RESEARCH ARTICLE   OPEN ACCESS

Retention Behavior of Lead Ion in Soil Bentonite Liner

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Abstract
In this study, it is proposed to obtain breakthrough curves for commonly occurring lead ions in any effluents through locally available soil amended with 10% bentonite and determine the diffusion coefficients. The theoretical breakthrough curves of migrating ions in the soil column experiment are generated using mathematical equation considering effective diffusion coefficients , knowing soil parameters and hydraulic head. These curves are then compared with experimental curves. In cases where the theoretical and experimental breakthrough curve do not match, there would be need to consider other parameter retardation factor along with diffusion coefficient. Theoretical curves are generated for sets of diffusion coefficient and retardation factor. The sets which give theoretical curve close to experimentally determined breakthrough curves are accepted. Thus it may be possible to bring out the condition for the dominance of diffusion coefficient and retardation factor. Then knowing the values of diffusion coefficient and retardation factor along with soil porosity and hydraulic gradient it is possible to predict the breakthrough times of different ions in the soil. In this work the breakthrough times of lead ion for the soil of 1m and 0.5m are established. The studies can be extended for any ion or soil after establishing diffusion coefficient and retardation for the considered ions in the selected liner under different hydrological regimes.
Keywords: Breakthrough curve, Column test, Diffusion Coefficient, Hydraulic Conductivity, Retardation Factor

I.   Introduction

The authorized sector of solid waste management has been facing tremendous problems in maintaining sustainable waste disposal**.** At present 70% of the total solid waste is disposed by the sanitary landfill method. It is important source of heavy metals and toxic chemicals that pollute the soil as well as the surrounding water body. Contamination of soil and groundwater occurs in different ways. [1]The movement of contaminants in the clay soil before it reaches the ground water is a very slow process and is favorable factor for attenuation of contaminants in various processes. Migration of ions in the subsurface from their point of origin assume great importance in the context of protecting ground water quality. Hence it is important to assess the travel time of polluting species in soil to plan for any remedial measures.

The aim of the present study is to investigate the extent of contaminant attenuation of chemical species by specific soil and whether the present retardation equation can successfully predict contaminant transport. These aspects form an important basis for design of clay liners for waste impoundment such as landfills. In order to predict the transport of lead pollutant species, the transport parameters involved in the governing set of equations that describes the transport processes need to be accurately defined. The laboratory column experiments, which can be used to estimate the transport parameters of chemicals species migrating through waste contaminant barriers, are discussed.

1.1 Contaminant Transport Processes Through Soil Liner
It is impossible to practically provide complete contaminant of leachate generated in a waste Landfill facility. Hence the design of a suitable (either as a primary barrier for municipal waste site or as a backup barrier for hazardous waste)requires an estimation of potential rate of contaminant transport through clay liner of landfill is useful in the design of secure waste storage facility. The following physical and chemical processes usually govern the contaminant transport.

1.1.1 Advection
Advection is the process by which solutes are transported along with the flowing fluid or solvent. Due to advection, non-reactive solutes travel at an average rate equal to the seepage velocity of the pore fluid

1.1.2 Diffusion

Diffusion is the transport process in which a chemical or chemical species migrate in response to a gradient in its concentration

1.1.3 dispersion

Dispersion refers to the spreading and mixing caused by the variation in velocity with which water moves

1.2 Determination of Diffusion Coefficients by Column Experiment

For predicting the effective diffusion coefficients of ionic species of interest using column experiments, a modified form of equation (1) and (2) are used. The column experiment results are commonly reported in terms of number of pore volumes that have passed through packed soil column wherein one pore volume, is the cross sectional area of column(A) times its length(L) times the porosity(n)i.e.,Aln.

Total number of pore volum U is the total discharge divided by value of one pore volume

$$U = \frac{vnAt}{ALn} = \frac{vt}{L} \qquad (1)$$

Thus with these definitions, the one dimensional approximate Ogata-Banks equation can be rearranged as:

$$\frac{C}{C_o} = \frac{1}{2}\left[erfc\left(\frac{1-U}{2\sqrt{UD_e/vL}} \right) \right] \qquad (2)$$

$$J_{0.84} = [\frac{(U-1)}{U^{1/2}}] \quad \text{when} \quad \frac{C}{C_o} = 0.84$$

$$J_{0.16} = [\frac{(U-1)}{U^{1/2}}] \quad \text{when} \quad \frac{C}{C_o} = 0.16$$

$$D_e = \frac{vL}{8}[J_{0.84} - J_{0.16}]^2$$

1.3 Retardation Factor

The migration of contaminants caused by the movement of chemicals dissolved in the water is described by the retardation factor. Attenuation of leachate contaminant species is one of important criteria for the choice of landfill liner.[2]The retardation factor for any particular chemical includes all the interactions between the many chemical species and the solid surfaces of the porous media. These interaction tend to retard the migration of the chemical behaviors need to be known.

Retardation factors, R_f, can be determined in flow experiment where R_f for particular species in the ratio of solution velocity to the contaminant velocity.

The retardation factor for that species is by equation (3) as below.[3]

$$R_f = \frac{v_{gw}}{v_{sp}} \qquad (3)$$

Where V_{gw} is the velocity of the water and V_{sp} is the velocity of the contaminant species

1.3.1 Analytical Solutions to One Dimensional Contaminant Transport Equations

Method used to solve the one dimensional governing equation, analytical methods are widely used for calculating the contaminant migration The best known analytical solution for concentration C at time t and depth x beneath the surface of a barrier, which is assumed to be infinitely deep and subject to a constant surface concentration, C_o is represented by equation (4) as [4]

$$\frac{C}{C_o} = \frac{1}{2}\left[erfc\left(\frac{R_f x - vst}{2\sqrt{(D_e t R_f)}} \right) + \exp\left(\frac{R_f vsx}{D_e} \right) erfc\left(\frac{R_f x + vst}{2\sqrt{(D_e t R_f)}} \right) \right]$$

II. Experimental Details

In order to predict the transport of lead pollutant specie, the transport parameters involved in the governing set of equations that describes the transport processes need to be accurately defined. The laboratory column experiments, which can be used to estimate the transport parameters of chemicals species migrating through waste contaminant barriers

2.1 Influent Reservoir

It consists of a tank made of polyethylene with two openings. One at the top for transferring the synthetic source solution of interest into it and the other at the bottom to allow it to migrate through the soil specimen.

2.2 Column Assembly

The column assembly consists of Plexiglas cylinder of 11-cm long, 4-cm inner dia and 1 cm thick wall. The Plexiglas cylinder is attached to the base plate, which houses a porous stone as shown in the Fig 2.1. The soil specimen of 4cm dia and 10 cm height is compacted into the Plexiglas cylinder in three equal layers using a screw jack to ensure uniform compaction for the entire specimen. Once the soil sample was in place, one more set of porous stone are placed at the top and capped with top plate as shown in the figure.

2.3 Effluent Collector

It consists of a jar covered at the top to avoid evaporation of collected leachate. The effluent collected in the collector is monitored regularly.
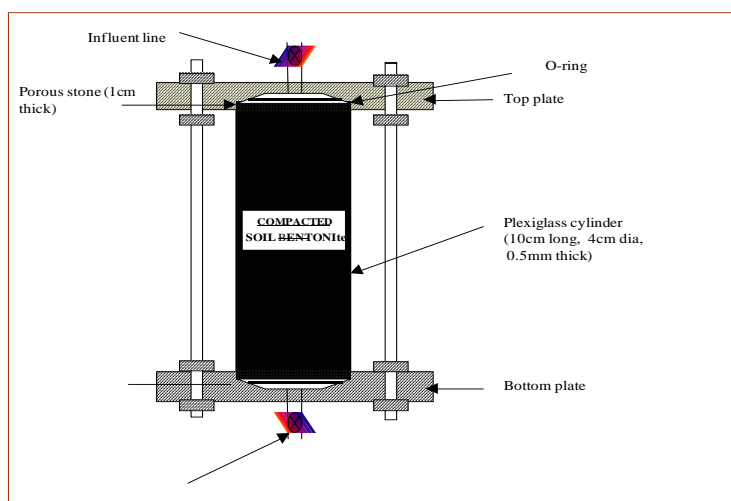
Fig 2.1 Components Of Experimental Set-Up Of Column Soil Test

III.   Experimental Procedure
3.1 Preparation of Soil Sample and Compaction
The oven dried soil is mixed with necessary amount of water separately as to prepare samples of required density. The details of experiment condition of soil specimen with source solutions are presented in Table 3.1. The soil is then compacted to required density by dividing the soil into 3 equal parts by weight and then, each part is compacted into plexglas cylinder,

3.2 Monitoring the effluent leachate
The desired solution is passed through the column. The volume of the effluent that comes out of the column with time was monitored at regular intervals and the concentration of ions measured. The interval selected varied with flow rate. The test is terminated once effluent concentration reaches influent concentration ($C=C_0$).

3.3 Chemical analysis of leachate
The chemical Analysis was performed by using AAS instrument. Dilution were made to bring the concentration into instrument range.

IV.   Materials and Methods
4.1 Clayey Soil
Clayey soil obtained from Mandur dumpsite in Bangalore was used in this study. The samples were collected by open excavation from a depth of 1 meter from natural ground. The soil was dried and passed through IS 452-micron sieve. The soil so obtained has clay content of 62%. The cation exchange capacity of soil is about 31meq/100 g.

4.2 Bentonite Used
Bentonite procured from Indian Institute from Bangalore was used in the present study. Bentonite is a natural clay mineral and is found in many places of the world it belongs to 2:1 clay family the basic structure in it is composed of two tetrahedrally coordinated sheets of silicon ions surrounding a sandwiched octahedrally coordinated sheet of aluminum ions. It has excellent sorption properties and possesses sorption sites available within its interlayer pace as well as on the outer edges

V.   Determination of Effective Diffusion Coefficients
The column method is used to calculate transport parameter and its is most preferred and is described here. This soil column test, traditionally known as leaching column test and has been used to study the adsorption and migration of contaminants through clay barriers. Firstly steady state flow is established through the soil sample by using distilled water in source reservoir. After steady state fluid has been established, the fluid in the influent reservoir is changed to a solution to a known and constant concentration (C_0) of particular chemicals constituents. The concentration (C) in the effluent reservoir is measured as a the data are reduced in the form of break through curves, the breakthrough curves are modelled using analytical solutions and hence the, Diffusion coefficient can be calculated by knowing C, C_0, v, L. This section describes some of the more common procedures, which have been used to calculate the transport parameters.

5.1 Ogata Bank's Method
In this method a plot of relative concentration versus time or number of pore volume are plotted from the plot the time ($t_{0.16}$) corresponding to $C/C_{0} = 0.16$ and time ($t_{0.84}$) corresponding to $C/C_0 = 0.84$ are obtained using these values and knowing the thickness of soil (L) and knowing the value of velocity, effective diffusion coefficient is calculated as follows:
Where, $U=vt/L$

5.2 Time Lag Method

In this method, the total amount of diffusion substance per cross sectional area, Q_t is plotted versus time and determining the values for the intercept, T_L then diffusion coefficient, D, is calculated from the equation,

$$T_L = \frac{L^2}{6D}$$

5.3 Root - Time Method

In this method, the time corresponding to relative concentration of 0.1 (90% equilibrium) is obtained from the breakthrough curve of the species. Then diffusion coefficient, D, is calculated using the equations,

$$D = \frac{0.2436L^2}{t_{90}}$$

VI. Ion Migration in Soil Bentonite Mixture Based on Diffusion Coefficient Only

From the fig. 6.1 it is clear that the effect of variation in diffusion coefficient of Lead obtained by different methods on breakthrough curves is marginal and none of the curves are close to the experimental curve. Thus the breakthrough time for lead with diffusion coefficient from theoretical curves for C/C_0 = 0.5 is 250 to 390 hours and the breakthrough time obtained experimentally from is 1300 hrs. It is clear that the theoretical breakthrough time is occurring earlier than the experimental breakthrough times.
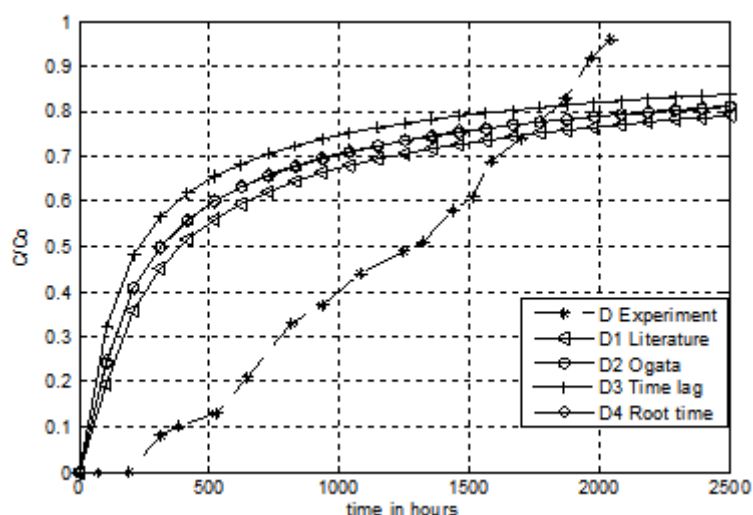

Fig. 6.1 Comparison of theoretical breakthrough curves obtained using different diffusion coefficients with experimental curve for Lead ion.

There is considerable difference in the nature of curves while the theoretical curve indicates piston flow, the experimental curve indicates presence of attenuation/ retardation process. This shows that the effective diffusion coefficient alone, as calculated by different methods, is not adequate to describe breakthrough curves. This also indicates that the effective diffusion coefficient as calculated by different methods is not fully accounting all the retardation processes that may occur while the lead ion is migrating through soil.

VII. Role of Retardation Factor in the Prediction of Experimental Breakthrough Curves of Ions in Soil

Fig.7.1 shows the theoretically obtained breakthrough curves, using diffusion coefficients obtained by different methods, with retardation factor selected on trial and error for lead ion along with experimental curve. From the figure is clear that all

the theoretical curves agree reasonably well with the experimental curve except Ogata bank's method. However some variation in the diffusion coefficients, even though the same retardation factor is used. Thus the breakthrough time for lead ion with any diffusion coefficient from theoretical curves for C/C_0 = 0.5 varies in the range of 1200 to 2000 hrs; and the actual breakthrough time obtained by experimental curve is 1300 hrs. Relatively the curves obtained using diffusion coefficient obtained by Root time method is closer to the experimental breakthrough curve.
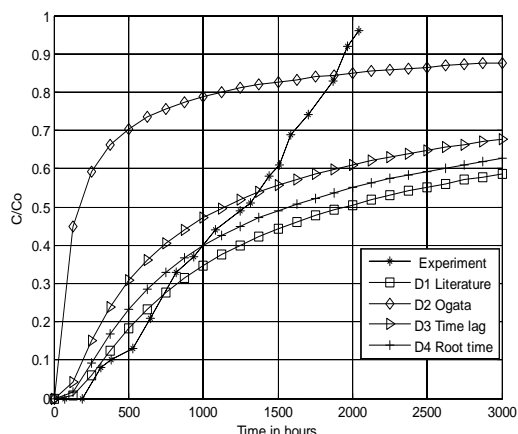
Fig. 7.1 comparison of theoretical breakthrough curves obtained using retardation factor and different diffusion coefficients with experimental curve for lead ion

Compared to the theoretical curves obtained without retardation factor, the theoretical curves with retardation factor shows considerable variation between $C/C_0 = 0.5$ and 1.0. this is due to difference in the nature of breakthrough curves. The curves exhibit lesser characteristics of piston flow. The theoretical curves obtained without retardation factor showed earlier breakthrough time, whereas the curve in this case showed not only higher breakthrough times but also nearer to the experimental value.

VIII.   Rate of Migration of Ions in Soil Bentonite Liner
8.1 Migration of Lead Ion Considering only Diffusion Conditions
Fig 8.1 shows the variation of relative concentration with time for lead ion using respective

diffusion coefficient and with retardation factor in soil bentonite mixture for lead and considering 1 m as thickness of the liner breakthrough occurred at about 500 years for lead ion.
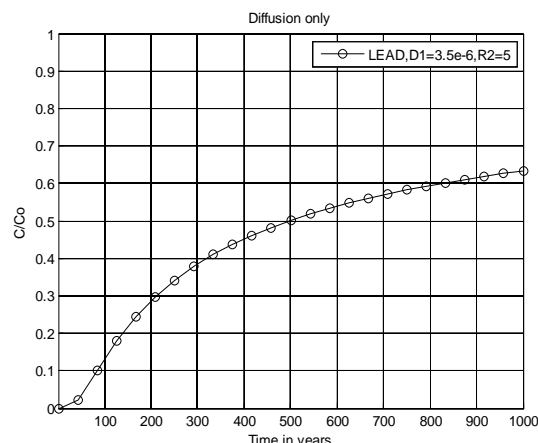

Fig 8.1 Variation of relative concentration with time for Lead ion considering diffusion only

The breakthrough time for any relative concentration can be obtained in any soil. The curve showing the variation of breakthrough time of lead ion in soil bentonite mixture with respect to relative concentration in the particular soil.

8.2 Migration of Lead Ion Considering both Advection-Diffusion Conditions
Fig.8.2 shows the variation of depth of arrival of C/C_0 of 0.5 front for Lead ion with 1 m thickness of liner considering both advection and Diffusion. It can be seen that the breakthrough concentration for lead ion reaches bottom of Soil Bentonite liner of 1 m thickness of about nearly 170 years.
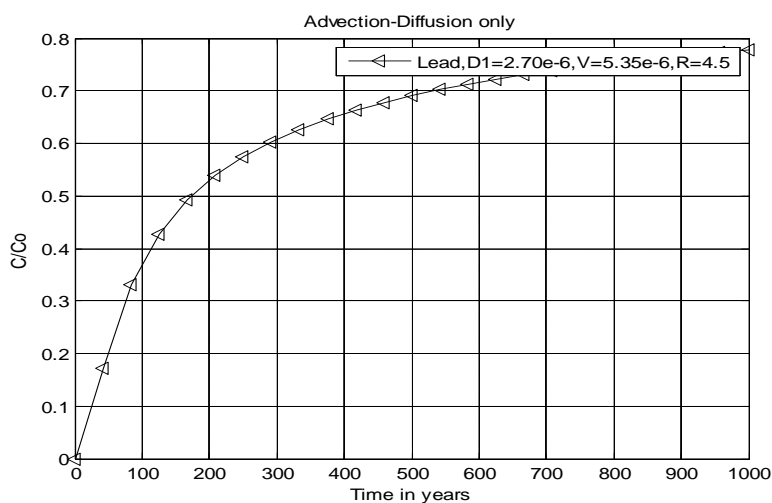

Fig.8.2 Variation of relative concentration with time for Lead considering both Advection-diffusion

Comparing the breakthrough times obtained in case of diffusion alone the breakthrough times are reduced considerably in the present case. Considerable reduction in breakthrough time occur due to advection in soil bentonite for lead ion.

Fig.8.3 shows the variation of depth of arrival of C/C_0 of 0.5 front for Lead ion with 0.5 m thickness of liner considering both advection and Diffusion. It can be seen that the breakthrough concentration for lead ion reaches bottom of Soil Bentonite liner of 0.5 m thickness within 100 years.
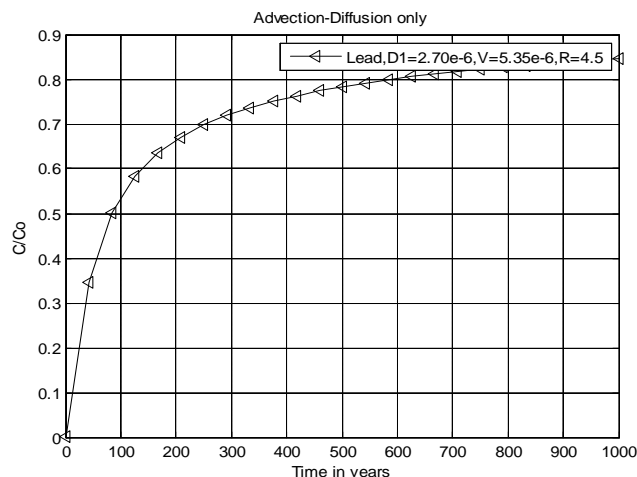

Fig.8.3 Variation of relative concentration with time for Lead ion considering both Advection-diffusion for 0.5m thickness of liner.

Comparing the breakthrough times obtained in case of Advection-Diffusion for 1 m thickness, the breakthrough times are reduced considerably in the present case. Considerable reduction in breakthrough time occur due to reduction in thickness of the soil Bentonite liner for lead ion.

IX. Conclusions

From the current research the following major conclusions are as follows:

1. Determining the diffusion coefficient of an ion experimentally is an important step for the calculation of rates of migration of ions.
2. Diffusion coefficients is sensitive to the method of determination, Generally, diffusion coefficient obtained from. Root-Time Method is lower and is matching with the literature value.
3. It is clear that prediction of breakthrough curve considering diffusion alone is not sufficient, hence there is a need to consider retardation factor too.
4. To obtain the values for retardation factor required, the breakthrough curve of ions in soil bentonite mixture using both the ions and different diffusion coefficients as determined above, are generated and compared with experimental breakthrough curves.
5. The evaluation is done both with and without Advective flow condition.
6. Breakthrough times will be more if we design appropriate thickness of liner.

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