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Research Paper

Soil Bentonite Liner to Control Migration of Sodium and Potassium Ions

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Abstract: *Soil liners amended with bentonite can be used for the control and containment of pollutant migration from landfills. Clay liners are preferred because of low hydraulic conductivity and high sorptive characteristics. To know the rates of migration under combined influence of advection and diffusion the required diffusion coefficient and retardation factor of ions like sodium and potassium in suggested soil has been assessed through laboratory column experiments.The breakthrough times of ions in a liner of thickness of 1m,2m under different transport phenomena, are compared.The breakthrough times under similar conditions are varied since process is influenced by the dominant transport mechanism.*

Keywords: Advection, Breakthrough time, Clay liner, Diffusion, Retardation factor.

Introduction

The design of any landfill facility for disposal of waste is required to ensure safety and reduce the environmental problems [1]. Migration of leachate generated in the landfill leads to soil and groundwater pollution [2]. There are various mechanisms involved in the migration of leachate from landfill into the surrounding environment. These include advection, diffusion of transport of contaminant. Dispersion involves the mixing of contaminant at relatively high flow [3]. However there are processes which can attenuate or retard the migration process. Sorption is a physical and chemical process by which one substance becomes attached to another [4].

In clayey soil diffusion will usually control parameter than dispersion. Geotechnical liners are widely used for the control and containment of pollutant migration in soils. Liners are frequently constructed with natural materials serving as the primary barrier to liquid movement. Fine-grained geologic materials are finding increased application as barrier materials for migration of contaminants from waste disposal sites into local hydrogeologic regimes. Clay is the most important component of soil liner because the clay fraction of the soil ensures low hydraulic conductivity. The soil comprising a high percentage of clay sized particles are most commonly used. However the thickness of any barrier material selected needs to be designed.

Design of Clay Liners

It is impossible to provide a complete containment of leachate generated from waste disposal facilities. The selection of liner material and design of thickness of liners require an estimation of potential rates of transport of critical contaminants through the clay materials considered for construction of liners. Hence a detailed knowledge of contaminant migration processes through the soil is required.

Contaminants or solutes are dissolved inorganic or organic substances in the solvent such as water or fluids. Contaminant transport through compacted soil liner is controlled by a variety of physical, chemical and biological processes. The physical processes include diffusion, advection and dispersion. The chemical process usually includes sorption, dissolution/ precipitation, complexation, hydrolysis/ substitution and oxidation. The biological process includes decay etc. Thus, the following physical and chemical processes usually govern the contaminant transport.[5]

- Advection
- Dispersion

1. Hydrodynamic or mechanical dispersion
2. Molecular diffusion

- Loss or gain of solute mass as a result of reaction

Advection

Advection is the process by which solutes are transported along with the flowing fluid or solvent, typically water in response to a gradient in total hydraulic head. Due to advection, non-reactive solutes travel at an average rate equal to the seepage velocity of the pore fluid,

$$v_s = \frac{v}{n} \tag{1}$$

Where

v_s = Seepage / average linear Velocity of the water (solvent) in cm/sec

n = Total Porosity of the porous material

v = Flux of water i.e., quantity of flow per unit area per unit time in cm/sec

The time required for solute to migrate through a saturated soil of thickness `L' known as solute transit time, due to advection can be estimated using seepage velocity, as follows:

$$t = \frac{L}{v_s} = \frac{nL}{Ki} \tag{2}$$

Where t = transit time

Diffusion

While advection is associated with the bulk macroscopic ground water movement, diffusion is a molecular based phenomenon. A hydraulic gradient is not required for transport of contaminants by diffusion. Diffusion is caused by random thermal motion, as is the Brownian movement of colloidal particles. The process of diffusion is often referred to as self-diffusion, molecular diffusion, or ionic diffusion. The mass of diffusion substance passing through a given cross-section per unit time is proportional to the concentration gradient. The proportionality constant is called diffusion coefficient. The diffusion coefficients obtained from laboratory or field measurements are of major importance in calculating the diffusion front in a compacted clay barrier. The diffusion coefficients are temperature dependent.

The fundamental equation for diffusion is Fick's first law which is, for one dimensional transport in free solution (i.e., no porous media), can be written as,

$$J_D = -D_o \frac{dC}{dx} \tag{3}$$

Where

J_D = Diffusive mass flux

D_o = Free solution diffusion coefficient

dC = Difference in concentration between 2 points

dx = Distance between the points

The coefficient D_o is Isotropic and can be expressed as,

$$D_o = \frac{RT}{N}\frac{1}{6\pi\mu r}$$

Where R = Gas constant of perfect gas

N = Avagadro's Number

T = Absolute temperature (Kelvin)

μ = Fluid viscosity

r = Mean radius of diffusing molecular aggregates.

Diffusion coefficients are rarely calculated theoretically but are obtained by column experiments. Further diffusion of ions is altered because of many processes that occur during migration of contaminants through the soil liners. Depending upon type of liner and the contaminating ion migrating through it, the diffusion process is modified.

Attenuation of Contaminants

The retardation of contaminants by clay is an important process in minimizing the thickness of the liner. Their capacity to retain ions is normally assessed from their retardation factor, which is normally obtained from column breakthrough curves. In the absence of these processes calculation of breakthrough times is simple and straightforward.

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[6] . The retardation factor for any particular chemical includes all of the interactions between the many chemical species and the solid surfaces of the porous media. These interactions tend to retard the migration of the chemical relative to the water and delay its arrival downstream or down gradient. To model or predict contaminant transport and plan remediation activities at a site, both hydrologic and chemical behaviors need to be known.

Retardation factors, R_f, can be determined in flow experiments where R_f for a particular species is the ratio of the solution velocity to the contaminant velocity. The retardation factor for that species is given by [7].

$$R_f = \frac{v_{gw}}{v_{sp}} \tag{5}$$

where v_{gw} is the velocity of the water and v_{sp} is the velocity of the contaminant species. This is a bulk property that describes the overall migration of the chemical species with respect to the water and can be thought of as a chemical front moving somewhere behind the water front, but retarded by the various chemical interactions. If none of a particular species is retarded then $R_f = 1$ and the contaminant travels along with the water at the groundwater flow rate. When R_f are large, as for plutonium ($R_f > 10^4$ in most soils) the contaminant can take many years to migrate offsite. Because R_f describes the chemical behavior, it depends upon any factor strongly affecting chemistry, e.g., temperature, pH, redox potential, salinity, organic content, and concentrations of other chemical species. Each chemical species has its own R_f, which changes as the chemistry changes. This complexity has resulted in unsuccessful predictions of retardation factors from general principles. R_f must be measured experimentally for each species under each condition for each system.

Using column experimental data the value of retardation factor for each chemical species can be calculated. In column experiments, contaminant of interest is pumped into a column of soil packed to required density. The effluent from the column is monitored for the contaminant of interest. A breakthrough curve is obtained for the particular contaminant and R_f is determined as the pore volume at which the concentration of the chemical species exiting the sample is 50% of the entering solution, or $C/C_0 = 0.5$.

Transport Governing Equations

The most common form of the advective-diffusive-dispersive transport governing equation that is applied for the one-dimensional transient transport of inorganic non-decaying contaminant in the soil is,

$$(\theta + \rho_d.K_d)\frac{\partial C}{\partial t} = \theta.D_e\frac{\partial 2C}{\partial x2} - \theta.v\frac{\partial C}{\partial x} \qquad (6)$$

Where C = Concentration of contaminant at depth x and at time t

$\theta = ns_r = n$ = Soil volumetric water content (since for saturated soil Sr = 100%)

v = Darcy velocity in cm/sec.

ρ_d= Dry bulk density of soil in g/cm^3

K_d = Distribution coefficient

D_e = Effective diffusion coefficient in cm^2/sec

Analytical Solution to One Dimensional Contaminant Transport Equations

The best known analytical solution for concentration C at time t and depth z beneath the surface of a barrier, which is assumed to be infinitely deep and subject to a constant surface concentration, C_o [8] is represented by

$$\frac{C}{C_o} = \frac{1}{2}\left[\operatorname{erfc}\left(\frac{R_f x - v_s t}{2\sqrt{(D_e t R_f)}}\right) + \exp\left(\frac{R_f v_s x}{D_e}\right)\operatorname{erfc}\left(\frac{R_f x + v_s t}{2\sqrt{(D_e t R_f)}}\right)\right] \qquad (7)$$

Where

erfc = 1 - erf(x)

V = Darcy velocity in cm/sec

C = Effluent concentration in mg/l

C_o = Influent concentration in mg/l

x = depth

D_e = Effective diffusion coefficient

R_f = Retardation factor Where R is given by equation (5)

t = time

Regional Soil as Liners

The relative advantage and suitability of locally available soil amended with bentonite as liner is studied in this paper. Rates of migration of ions through selected soil under similar hydrological conditions have been assessed. These are required to assess the thickness of any liner considering the type of contaminant and acceptable level of leachate purity. To know the rates of migration using the advection diffusion equation, the retardation factors of ions in soil have been assessed through laboratory column experiments.

Relative migration rates of ions

Effective diffusion coefficient (De) takes into consideration other attenuation processes. Determination of diffusion coefficients of some common ions is important in estimating the total Breakthrough times. Column tests are usually employed [9] to determine the diffusion coefficient. Diffusion coefficients are determined from the break-through curves plotted using column test data. It has been brought out that the cation exchange capacity of soil plays an important role in the attenuation of cations. Sodium ion is considered as conservative ion because normally sodium cannot replace other exchangeable ions of soil and adsorbed on to the clay surface. The adsorption of sodium and potassium are affected by other exchangeable ions in the leachate. Knowing the effective diffusion coefficient (De), the rate of migration of species can be calculated.

The data obtained by column experiments and using Ogata-Bank's equation, the values of effective diffusion coefficients of individual ions sodium and potassium are calculated. The variation of relative concentration with time is discussed under two conditions of contaminant migration processes, that is, (i) contaminant migration with diffusion alone; (ii) contaminant migration with advection and diffusion. For each condition, the variation of relative concentration of different ions with time are plotted by taking experimental values of diffusion coefficients and then they are compared with the same plots prepared by taking literature values of diffusion coefficients.

BTCs can be measured in the laboratory for a column of a porous medium of length L by (i) establishing steady-state seepage conditions, (ii) continuously introducing at the influent end of the column a chemical solution containing a known chemical species at a concentration Co, and (iii) monitoring the concentration of the same chemical species emanating from the column as a function of time, or C(L,t).

Because the source concentration, Co, is constant, the BTCs typically are presented in the form of dimensionless relative concentration, C(L,t)/Co, versus elapsed time. The time required for the solute to migrate from the influent end to the effluent end of the column is referred to as the "breakthrough time" or the "transit time".[9]

The breakthrough times of ions in soil are about the same under the processes of advection and diffusion. Thus the effect of variation in diffusion coefficients is masked by advection.

By knowing actual transport parameters and the rates of migration of ions, the thickness of the liner can be obtained. In this study the migration of conservative sodium ion in the presence of potassium and the effect of sodium on the transport of potassium has been studied. The breakthrough times of both the ions for liner thicknesses of 2m and 1m have been established.

Experimental Procedure

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 has clay content of 62%. The cation exchange capacity of soil is about 31meq/100 g. The properties of soil are as listed in Table 1.

Table 1: Properties of Soil used

pH	9.3
Proctor's Max dry density, g/cm^3	1.75
Optimum Moisture Content (%)	26.00
Gravels, %	1.32
Sand, %	41.23
Silt & clay, %	57.45
Specific gravity	2.45
Liquid Limit (%)	37
Plastic Limit (%)	19
Shrinkage Limit (%)	16.7
Permeability, cm/sec	2.4 X 10^{-6}

Since the permeability of the soil is high, the soil with 10% of Bentonite has been considered as a liner material. Bentonite 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 aluminium ions. It has excellent sorption properties and possesses sorption sites available within its interlayer pace as well as on the outer edges. Properties of bentonite used are as listed in Table 2.

Table 2: Physical Properties of Bentonite

Properties	Bentonite
Specific gravity	2.76
Liquid limit (%)	374
Plastic limit (%)	63
Plasticity index (PI)%	311
Sediment volume in water (ml/g)	16
Optimum moisture content (%)	45
Percentage Clay fraction (%)	100

Soil Column Assembly

Soil columns were designed to simulate simple, one dimensional contaminant migration through a compacted clay liner. The apparatus used in this study was designed such that both diffusion and advective-diffusion tests could be performed. Each column consist of a hollow Plexiglas cylinder with 4 cm inside diameter and a total length of 11cm, Plexiglas plates were screwed to the top and bottom of each cylinder and fitted with polyethylene rubber fittings, a 5 mm thick porous stone was placed at the bottom and on the top of the soil to provide a constant concentration over the soil surface as shown in Fig. 1. The experimental set up consists of following three major components namely:

(i) Influent Reservoir, (ii) Column Assembly and (iii) Effluent Collector

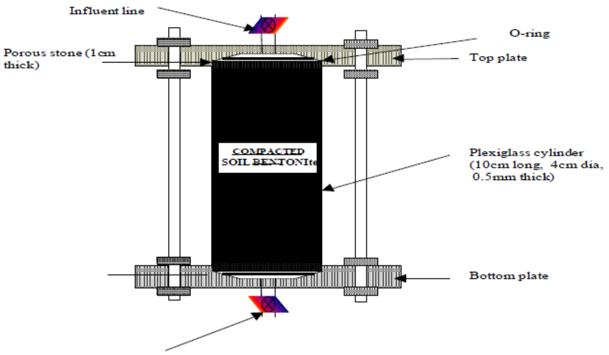

Figure 1: Experimental Set-Up Of Column Soil Test

Sample Preparation and Placement in the Column

The oven dried soil of required quantity were mixed with necessary amount of water as to prepare sample to their respective Proctor's maximum dry density on wet of optimum moisture content to allow easier handling. The soil was compacted into the column assembly in 3 equal layers using a static screw jack apparatus to ensure uniform compaction. Care was taken to ensure that no voids or fractures were left within the soil layer. After assembling the sample it is subjected to saturation by using distilled water. After saturation, the compacted soil in the columns were permeated with sodium and potassium salt solution.

The solution had a concentration of 100 ppm of sodium ion and potassium ion. The rate of flow of the leachate through the soil column and the concentration of ions in the effluent are monitored. Then the variation of concentration of the ion in the effluent as ratio of influent concentration as a function of number of pore volumes of flow is plotted. The diffusion coefficients are calculated by Root time, Ogata bank and Time lag methods. The number of pore volumes at which the breakthrough of C/C_0 of 0.5 occurs is taken as the retardation factor. Using these values and applying advection diffusion equation the breakthrough times for sodium ion and potassium ion in considered soil of 1m thickness,2m thickness are calculated.

Results and Discussion

Ion migration in soil bentonite mixture based on diffusion only for sodium ion

Figure 2 compares the theoretically obtained breakthrough curves of variation of relative concentration of sodium ion with time using diffusion coefficients obtained by different methods for sodium ion in soil bentonite with experimental curve. From the figure it is clear that the effect of variation in diffusion coefficient of sodium ion 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 sodium with diffusion coefficient from theoretical curves for $C/C_0 = 0.5$ is in between 150 to 200 hrs; the breakthrough time obtained experimentally from is 2000 hrs. It is clear that the theoretical breakthrough time is occurring earlier than the experimental breakthrough times.

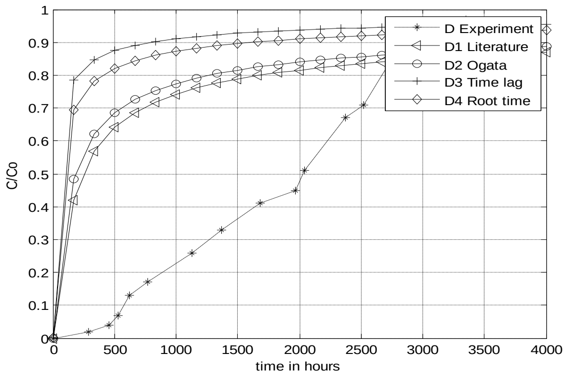

Figure 2: Comparison of theoretical breakthrough curves obtained using different diffusion coefficients with experimental curve for sodium ion in sodium chloride solution

There are considerable differences in the nature of curves while the theoretical curve indicate 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 sodium ion is migrating through soil.

Ion migration in soil bentonite mixture based on diffusion only for Potassium ion

Figure 3 compares the theoretically obtained breakthrough curves of variation of relative concentration of potassium ion with time using diffusion coefficients obtained by different methods for potassium ion in soil bentonite with experimental curve.

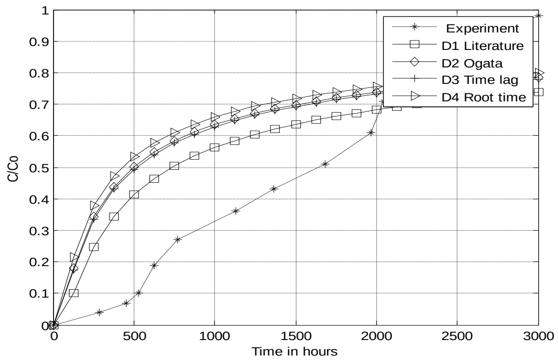

Figure 3: comparison of theoretical breakthrough curves obtained using different diffusion coefficients with experimental curve for Potassium ion

From the figure it is clear that the effect of variation in diffusion coefficient of potassium ion 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 potassium with diffusion coefficient from theoretical curves for $C/C_0 = 0.5$ is in between 300 to 700 hrs; the breakthrough time obtained experimentally is 1700 hrs. It is clear that the theoretical breakthrough time is occurring earlier than the experimental breakthrough times.

There are considerable differences in the nature of curves while the theoretical curve indicate piston flow, the experimental curve indicate 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 indicates that the effective diffusion coefficient as calculated by different methods is not fully accounting all the retardation processes that may occur while the potassium ion is migrating through soil.

Ion migration in soil bentonite mixture based on diffusion with advection for sodium ion

Figure 4 shows the theoretically obtained breakthrough curves, using diffusion coefficients obtained by different methods, with retardation factor selected on trial and error for sodium ion along with experimental curve.

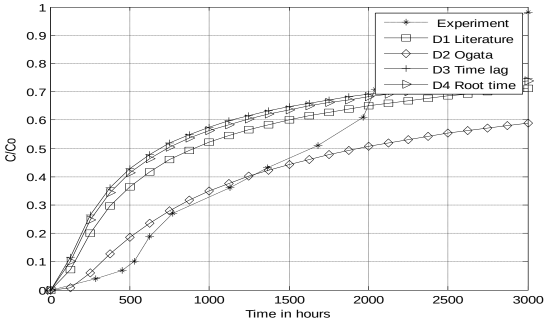

Figure 4: Comparison of theoretical breakthrough curves obtained using different diffusion coefficients with experimental curve for sodium ion in considering advection

From the figure it is clear that all the theoretical curves agree reasonably well with the experimental curve. However some variation in the diffusion coefficients, even though the same retardation factor is used. Thus the breakthrough time for sodium ion with any diffusion coefficient from theoretical curves for $C/C_0 = 0.5$ varies in the range of 700 to 1600 hrs; and the actual breakthrough time obtained by experimental curve is 1600 hrs. Relatively the curves obtained using diffusion coefficient obtained by ogata method is closer to the experimental breakthrough curve.

The values of diffusion and retardation factors for sodium are 0.7x $e^{-6}cm^2$/sec. and 5.1 respectively. 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.

Ion migration in soil bentonite mixture based on diffusion with advection for potassium ion

Figure 5 shows the theoretically obtained breakthrough curves, using diffusion coefficients obtained by different methods, with retardation factor selected on trial and error for potassium ion along with experimental curve.

From the figure it is clear that all the theoretical curves agree reasonably well with the experimental curve. However some variation in the diffusion coefficients, even though the same retardation factor is used. Thus the breakthrough time for potassium ion with any diffusion coefficient from theoretical curves for $C/C_0 = 0.5$ varies in the range of 500 to 2500 hrs; and the actual breakthrough time obtained by experimental curve is 1675 hrs. Relatively the curves obtained using diffusion coefficient obtained by Ogata method is closer to the experimental breakthrough curve.

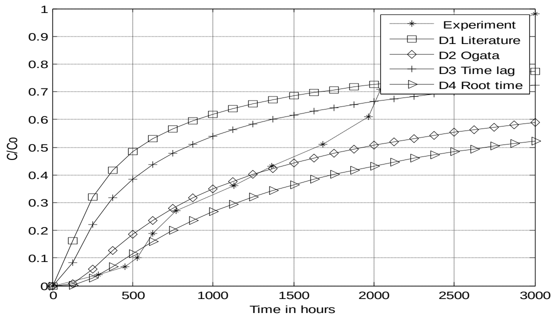

Figure 5: comparison of theoretical breakthrough curves obtained using different diffusion coefficients with experimental curve for potassium ion considering advection

The values of diffusion and retardation factors for potassium are $3.87xe^{-6}cm^2$/sec. and 1.9 respectively. 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.

Performance of liner for migration of ions

Break through times for 2m thickness of liner for sodium and Potassium ions considering diffusion only

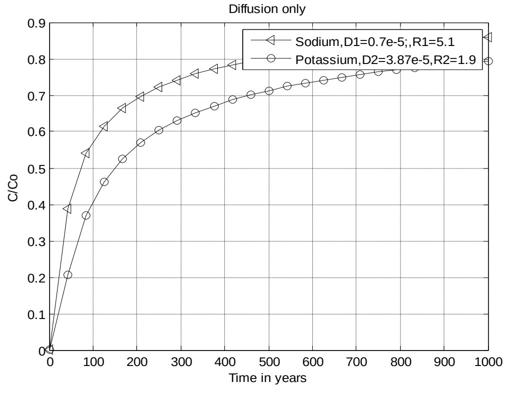

Figure 6: Variation of relative concentration with time for Sodium and Potassium considering diffusion only at 2m thickness

Figure 6 shows the variation of relative concentration with time for Sodium and Potassium ion using respective diffusion coefficient in soil bentonite mixture for Sodium and Potassium contaminating fluid and considering 2m as thickness of the liner.

The breakthrough time for any relative concentration can be obtained in any soil. The curve showing the variation of breakthrough time of Sodium and Potassium ions in soil bentonite mixture with respect to relative concentration, C/C0=0.5,for sodium break through occurs at 80 years where as for potassium it is 150 years which clearly shows that Potassium ion is more retarded than Sodium ion.

Break through times for 1m thickness of liner for sodium and Potassium ions considering diffusion only

Figure 7 shows the variation of relative concentration with time for Sodium and Potassium ion using respective diffusion coefficient in soil bentonite mixture for Sodium and Potassium contaminating fluid and considering 1m as thickness of the liner.

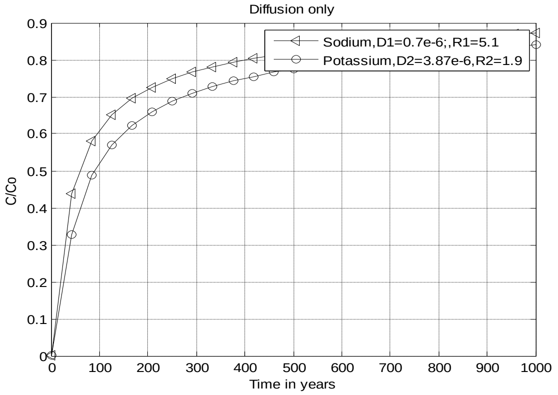

Figure 7: Variation of relative concentration with time for Sodium and Potassium considering diffusion only at 1m thickness

The breakthrough time for any relative concentration can be obtained in any soil. The curve showing the variation of breakthrough time of Sodium and Potassium ion in soil bentonite mixture with respect to relative concentration, C/C0=0.5,for Sodium break through occurs at 50 years where as for potassium it is 80 years which clearly shows that potassium ion is more retarded than sodium ion because of lower diffusion coefficient and higher retardation factor in the particular soil.

Break through times for 2m thickness of liner for sodium and Potassium ions considering advection

Figure 8 shows the variation of depth of arrival of C/C_0 of 0.5 front for Sodium and Potassium with 2 m thickness of liner considering both advection and Diffusion

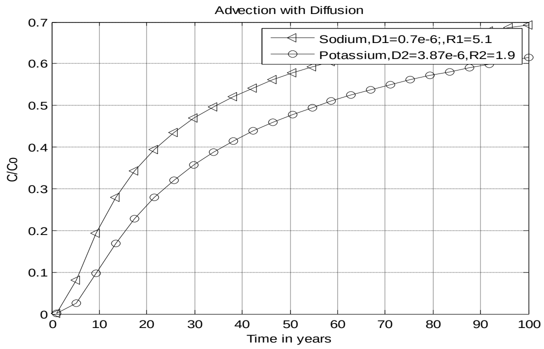

Figure 8: Variation of relative concentration with time for Sodium and Potassium considering advection with diffusion at 2m thickness. It can be seen that the breakthrough concentration for Sodium ion reaches bottom of Soil Bentonite liner of 2 m thickness within 35 years, and Potassium ion takes about nearly 55 years

Break through times for 1m thickness of liner for sodium and Potassium ions considering advection

Figure 9 shows the variation of depth of arrival of C/C_0 of 0.5 front for Sodium and Potassium with 1 m thickness of liner considering both advection and Diffusion.

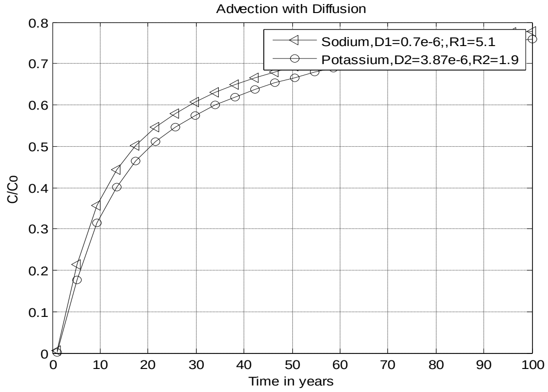

Figure 9: Variation of relative concentration with time for Sodium and Potassium considering advection with diffusion at 1m thickness

It can be seen that the breakthrough concentration for Sodium ion reaches bottom of Soil Bentonite liner of 1m thickness within 17 years, and Potassium ion takes about nearly 22 years.

The usual practice is to define breakthrough time as the time corresponding to relative concentration, C/Co of 0.5. As the thickness of liner increases, break through time also increases. However, breakthrough curve with experimentally obtained diffusion coefficient is slightly below the curve obtained with diffusion coefficient reported in literature. Beyond C/Co of 0.5, the breakthrough curve obtained with experimentally determined diffusion coefficient is above that of the curve obtained with reported diffusion coefficient. The consequence of this behavior is that the breakthrough time for C/Co of 0.5 are very nearly the same for both values of diffusion coefficient.

Table 3. Breakthrough Times for ions in soils

Thickness of Liner (In meters)	**Break through time at C/Co= 0.5**	
(In Years)	**Diffusion Only**	**Advection with diffusion**
For 2m thick Liner (Sodium)	80	35
For 1m thick Liner (Sodium)	50	17
For 2m thick Liner(Potassium)	150	55
For 1m thick Liner (Potassium)	70	22

The effect of advection masks the effect of variation in diffusion coefficient. Thus it can be observed that, for the proposed liner for 2 m thickness of liner C/C0 = 0.5 the breakthrough cannot occur before 55 and 35 years and for 1m thick liner C/C0 = 0.5 before 22 and 17 years. The corresponding breakthrough times with literature diffusion coefficients are 37 and 26 years for 2m and 20 and 15 for 1 m thickness of liner. Thus the result shows that the proposed soil bentonite liner can safely be used for 55 years with 2 m thickness before the breakthrough of Sodium and Potassium ions occur.

Conclusion

- The breakthrough curves of Sodium and Potassium ions with time in soil are obtained using column tests.
- The adsorption of ions is initially slow but increases rapidly with number of pore volumes or time.
- To know the adequacy of diffusion coefficient alone, the theoretical breakthrough curves of ions in soil bentonite mixture are obtained using advection-diffusion equation using different diffusion coefficients for ion obtained by different methods and are compared with experimental curve. It is clear that prediction of breakthrough curve considering diffusion alone is not sufficient, hence there is a need to consider retardation factor too.
- The transport of ions in soil bentonite mixture can be modeled by using both diffusion coefficient and retardation factor.
- To obtain the values for retardation factor required, the breakthrough curve of ion in soil bentonite mixture using the ion and different diffusion coefficients as determined, are generated and compared with experimental breakthrough curves.
- It has been observed that Potassium and Sodium ions are better retarded in considered soil bentonite mixture under the processes of advection-diffusion. Thus the effect of variation in diffusion coefficients is governed by advection.
- The theoretical breakthrough curves can be obtained using experimentally verified transport parameters, from which breakthrough times for any given thickness of the liner can be determined. This data helps to design liner thickness for a specified time.

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