 2.4 l/min/m<sup>2</sup> (6, 9, 12 ml/min respectively).

Leachate samples of treated wastewater were collected through the outlets. The samples were filtered through Whatman No. 44 filter papers and digested with concentrated HNO<sub>3</sub>. The digested samples were then topped up to the initial volume using distilled water. The equilibrium concentrations ( $C_e$ ) of zinc and copper were determined using AAS. The adsorption column height which gave the highest heavy metal removal efficiency at a given flow rate was selected for application in the treatment of wastewater. The experimental set up is as shown in figure 1.

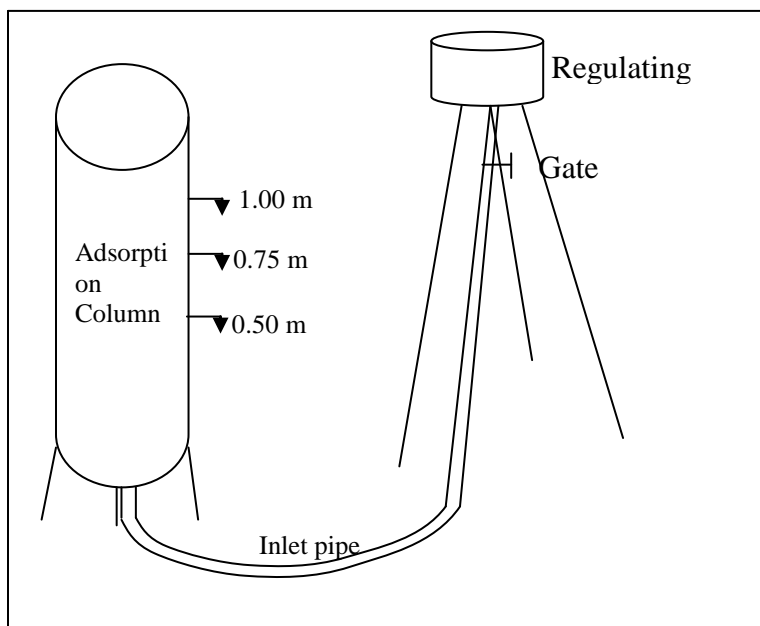


Figure 1: Schematic diagram of adsorption column

#### 2.4 Determination of Adsorption Capacity of WQD

The determination of adsorption capacity of WQD assists in the determination of the time for replacement or regeneration of WQD. The WQD was put in the column up to 1 m bed height. Once the WQD was packed inside the column, the column was fully filled with deionized water for 24 hours to 'wet' the column. The pH of the wastewater sample was adjusted to  $7 \pm 0.2$  by use of 0.1 N HCl and 0.1 N NaOH. After flushing the column with deionized water, wastewater was then passed up the column. Flow rate of 12 ml/min was used as determined in the experiment above. Leachate samples of 50 ml were collected through the outlets at intervals of 60 minutes. The flow of wastewater was continuous until the leachate concentration ( $C_e$ ) of zinc and copper collected at the outlets was equal to wastewater concentration  $C_o$ . The samples were filtered and then digested with concentrated  $\text{HNO}_3$ . The digested samples were topped up to initial volume of 50 ml using distilled water. The equilibrium concentrations ( $C_e$ ) of zinc and copper were determined using AAS. Preference was given to testing the samples immediately after adsorption for more reliable analytical results. However in cases where the concentrations of heavy metals in the samples was not determined immediately, they were preserved by acidifying them with concentrated  $\text{HNO}_3$  to pH of less than 2. The samples were kept and tested at room temperature.

### 3.0 Results and Discussion

#### 3.1 Quarry Dust Characterization

Table 1 shows the results of elemental analysis of the quarry dusts. From Table 1, quarry dusts from aggregate and building stone quarries are predominantly siliceous, followed by the insoluble oxides of aluminium, iron, manganese, calcium, magnesium and alkaline salts (sodium oxide and potassium oxide). However quarry dusts from aggregate quarries have higher contents of silica and aluminum oxide.

Table 1: Characterization of washed quarry dust

Parameters/elements	Sample from aggregate quarries	Sample from building stone quarries
	Contents (%)	Contents (%)
SiO <sub>2</sub>	53.10	62.50
Al <sub>2</sub> O <sub>3</sub>	20.40	11.42
Na <sub>2</sub> O	8.40	5.80
K <sub>2</sub> O	5.80	4.57
Fe <sub>2</sub> O <sub>3</sub>	5.10	6.22
MnO	1.90	0.22
MgO	0.89	0.46
CaO	0.85	0.71
LOI	4.09	8.65

Samples from machine cut building stones are grey silica whose bulk density was 1.5 g/cm<sup>3</sup>. Quarry dust samples from aggregate quarries have a bulk density of 2.4 g/cm<sup>3</sup>. Quarry dusts from aggregate quarry are crushed from pyroclastic type of rock and are better adsorbent than building stone quarry dusts due to higher content of alumina element. Quarry dusts from building stone quarries were not used in the treatment of industrial effluent due to their low alumina content and inability to be crushed into sizes 0-3 mm.

#### 3.2 Industrial Effluent Ph and Heavy Metal Concentration

Table 2 shows industrial effluent pH and concentrations of various heavy metals in the effluent. The test results indicate that wastewater was acidic with a pH of 2. It was also established that zinc and copper are the major polluting elements in the effluent.

Table 2: Industrial effluent pH and heavy metal concentration

Samples	pH	Heavy metal's effluent concentration, C <sub>o</sub> in mg/l						
		Zinc	Copper	Cadmium	Chromium	Arsenic	Lead	Iron
1	2	41.09	10.08	0.03	0.03	0.01	0.03	0.04
2	2	40.15	9.81	0.03	0.03	0.01	0.02	0.03

3	2	38.32	9.69	0.03	0.02	0.01	0.02	0.03
4	2	36.05	9.45	0.01	0.02	0.01	0.01	0.03
5	2	35.07	9.32	0.01	0.02	0.01	0.01	0.03

The concentration of Zinc varied from 41.09 mg/l to 35.08 mg/l while that of copper varied from 10.08 mg/l to 9.32 mg/l. Other elements such as cadmium, chromium, arsenic, lead and iron contributed insignificant amounts (below 0.05 mg/l) which are within the requirements of the Kenya Standard KS 1966-2:2007, Kenya Standard Specification Effluent tolerance limits, Part 2: Effluent discharged into public sewers. The variation in the concentrations of zinc and copper was attributed to metals used for electroplating in the industry. Zinc and copper were selected for adsorption study due to their high concentrations unlike other metals which were within the requirements of the Kenya Standard.

**3.3 Calculation of Heavy Metal Ions Adsorbed**

The amount of metal ions adsorbed was determined using a mass balance equation:

$$q = \frac{v}{m} (C_o - C_e) \dots\dots\dots (1)$$

Where

q is the metal uptake (mg/g)

C is the initial metal concentration of the wastewater sample (mg/l)

C<sub>e</sub> is the equilibrium metal concentration of the wastewater leachate collected at the outlet (mg/l)

V is the volume (l) of the treated wastewater collected at the column outlet after sampling time interval.

m is the mass of adsorbent used in the column (g).

The definition of removal efficiency is given by Equation 2:

$$\text{Removal efficiency (\%)} = \left[ \frac{(C_o - C_e)}{C_o} \right] * 100 \dots\dots\dots (2)$$

C<sub>o</sub> is the metal concentration in the wastewater sample before treatment (mg/l)

C<sub>e</sub> is the metal concentration in the wastewater sample after treatment (mg/l)

**3.4 Effect of Adsorption Bed Depth and Effluent Flow Rate**

Adsorption bed depth determines the amount of WQD used. Shorter bed depth means smaller amount of WQD thus availability of less adsorption sites.

### 3.4.1 Effect of Adsorption Bed Depth and Effluent Flow Rate on Removal Efficiency of Zinc

Table 3 shows the effect of flow rate and column depth on zinc ions removal efficiency. From table 3 at a bed depth of 0.50 m, the percentage removal of zinc decreases from 93.37 to 67.88 % as flow rate is increased from 6 to 12 ml/min. This can be attributed to reduction in contact time from 120 minutes to 60 minutes.

*Table 3: Effect of Effluent Flow Rate and Column Depth on the Removal Efficiency of Zinc Ions*

Bed depth (m)	Zinc concentration (mg/l)			Zinc percentage removal (%)		
	6 (ml/min)	9 (ml/min)	12 (ml/min)	6 (ml/min)	9 (ml/min)	12 (ml/min)
0.50	2.33	7.30	11.26	93.37	79.20	67.88
0.75	2.09	2.15	7.27	94.04	93.86	79.26
1.00	1.88	1.81	1.81	94.65	94.83	94.83

At a bed depth of 0.75 m, the percentage removal of zinc decreased from 94.04 to 79.26 % as flow rate increased from 6 to 12 ml/min. This can be attributed to reduction in contact time from 180 to 90 min as flow rate increased from 6 to 12 ml/min. At a depth of 1.00 m, there was negligible change on percentage removal of zinc. The change in removal efficiency increased from 94.65 to 94.83 % as flow rate increased from 6 to 12 ml/min.

Figure 2 shows the effect of influent injection rates at various column depths. It was observed that zinc removal efficiency increased with increase in column depth at a given flow rate. At a sample flow rate of 12 ml/min, the percentage removal increased from 68 to 95 % as the adsorption column depth increased from 0.50 m to 1.00 m. The time taken to sample leachate at column depths 0.50, 0.75 and 1.00 m was 60, 90 and 120 min, respectively.



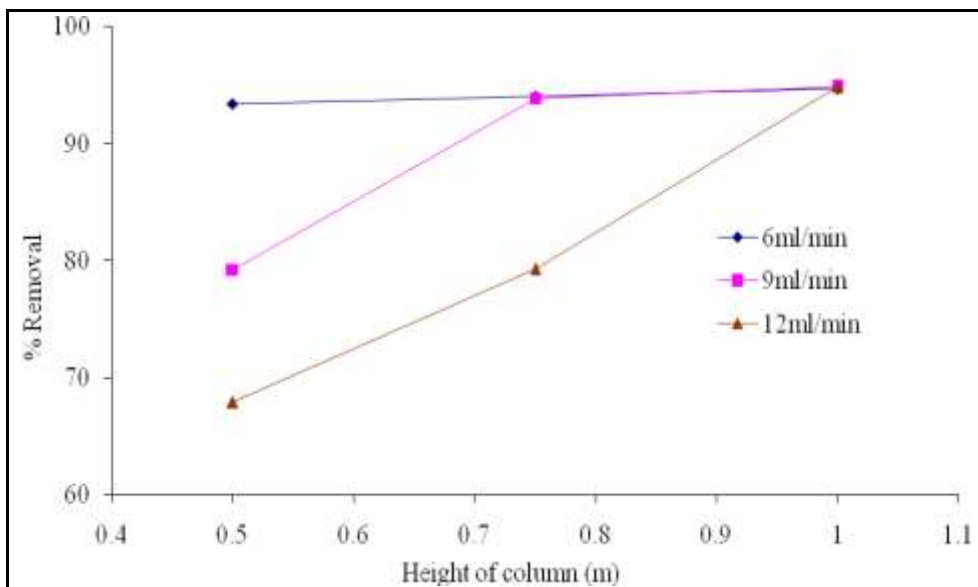


Figure 2: Effect of effluent flow rate and column depth on removal efficiency of zinc ions

At sample flow rate of 9 ml/min, the percentage removal increased from 79 to 95 % as the adsorption column depth increased from 0.50 m to 1.00 m. The time taken to sample leachate at column depth 0.50, 0.75 and 1.00 m was 90, 120 and 180 min respectively.

At a sample flow rate of 6 ml/min, there was negligible decrease on the removal efficiency of zinc. The change in percentage removal decreased from 94.83 % to 94.65 % as the adsorption column depth increased from 0.5 m to 1.00 m. The time taken to sample leachate at column depths of 0.50, 0.75 and 1.00 m was 120, 180 and 240 minutes respectively.

**3.4.2 Effect of adsorption bed depth and effluent flow rate on removal efficiency of copper ions**

Table 4 shows the effect of flow rate and column depth on the removal efficiency of copper ions.

Table 4: Effect of effluent flow rate and column depth on removal efficiency of copper ions

Bed depth (m)	Copper concentration (mg/l)			Copper percentage removal (%)		
	6 (ml/min)	9 (ml/min)	12 (ml/min)	6 (ml/min)	9 (ml/min)	12 (ml/min)
0.5	0.84	1.91	3.14	90.97	79.52	66.29
0.75	0.75	0.77	1.86	91.94	91.77	80.00
1	0.74	0.72	0.72	92.10	92.26	92.26

At a column depth of 0.5 m, the mean percentage removal of copper decreased from 90.97 % to 66.29 % as flow rate increased from 6 to 12 ml/min. This can be attributed to reduction in contact time from 120 minutes to 60 minutes. At a column depth of 0.75 m, the mean percentage removal of copper decreased from 91.94 % to 80 % as flow rate is increased from 6 to 12 ml/min. This can be attributed to reduction in contact time from 180 minutes to 90 minutes. At a column depth of 1.00 m, there was negligible change on the removal efficiency of copper. The change in percentage removal increased from 92.1 % to 92.26 % as flow rate is increased from 6 to 12 ml/min.

Figure 3 shows the effect of influent injection rates at various column depths. It illustrates the deviation in heavy metal removal efficiency with changes in quarry dust column depth at various flow rates. The results show that copper removal efficiency increased with increase in the column depth at a given flow rate.

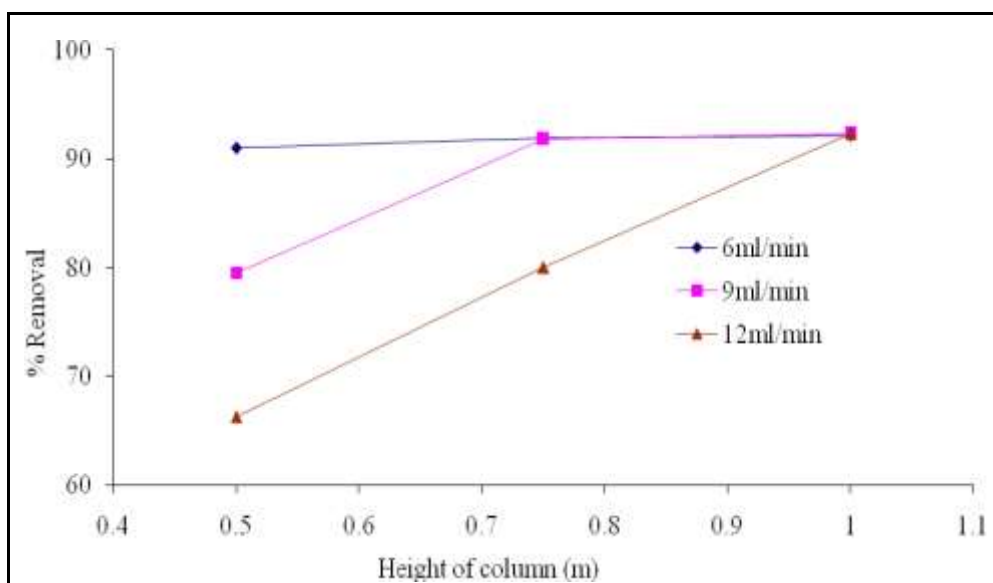


Figure 3: Effect of effluent flow rate and column depth on removal efficiency of copper ions

At flow rate of 12 ml/min, the percentage removal increased from 66 % to 92 % as the adsorption column depth increased from 0.5 m to 1.00 m. The time taken to sample leachate at column depths of 0.5, 0.75 and 1.00 m was 60, 90 and 120 minutes respectively.

At a sample flow rate of 9 ml/min, the percentage removal increased from 79 % to 92 % as the adsorption column depth increased from 0.5 m to 1.00 m. The time taken to sample leachate at column depths of 0.5, 0.75 and 1.00 m was 90, 120 and 180 minutes respectively.

At a sample flow rate of 6 ml/min, there was negligible change on the removal efficiency of copper. The change in removal efficiency increased from 91 % to 92 % as the adsorption column depth increased from 0.5 m to 1.00 m. The time taken to sample leachate at column depths of 0.5, 0.75 and 1.00 m was 120, 180 and 240 minutes respectively.

### **3.5 Adsorption capacity of WQD**

Passage of wastewater through the adsorption column causes the fill up of adsorption sites over a period of time and exhausts the removal capacity of WQD. The effect of column height on the adsorbate concentration is presented for a flow rate of 12 ml/min and inlet wastewater concentrations of 35.1 mg/l and 9.3 mg/l for zinc and copper respectively. The bed heights considered were 0.5, 0.75 and 1.00 m. Figures 3 and 4 show plots of concentration ratio  $C_e/C_o$  against time. It was observed that at smaller column heights, the adsorbate concentration ratio approached 1 faster than for bigger column heights. The adsorption column was saturated in less time for smaller column heights than for bigger heights. Smaller column heights correspond to less amount of adsorbent which means reduced capacity for the column to adsorb heavy metals from wastewater.

Figure 4 shows that a zinc concentration ratio of 1 was attained in 360, 480 and 600 minutes at 0.5, 0.75 and 1.00 m adsorption depth respectively. This means that at column height of 0.5, 0.75 and 1.00 m, the WQD adsorption sites get filled up in 360, 420 and 600 minutes, when wastewater is passed up the column at a flow rate of 12 ml/min.

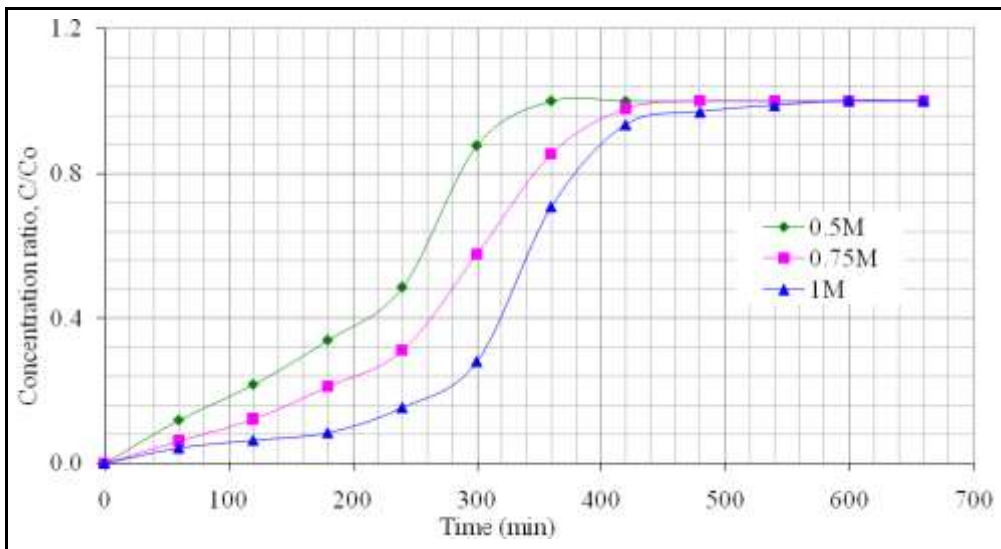


Figure 4: Effect of bed height on breakthrough curve in the adsorption of zinc ions

Figure 4 shows that copper concentration ratio of 1 was attained in 360, 480 and 580 minutes at 0.5, 0.75 and 1.00 m column depth respectively. This means that at column heights of 0.5, 0.75 and 1.00 m, the WQD adsorption sites get filled up in 360, 420 and 580 minutes respectively when wastewater is passed up the column at a flow rate of 12 ml/min.

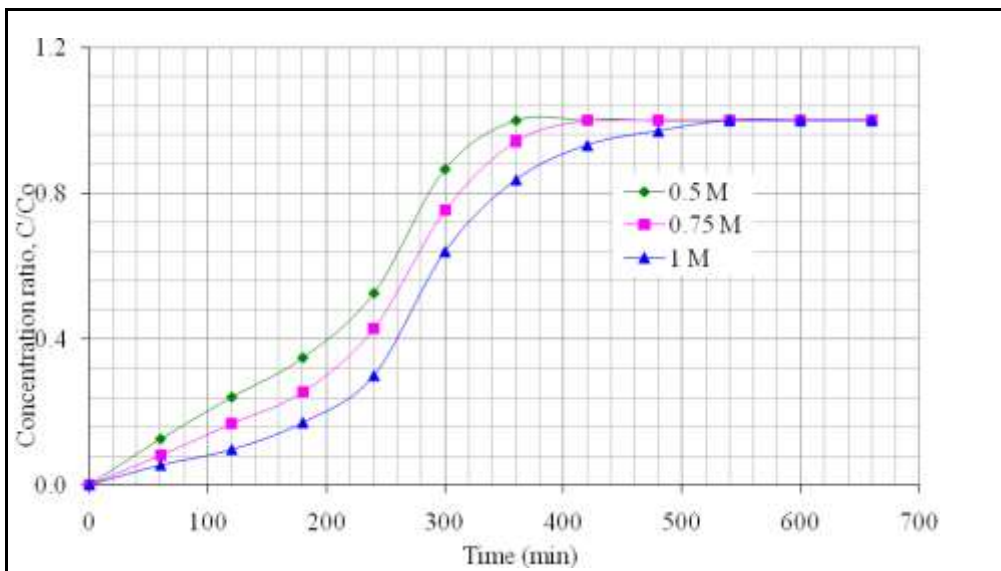


Figure 5: Effect of column height on breakthrough curve in the adsorption of copper ions

**3.6 Design of Adsorption Column Based on Bohart –Adams Equation**

Hutchins (1973) presented a technique that requires three columns to collect data for design of adsorption column which can be used under given parameters. The technique uses bed depth service time (BDST) approach. In this technique, the Bohart-Adams equation (Bohart and Adams, 1920) can be expressed as

$$t = ax + b \dots\dots\dots (3)$$

$$a = Slope = \frac{N_o}{C_o(V)} \dots\dots\dots (4)$$

$$b = Intercept = \frac{1}{K(C_o)} \ln\left(\frac{C_o}{C_B} - 1\right) \dots\dots\dots (5)$$

Where;

$N_o$  = adsorptive capacity of WQD in mg/l.

$C_o$  = initial concentration of solute in mg/l.

$C_B$  = desired concentration of solute at breakthrough in mg/l.

$V$  = Linear flow velocity of feed to bed in l/min/m<sup>2</sup>

= Flow velocity of feed to column  $v$  in ml/min divide by cross-section area

$$= \frac{v}{1000 * \Pi D^2 / 4}$$

$K$  = rate constant in l/mg-min

If a value of  $a$  is determined for one flow, values for other flow rates can be calculated by multiplying the original slope  $a$  by the ratio of the original and new flow rates. However it is not necessary to adjust the value of  $b$  since it is insignificantly affected by changing the flow rates.

Laboratory test is conducted at solute concentration  $C_1$ , to yield Equation 6

$$t = a_1x + b_1 \dots\dots\dots (6)$$

To predict the equation for concentration  $C_2$  can be done as follows,

$$a_2 = a_1 \frac{C_1}{C_2} \dots\dots\dots (7)$$

$$b_2 = b_1 \left(\frac{C_1}{C_2}\right) \frac{\ln\left(\frac{C_2}{C_F} - 1\right)}{\ln\left(\frac{C_1}{C_B} - 1\right)} \dots\dots\dots (8)$$

Where;

- $a_1$  = Slope at concentration  $C_1$ .
  - $a_2$  = Slope at concentration  $C_2$ .
  - $b_1$  = Intercept at concentration  $C_1$ .
  - $b_2$  = Intercept at concentration  $C_2$ .
  - $C_F$  = Effluent concentration at influent concentration  $C_2$ .
  - $C_B$  = Effluent concentration at influent concentration  $C_1$
  - $N_o$  = adsorptive capacity of WQD in mg/l.
  - $C_o$  = initial concentration of solute in mg/l.
  - $C_B$  = desired concentration of solute at breakthrough in mg/l.
  - $V$  = Linear flow velocity of feed to bed in l/min/m<sup>2</sup>
  - $V$  = Flow velocity,  $v$  in ml/min divided by column cross-sectional area =  $\frac{v}{\pi r^2}$
- $$V = \frac{v}{\pi r^2 * 1000} = \frac{v}{\pi * 0.04^2 * 1000} = \frac{v}{5} \text{ l / min / m}^2$$
- $K$  = rate constant in l/mg-min

**3.7 Validation of the Bohart-Adams Equation**

From the adsorption column data operating at a flow rate of 12 ml/min (linear flow rate = 2.4 l/min/m<sup>2</sup>) which was used to study the removal of heavy metals from wastewater, other adsorption columns operating under different parameters can be designed. For example, zinc concentration was reduced from 35.1 mg/l to 1.8 mg/l with laboratory column depths and service times as tabulated in Table 5:

*Table 5: Laboratory service time data for zinc*

Bed depth (m)	Time to breakthrough (min)
0.50	360
0.75	480
1.00	600

Bohart-Adams equation can be used to predict the operating time for a 0.75 metre column operating at a flow rate of 9 ml/min (linear flow rate = 1.8 l/min/m<sup>2</sup>). Moreover, the operating time (regeneration time) for this column can be predicted, if the influent concentration of zinc increased from 35.1 mg/l to 50 mg/l at a linear flow rate of 1.8 l/min/m<sup>2</sup>.

Figure 6 shows a plot of bed depth verses service time using data from Table 5. The constants for the linear equation  $t = ax + b$ , are  $a = 480$  min/m and  $b = 120$ .

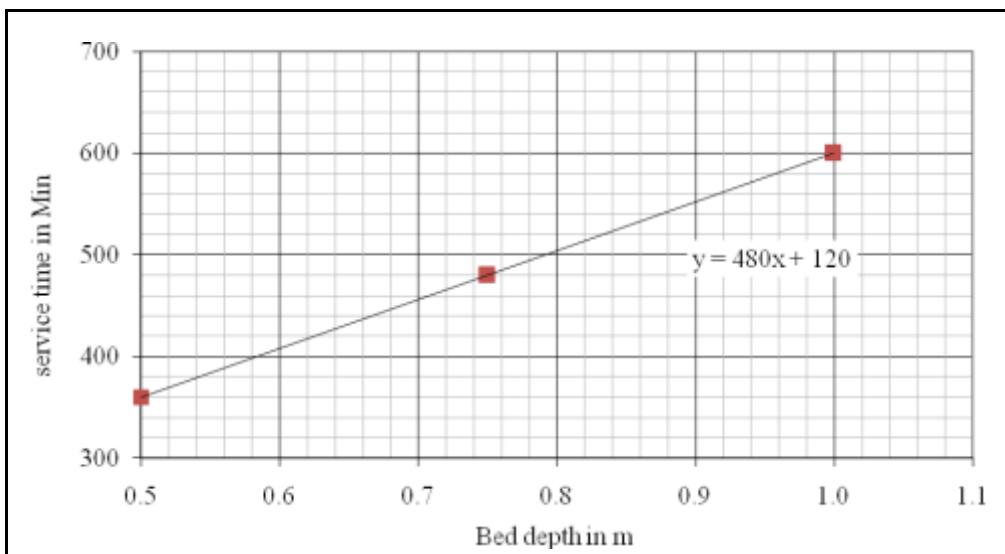


Figure 6: Bed depth service time plot

Thus, for a linear flow rate of 2.4 l/min/m<sup>2</sup> the equation for the line is  $t = 480x + 120$

To determine the equation for a linear flow rate of 1.8 l/min/m<sup>2</sup>, slope term  $a$  need to be adjusted without necessarily adjusting  $b$ .

$$a_1 = a \frac{V}{V_1}$$

Where;

$a$  = Slope of the line at the original linear flow rate ( $V$ ).

$V$  = Original linear flow rate in l/min/m<sup>2</sup>.

$V_1$  = Revised linear flow rate in l/min/m<sup>2</sup>.

$a_1$  = Revised slope for new linear flow rate in ( $V_1$ ).

$$a_1 = 480 * \frac{2.4}{1.8} = 640$$

Hence the predicted equation at  $V_1 = 1.8$  l/min/m<sup>2</sup> is

$$t = 640x + 120 \dots\dots\dots (9)$$

Equation 9 can be used to predict the service time (regeneration time) for a 0.5, 0.75 and 1 m column operating at a linear flow rate of 1.8 l/min/m<sup>2</sup> with an influent zinc concentration of 35.1 mg/l. For 0.5 m adsorption column depth, regeneration time

$$t = 640x + 120 = 640(0.5) + 120 = 440 \text{ min}$$

For 0.75 m adsorption column depth, regeneration time

$$t = 640x + 120 = 640(0.75) + 120 = 600 \text{ min}$$

For 1 m adsorption column depth, regeneration time

$$t = 640x + 120 = 640(1) + 120 = 760 \text{ min}$$

The above regeneration times are similar to the ones found in the laboratory experiments as shown in Figure 7 and table 6 which show the service times for various column depths when wastewater is passed through the column at a linear flow rate of 1.8 l/min/m<sup>2</sup>.

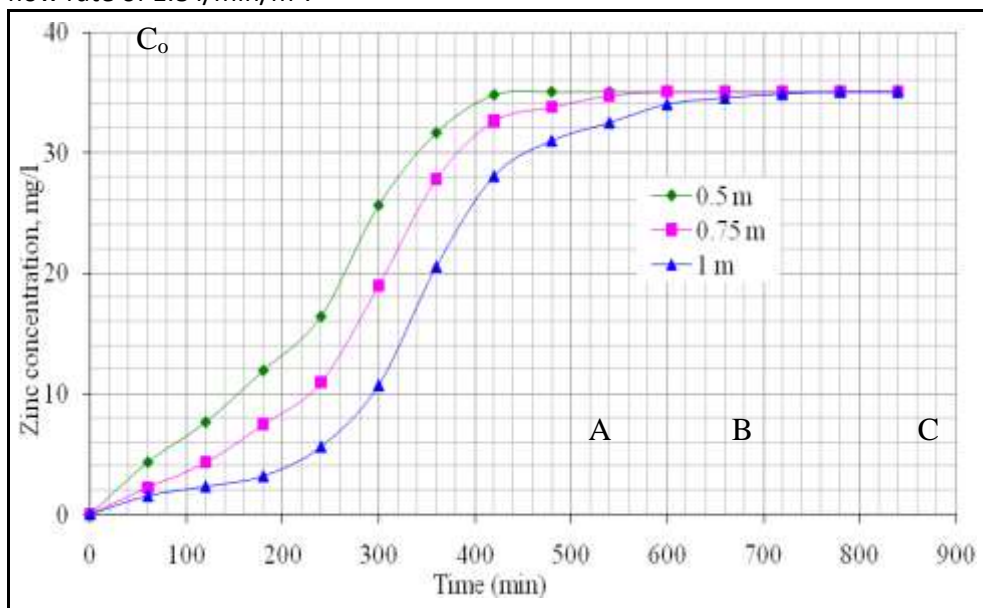


Figure 7: Service time curve for 9 ml/min flow rate

C<sub>o</sub> is the zinc concentration of the effluent which was 35.1 mg/l. Letters A, B and C indicates the service time at various depths. Wastewater was continuously passed through the column and leachate samples collected at respective outlets for analysis until the inlet concentration (C<sub>o</sub>) and outlet concentration (C) were equal.

Table 6: Laboratory and Bohart-Adams equation service time

Adsorption bed depth in metres	Laboratory column service time in minutes	Service time using BDST approach in minutes
0.50	440	440
0.75	580	600
1.00	740	760

It was observed that when Bohart-Adams equation was used to predict service time, results were very similar to those found in the laboratory tests. Therefore it was concluded that Bohart-Adams equation can be used to predict the service



time for a given column at a given flow rate using the data generated in the laboratory experiments. If zinc concentration changes at a given flow rate, both  $a$  and  $b$  must be corrected. For example if zinc concentration changes from 35.1 mg/l to 50 mg/l at a linear flow rate of 1.8 l/min/m<sup>2</sup>, then

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

Where;

$a_1$  = Slope value for 2.4 l/min/m<sup>2</sup> corrected to a linear flow rate of 1.8 l/min/m<sup>2</sup>,

$C_1$  = old influent concentration in mg/l.

$C_2$  = new influent concentration in mg/l.

$$\text{Thus } a_2 = a_1 \frac{C_1}{C_2} = 640 * \frac{35.1}{50} = 449.3$$

$$\text{Intercept for an influent concentration of 50 mg/l, } b_2 = b_1 \left( \frac{C_1}{C_2} \right) \frac{\ln \left( \frac{C_2}{C_F} - 1 \right)}{\ln \left( \frac{C_1}{C_B} - 1 \right)}$$

Where;

$b_1$  = Intercept at influent concentration  $C_1$ .

$C_1$  = Influent concentration of 35.1 mg/l.

$C_2$  = Influent concentration of 50 mg/l.

$C_B$  = Effluent concentration at influent concentration  $C_1$

$C_F$  = Effluent concentration at influent concentration  $C_2$ .

$C_B$  = Effluent concentration at influent concentration  $C_1$

$C_B = C_F = 1.8 \text{ mg/l}$

Hence

$b_2$  = slope corrected for change in influent solute concentration

$$b_2 = b_1 \left( \frac{C_1}{C_2} \right) \frac{\ln \left( \frac{C_2}{C_F} - 1 \right)}{\ln \left( \frac{C_1}{C_B} - 1 \right)} = 120 \left( \frac{35.1}{50} \right) \frac{\ln \left( \frac{50}{1.8} - 1 \right)}{\ln \left( \frac{35.1}{1.8} - 1 \right)} = 120(0.702) \frac{\ln 26.8}{\ln 18.5} = 84.24 * \frac{3.29}{2.9} = 95.6$$

Thus the new equation corrected for 1.8 l/min/m<sup>2</sup> linear flow rate and 50 mg/l influent concentration is

$$t = 449.3x + 95.6$$

Therefore, the operating time for a 0.75 metre column under these conditions is

$$t = 449.3x + 95.6 = 449.3 * 0.75 + 95.6 = 432 \text{ minutes.}$$

#### **4.0 Conclusions**

Use of WQD in the removal of heavy metals is technically feasible, eco-friendly and efficient. It compares well with other adsorbents with 94% and 92% removal efficiencies for zinc and copper respectively. It was observed that adsorption columns can be designed based on Bohart-Adams equation since service time calculated using the equation, for 0.50, 0.75 and 1.00m columns at a linear flow rate of 1.8 l/min/m<sup>2</sup> were similar to those found in the laboratory column experiment. The treated wastewater complies with the requirements of KS1966-2:2007, Kenya Standard Specification Effluent tolerance limits, Part 2: Effluent discharged into public sewers.

#### **5.0 Recommendations**

The authors recommend that further research be done to test the applicability of other adsorption isotherms other than Bohart-Adams equation to predict heavy metal removal accuracy.

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