

Role of Sorption Characteristics of Geomaterials on Long Term Performance of Landfill Barrier

K. M. Nithya, D. N. Arnepalli, S. R. Gandhi

Abstract—Among the methodologies adopted for safe disposal of various hazardous municipal and industrial solid wastes into environment, the land-filling is considered to be most safe and cost-effective method. For this purpose, compacted clay liners, CCL's, made up of different geomaterials are popularly used as a barrier to contain the waste and to isolate it from the surrounding environment. The efficiency of the engineered landfills in minimizing the contamination of ground water aquifers highly depends on the hydraulic conductivity, sorption capacity and chemical compatibility of the liner materials. In general, the hydraulic conductivity of the liner material is considered while selecting material and designing the engineered landfill liner system, however, sorption characteristics of the geomaterials play a predominant role in mitigating the transport of the contaminants through the liner system and determine its long term performance. In view of the above facts, three different locally available geomaterials have been selected to evaluate their suitability as liner material based on the physical, chemical and hydraulic characteristics. The sorption characteristics of these geomaterials were established by conducting batch sorption experiments, for different heavy metal contaminants and suitable isotherm has been identified to represent the geomaterial-contaminant interaction. Further, the study illustrated its potential application for obtaining the design thickness of landfill liner based on the sorption characteristics of the geomaterial by using the simple numerical tool, POLLUTE.

Index Terms— Landfill barrier, heavy metal, geomaterial, sorption isotherms, distribution coefficient

I. INTRODUCTION

Indiscriminate mining activities and improper disposal of industrial and municipal solid and liquid wastes are responsible for degradation of the environment by introducing high concentration of hazardous toxic heavy metal contaminants into it [1]. Heavy metals such as lead, Pb; cadmium, Cd; zinc, Zn; nickel, Ni and chromium, Cr, are the most commonly found species in both industrial and municipal waste which are considered to be harmful to human, animal and ecosystem [2].

To minimize contamination of the ground water aquifers and surrounding environment due to the migration of heavy metals, researchers, planners and engineers, have adopted various waste disposal strategies such as solidification and immobilization, incineration and land-filling to dispose these wastes into the environment. Among these methodologies land-filling is considered to be most safe and cost-effective

method. This is mainly attributed to the fact that, solidification/immobilization requires expensive chemicals and sophisticated equipment; on the other hand incineration may further deteriorate the air quality of the surrounding atmosphere and produces residues which may pose great threat to environment [3].

For this purpose, compacted clay liners, CCL's, are popularly used as a barrier to contain hazardous waste and to isolate it from the surrounding environment [4]. In order to achieve this, the liner should have most desirable properties such as low hydraulic conductivity and higher affinity to absorb the contaminants. If natural clay or clayey soils are not abundantly available, commercially available high reactive materials such as bentonite and natural or synthetic zeolites are commonly amended with locally available geomaterials to construct the liners to satisfy the liner criteria [5].

The efficiency of the engineered landfills in minimizing the contamination of ground water aquifer, due to the disposal of the waste highly depends on the hydraulic conductivity, sorption capacity and chemical compatibility of the liner materials. In general, the hydraulic conductivity of the liner material is considered while selecting material and designing the engineered landfill liner system [6], however, sorption characteristics of the geomaterials plays a predominant role in mitigating the transport of the contaminants through the liner system and determines its long term performance.

Keeping in view of the above facts, three different geomaterials namely clayey soil, moorum and composite material (i.e., quarry dust with fifteen percent bentonite) have been identified for assessing their suitability as liner material for construction of waste containment facilities. The percent of bentonite in composite material has been chosen based on the study conducted by [7]. Furthermore, the study aims to identify the suitable liner thickness based on the sorption characteristics of the liner material using simple numerical tool POLLUTE.

A. Sorption isotherms

Batch sorption experiments provide a quick understanding of the geomaterial-contaminant interaction and to aid in obtaining the mass of the contaminant that can be sorbed by the geomaterial when the liquid contaminant come in contact with it under different environmental conditions [8]. For this purpose, the results obtained from the batch sorption experiments are usually modeled using the various theoretical sorption isotherms available in the literature [9]. In order to achieve this, the amount of contaminants sorbed by the geomaterial, C_s , and the equilibrium concentration of the solute, C_e are commonly used as model parameters.

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If the variation of the C_s is linear with C_e over a range of concentration, then it can be modeled with the help of linear sorption isotherm, designated as LR. The mathematical form of the linear sorption isotherm can be represented by (1) [10]:

$$C_s = K_d \times C_e \quad (1)$$

where K_d is the partition coefficient. The researchers from the soil science have classified the linear sorption isotherm as C-type isotherm, which indicates constant partitioning of heavy metals between the solute and geomaterial [11], over a range of solute concentrations.

If the relationship between C_s and C_e is nonlinear in nature, can possibly be modeled by Freundlich sorption isotherm, designated as FH, and represented by (2) [12]:

$$C_s = K \sqrt[n]{C_e} \quad (2)$$

where K is the Freundlich sorption constant, which is a measure of the sorption capacity, and n is a constant.

It can be noted from the above equation that, the linear sorption isotherm is a special case of the Freundlich isotherm when n value equals to one. When the value of n is found to be less than one indicates the unfavorable sorption scenario, as the mass of the contaminant present in the solution is quite higher than that of sorbed by the geomaterial. Similarly, if the geomaterial-contaminant interaction exhibits n value greater than one, it is said to be favorable condition for sorption phenomena to take place. In such a scenario, the Freundlich sorption isotherms with greater n value are classified as the L-type sorption isotherms which reflect the higher affinity of the geomaterial, as a result of chemi-sorption, towards various contaminants, [13]. For analysis purpose, (2) is modified to (3):

$$\log(C_s) = \log(K) + n^{-1} \times \log(C_e) \quad (3)$$

The Langmuir sorption isotherm was developed based on the fundamental assumption that, solid surface have finite amount of active sorption sites for sorption phenomena to take place [14]. This means that, if all the active sorption sites are occupied with contaminant(s), the solid surface will no longer be able to exhibit the affinity towards the contaminants present in the solution. Hence Langmuir sorption isotherm offers an advantage over Linear and Freundlich sorption isotherms by limiting the amount of contaminant sorbed by the geomaterial [13]. That means, when the mass of contaminant sorbed by the geomaterial, C_s , reaches its threshold limit, further there will not be any significant change in its value, even initial concentration of solution increases. The mathematical form of Langmuir sorption isotherm is presented in the following:

$$C_s = \left(\frac{K_I C_e b}{1 + K_I C_e} \right) \quad (4)$$

where K_I is sorption constant related to the binding energy or the “affinity” parameter and b is the maximum amount of solute that can be sorbed by the geomaterial [15].

II. MATERIAL SELECTION AND CHARACTERIZATION

A. Materials

Samples of the locally available clayey soil designated as CS and moorum designated as MO were collected from hazardous waste disposal facility, Gummidipoondi and Thirisoolum of Tamil Nadu, India. Similarly quarry dust designated as QD was collected from a locally available stone crusher plant near Tambaram, south of Chennai, India. Furthermore, the commercially available bentonite designated as BT was chosen as an additive to enhance the suitability of the quarry dust as a liner material. The geomaterials were processed by removing the gravel size particles. Heavy metals such as Copper, Cu^{2+} , in its Sulphate form; Zinc, Zn^{2+} , and Lead, Pb^{2+} , in their Nitrate form and Manganese, Mn^{2+} , in its Chloride form were used as model contaminants. It can be observed that the majority of the heavy metals considered in this study may get precipitated at pH value of 6 and above, hence to avoid the precipitation phenomena the pH of the model contaminant solution was maintained close to 5. Further, the batch sorption experiments to determine sorption characteristics of selected geomaterials were conducted by maintaining the solution pH of 5. To achieve this, the pH of the solution, with different contaminants was adjusted with the help of NaOH and 0.1M HNO_3 . The concentration of the heavy metals present in the solution is determined using an Atomic Absorption Spectrometer, AAS.

B. Physical and geotechnical characteristics

The specific gravity, G , of the soil solids was obtained using a water pycnometer by following the guidelines presented in [16]. The particle size distribution characteristics of the geomaterials were assessed as per [17]. The consistency limits such as liquid limit, LL, plastic limit, PL and shrinkage limit, SL, along with differential free swell index, FSI, were determined by following the guidelines presented in ASTM [18], [19] respectively, and the results obtained are presented in Table I. Based on the particle size distribution characteristics and consistency limits, the geomaterials were classified according to Unified Soil Classification System, USCS, [20], as depicted in Table II.

The compaction characteristics of the geomaterials including maximum dry density, γ_{dmax} and optimum moisture content, OMC, were determined as per the guidelines presented in [21] and results are presented in Table II. The hydraulic conductivity of the selected geomaterials is evaluated using the flexible wall permeameter by following the guidelines presented in [22] and the results obtained are illustrated in Table II.

C. Chemical and Mineralogical characteristics

As depicted in Table III, chemical characteristics of the geomaterials such as cation exchange capacity, CEC [23], Carbonates [24], Organic Matter [25] and pH [26] were determined. The Specific Surface Area, SSA, of these samples was also obtained by employing the nitrogen gas adsorption technique with the help of BET surface area analyzer. Further, the chemical composition of the geomaterials in the form of major oxides was

determined using an X-ray Fluorescence setup, XRF, and the obtained results are presented in Table III.

In addition to this, the mineralogical characteristics of the materials were also determined using X-ray Diffraction Spectrometer, XRD, utilizing a graphite monochromator and Cu-K α radiation. Minerals present in these samples were identified using data base "Joint Committee on Powder Diffraction Standards" [27] search files and the results are presented in Table III.

D. Sorption characteristics

Sorption characteristics of geomaterials predominantly depend on its physico-chemico-mineralogical characteristics; liquid to solid ratio, L/S , temperature, chemical composition of the contaminant and interaction time [28]. Keeping these parameters in mind, batch sorption experiments were conducted over wide range of L/S at pH of 5. The ambient temperature, $27\pm1^\circ\text{C}$ and relative humidity, 50% was maintained constant throughout the experiment. The detailed methodology adopted for conducting these tests is presented in this section.

The processed material, i.e., the materials passing through 2mm sieve was employed to perform batch sorption experiments [29]. To achieve different L/S values (10, 20, 50, 100 and 200), the samples weighing 10, 5, 2.5, 1 and 0.5 g, respectively, were mixed with 100ml of the corresponding heavy metal solution with different initial concentration in the air tight polypropylene sample bottles. Since sorption is a physico-chemical phenomena, it is essential to evaluate its time dependant behaviour and to obtain the optimal geomaterial-interaction time i.e., equilibration time. In order to obtain the equilibration time under different environmental conditions, the recommendations made by [30] and [31] were followed. Equilibrium is considered to be achieved if the change is not more than 5 percent between two consecutive solution concentration values during 24 h interaction. To obtain equilibration sorption time, t_s , experiments were conducted with different L/S . The geomaterial is allowed to interact with various heavy metal solution of initial concentration, C_i , equal to 100 ppm. The mixture of heavy metal solution and geomaterial, in sample bottle, was allowed to interact over wide range of interaction time i.e., as minimum as 5 minutes duration and as longer as 10 days time. The sample bottles were gently shaken by mounting them on a mechanical shaker for specified interaction time, later these bottles were removed from the shaker and their contents were centrifuged at 1000g for a duration of 30 minutes, which helps in separating solid particles from the solution. The clear solution was decanted from these bottles and was filtered using a 45 μm filter paper. The filtrate i.e., clear solution was analyzed for various heavy metals using Atomic Absorption Spectrometer. Though the experiments were conducted for geomaterials and heavy metals considered in this study, the variation of concentration of Copper solution, C_{solution} , corresponding to L/S of 20 and 200 for different interaction times were plotted only for geomaterial CS, as depicted in Fig. 1.

Further, blank test i.e., sampling bottle filled with a certain concentration of heavy metal without the geomaterial and control experiments i.e., sampling bottle filled with the

geomaterials and the distilled water were performed to establish the sorption capacity of the sample bottle and the trace level concentrations of the concerned heavy metal residual present in the geomaterial [29]. The obtained sorption capacity of the sample bottle and trace level residual concentrations present in the geomaterial were used to compute the corrected initial concentration of the solution, C_i and equilibrium solution concentration, C_e , i.e., the concentration of heavy metal present in the solution after equilibration time. Later, the normalized mass of the heavy metal sorbed on the geomaterial, C_s , was computed using the following relationship:

$$C_s = (C_i - C_e) \times L/S \quad (5)$$

III. RESULTS AND DISCUSSION

A. Selection of suitable liner material

To safe guard the surrounding environment, various regulatory agencies and researchers have developed relevant guidelines for design and construction of the liner systems, based on the long term performance of existing compacted clay liners [4]. To minimize the contamination of surrounding ground water reservoirs due to the leakage of contaminants from the landfill, stringent specifications are imposed in terms of hydraulic characteristics of the liner material [32]. To meet the above mentioned liner criterion, researchers have specified threshold values of the geomaterials in terms of physical and hydraulic characteristics, as depicted in Table I [4], [33]. In addition, the presence of Carbonates, Fe and Mn Oxides and Hydroxides in the geomaterial significantly increases the sorption capacity of the geomaterial [28] by forming the complexation which in turn reduces the mobility of heavy metal [34].

Furthermore, the presence of active clay minerals such as montmorillonite in the geomaterial may result in very low hydraulic conductivity for polar permeants. However, permeation of reactive chemical constituents including the organic permeants may increase the hydraulic characteristics of geomaterial dramatically; this is mainly attributed to the relatively high reactivity of these clay minerals with the chemical constituents [35]. On the other hand, if the geomaterial containing relatively inactive clay minerals such as kaolinite, illite and attapulgite (palygorskite), will exhibit nominal changes in their hydraulic characteristics even for reactive inorganic and organic chemical permeants.

With this in view, the physico-chemical, mineralogical and hydraulic characteristics of the selected geomaterials such as clayey soil, moorum, quarry dust with 15 percent bentonite and bentonite were assessed and the results were presented in Table II and III. It can be observed from Table II and III that the locally available clayey soil, moorum and quarry dust with fifteen percent bentonite satisfies the limiting value specified by the USEPA and recommendations made by researchers (Table I). Further, the selected geomaterials were assessed for their sorption characteristics, in order to confirm their potentiality to mitigate the migration of contaminants.

B. Effect of geomaterial-contaminant interaction time

It can be observed from Fig. 1 that, the concentration of Copper in the solution for L/S of 200 decreased gradually from concentration of 100 ppm to 80 ppm corresponding to 96 h interaction time, there after it remains practically constant.

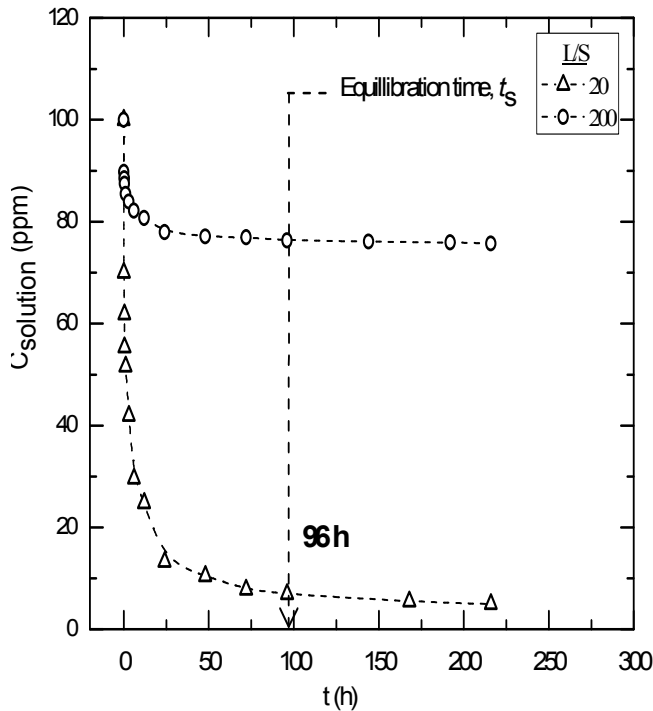


Fig. 1 Variation of concentration of Copper with interaction time for geomaterial CS

On the other hand, the Copper concentration corresponding to L/S equals to 20 is decreased drastically to very low concentration values during its initial period of interaction and incidentally, attained a constant concentration value of 7 ppm corresponding to 96 h interaction time. Similarly, the equilibration interaction time, t_s , corresponding to different L/S and heavy metal solutions for both locally available clayey soil, CS, and bentonite, BT, was established. It has been observed that, the equilibrium interaction time, t_s , is varying from 48 h to 96 h under different testing conditions and hence 96 h can be considered as equilibrium interaction time, t_s , to obtain sorption characteristics of the geomaterials

C. Selection of suitable sorption isotherm

The sorption isotherms for selected geomaterials were developed and modeled using (1), (2) and (4). The variation of normalized mass of contaminant sorbed on the geomaterial, C_s , is plotted as a function of the equilibrium concentration of the solution, C_e , corresponding to interaction time of 96 h over a wide range of L/S , for different heavy metals. The results obtained from the modeling i.e., various sorption parameters such as K_d , K , n , K_1 and b along with regression coefficients, R^2 , for different isotherms were presented in Tables IV, V, VI and VII. The different sorption isotherms of locally available clayey soil, CS, and bentonite, BT, for the contaminant Zinc is only, presented in Fig. 2 and 3.

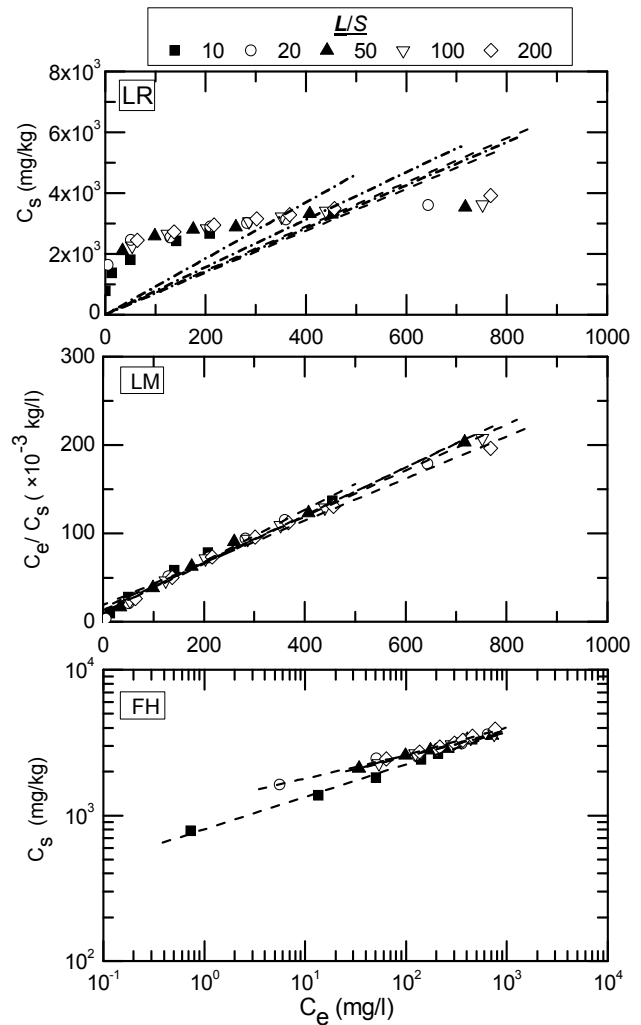


Fig. 2 Different sorption isotherms for clayey soil with heavy metal Zinc

It can be observed from the trends illustrated in Fig. 2 and 3 and data presented in Tables IV to VII that, the sorption phenomena of geomaterials for different heavy metal contaminants is non-linear in nature and hence the geomaterial-contaminant interaction over wide range of L/S can be represented, effectively, using Freundlich or Langmuir sorption isotherms. It can be noted that, the Langmuir sorption isotherm assumes monolayer sorption and uniform surface energy distribution within the geomaterial [36]. However, majority of the geomaterials are heterogeneous in nature and they exhibits non-uniform site energy distribution which results in multilayer sorption of the heavy metals. Further, the Freundlich sorption isotherm, FH, yields higher regression coefficients, R^2 , when compared to other sorption isotherms and its values are close to unity. In addition to this, Freundlich sorption isotherm is considered to be appropriate isotherm to model the multilayer sorption mechanism of heterogeneous materials similar to those geomaterials considered in the present study [37].

Based on the above facts, it can be concluded that, the Freundlich sorption isotherm is considered to be best suitable theoretical sorption isotherm to represent geomaterial-contaminant interaction of the selected geomaterials. These findings are in reasonable agreement with the literature [37], [38].

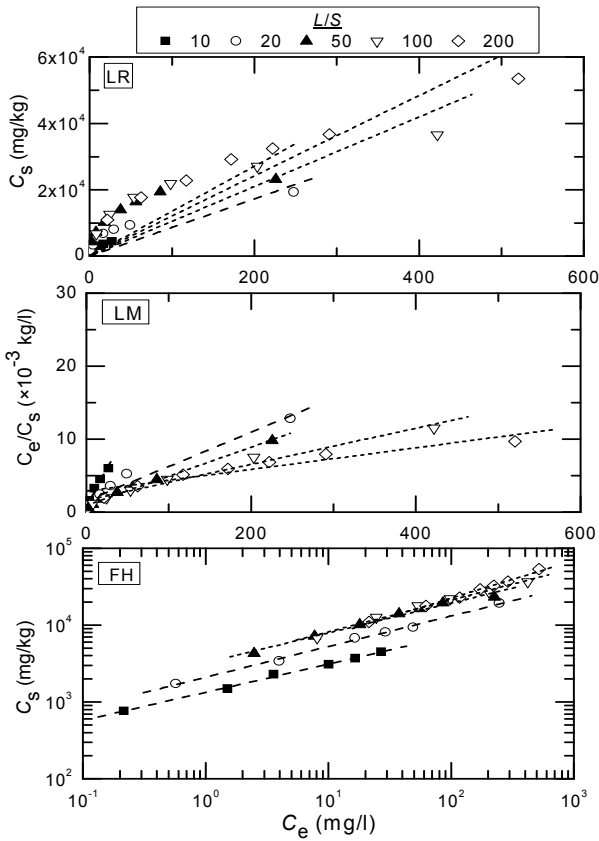


Fig. 3 Different sorption isotherms for bentonite with heavy metal Zinc

D. Implication of batch data to assess the thickness of clay barrier

To understand the importance of sorption characteristics of the geomaterial, the sorption parameters obtained in this study were applied to field scenario. For this purpose a typical single lined landfill underlined by a porous ground water aquifer was considered and the details are presented in Fig. 4. Fig. 4 shows the schematic diagram of the assumed landfill, consists a 0.3 m thick granular leachate collection system placed directly on the top of clayey soil of varying thickness (0.9, 1.5, 3, 4.5, and 6m) followed by an aquifer of 3m thick. Based on the literature study, the following values were assumed for the present study [39], [40], [33] and [41]. The clayey soil is assumed to have a porosity (n) of 0.4 and diffusion coefficient of $0.02\text{m}^2/\text{yr}$. The ground water table is assumed to be present at the top of the aquifer. The head difference between the leachate in landfill and water table results in a downward Darcy velocity v_a of $0.0024\text{m}/\text{yr}$. The infiltration through landfill cover is assumed to be $0.15\text{m}/\text{yr}$. The initial concentration of the contaminant after closure of the landfill is assumed to be 100 mg/l , and the mass of the contaminant was assumed to represent 0.01% of the waste. In this analysis, the waste was assumed to have an average thickness of 10 m and an apparent waste density of $600\text{ kg}/\text{m}^3$. In assessing the impact of the landfill, the mass of the contaminant was modeled as described by [42]. The outflow horizontal Darcy velocity (v_b) in the aquifer down gradient of the landfill is given by the following relationship with the consideration of the flow continuity.

$$v_b = v_h + \frac{L}{h} v_a \quad (6)$$

where v_h = the inflow horizontal Darcy velocity in the aquifer upgradient of the landfill assumed as $1\text{m}/\text{yr}$ in this study, L = length of the landfill and h = thickness of the aquifer.

The computer based semi-numerical and semi-analytical finite layer technique, POLLUTE, was used in this study which implements a solution to the one dimensional advection-dispersion contaminant transport equation (7) for layered deposits of finite or infinite in nature [43], [44]:

$$\frac{\partial C}{\partial t} = \frac{D_l}{R} \left(\frac{\partial^2 C}{\partial x^2} \right) - \frac{v_f}{R} \left(\frac{\partial C}{\partial x} \right) \quad (7)$$

where C is the concentration of the contaminant, t is the time, D_l is the longitudinal hydrodynamic dispersion coefficient, R is the retardation coefficient, v_f is the seepage velocity and x is the distance. This technique enables the user to predict the concentration profiles in spatial and temporal domains for a given set of boundary and initial conditions. One of the commonly used realistic upper boundary conditions is the finite mass during post closure [45] which is used in the present simulation study. The input parameters are listed in Table VIII.

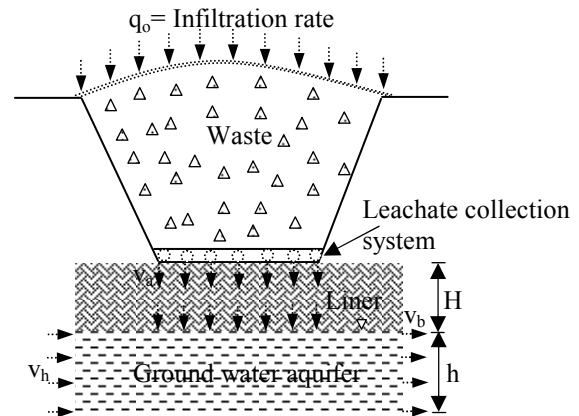


Fig. 4 Schematic diagram of the single lined landfill configuration

The contaminant impact analysis was carried out for the geomaterial clayey soil with a varying liner thickness of 0.9m , 1.5m , 3m , 4.5m and 6m . The obtained variation of heavy metal concentration, with time, at the bottom of clayey geomaterial liner of 1.5 thick is only presented in Fig. 5. From Fig. 5, it can be noticed that the concentrations of contaminant in the aquifer increases with time before it reaches the peak concentration and then decreases. This may be attributed to finite mass of contaminant present in the landfill waste.

Further, the study demonstrates its applicability to arrive the design thickness of the landfill liner that satisfies the threshold peak concentration values for different contaminants specified by the regulatory authorities. The obtained peak concentration of contaminants, with time, at the bottom of clayey liner of 1.5 , 3 , 4.5 and 6 m thick is presented in Fig. 6.

It can be noticed from Fig. 6 that as the thickness of clayey geomaterial liner increases, the peak concentration of heavy metals decreases and its arrival time increases. The obtained peak concentration values corresponding to

different liner thickness are compared with typical drinking water quality guidelines presented in Table IX. It has been noticed that except for the heavy metal Zinc, the peak concentration of the heavy metals such as Copper, Manganese and Lead are higher compared to that of allowable heavy metal values for the liner thickness of 0.9m and 1.5m. It has been observed from Fig. 6 that required minimum thickness of clayey geomaterial liner to satisfy the threshold concentration specified by regulatory standards should be minimum 2.9m.

Based on the results and discussion of contaminant impact analysis, it can be concluded that, along with the hydraulic characteristics, the sorption characteristics of the geomaterial should be considered while evaluating the suitability of the geomaterials (may be locally available) as liner material.

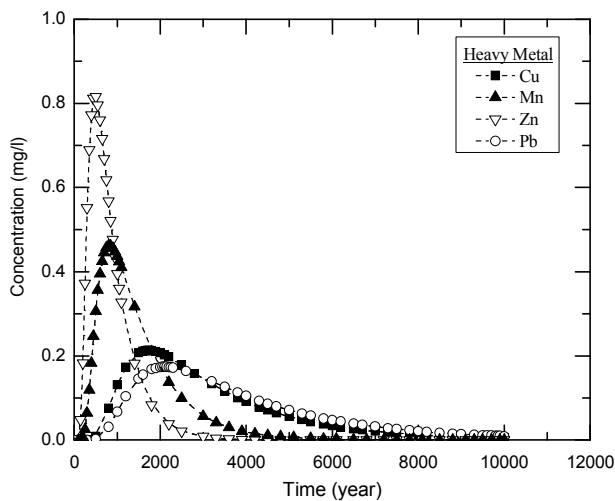


Fig. 5 Variation of contaminant concentration in the aquifer with time for 1.5m thick liner

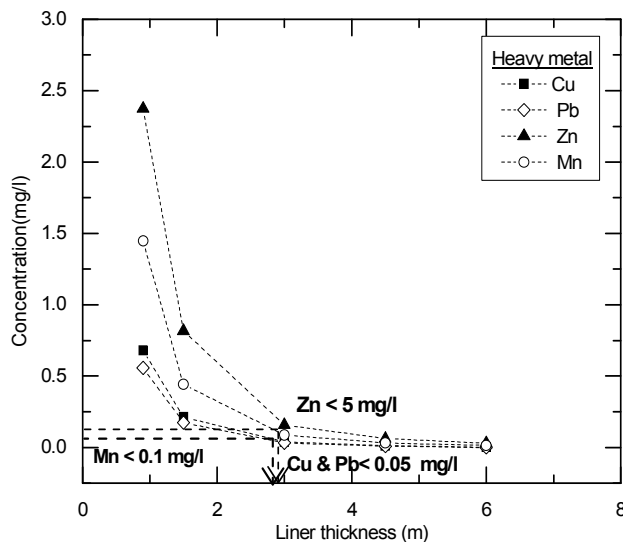


Fig. 6 Variation of peak contaminant concentration in the aquifer with liner thickness

IV. CONCLUSIONS

Based on the physico-chemico, mineralogical and hydraulic characteristics of the clayey soil, moorum and quarry dust with fifteen percent bentonite, it has been concluded that these geomaterials can be effectively used as barrier material in waste containment facilities. Further, based on the extensive laboratory investigations on sorption

characteristics of selected geomaterials using batch sorption experiments, it has been demonstrated that Freundlich sorption isotherm is the best suitable isotherm to precisely represent geomaterial-contaminant interaction. A 96 h geomaterial-contaminant interaction time is found to be required as equilibration time to obtain the optimal sorption characteristics of the geomaterials considered in this study. This fact emphasizes the role of geomaterial-contaminant interaction time on the sorption characteristics of geomaterials under different environmental conditions. The study cautions against the utilization of locally available low permeable clayey soils as liner material, without understanding their sorption characteristics, as the sorption characteristics determine the long term performance of the liner in terms of contaminant impact. The study also demonstrated its applicability to arrive to the design thickness of the liner based on the sorption characteristics of the geomaterial using simple numerical tool POLLUTE.

V. TABLES

Table I Specifications of geomaterial to meet the liner criteria*

Property	Limiting Value
Gravels (%)	< 30
Maximum particle size (mm)	25
Fines content (%)	> 30
Liquid limit (%)	≥ 20
Plasticity index (%)	> 10 and ≤ 35
Shrinkage limit (%)	> 12
Cation exchange capacity (meq./100g)	10
Coefficient of hydraulic conductivity (m/s)	≤ 1×10 ⁻⁹

*Adopted from [4], [33]

Table II Physical and geotechnical characteristics of the geomaterials

Property	Value			
	CS	MO	QD+15%BT	BT
<i>G</i>	2.7	2.71	2.75	2.6
Particle size distribution characteristics				
<i>Size</i>	<i>Percent fraction (%)</i>			
Gravel	0	3	1	0
Sand	24	59	72	1
Silt	42	21	12	34
Clay	34	17	15	65
Consistency limits (%)				
LL	49	49	NP	206
PL	22	21	NP	43
SL	13	14	---	10
PI	27	28	---	163
USCS*	CL	SC	SM	CH
Geotechnical characteristics				
γ_{dmax} (kN/m ³)	16.9	18.1	20.6	13.5
OMC (%)	18	15	12.5	30
k (×10 ⁻¹⁰ m/s)	0.71	4.8	7.4	0.053

--- Not applicable

*Unified Soil Classification System [20]

Table III Chemical and mineralogical characteristics of the geomaterial

Property	Materials			
	CS	MO	QD+15%BT	BT
<i>Chemical characteristics</i>				
pH	6.5	8.9	9.8	10.3
CEC (meq./100g)	18.1	24.2	15.1	71
SSA (m ² /g)	53.7	65.9	7.9	94.6
Carbonates (%)	9	9.3	7	9
Organic Matter (%)	8.6	9.8	3.5	11.9
<i>Major Oxides (%)</i>				
MgO	0.4	0.4	1.0	0.5
Al ₂ O ₃	12.4	13.2	8.6	14.5
SiO ₂	52.8	44.2	33.9	42.9
P ₂ O ₅	1.0	0.8	1.1	1.2
K ₂ O	4.9	0.5	0.9	1.8
CaO	3.8	2.3	16.0	3.0
TiO ₂	2.3	5.9	2.5	2.5
MnO	0.4	0.7	0.5	--
Fe ₂ O ₃	21.6	31.6	34.4	32.5
Na ₂ O	--	---	0.3	0.2
SO ₃	--	---	0.8	0.2
<i>Mineral present</i>				
Mineral Name	Kaolinite, Illite, Quartz, Feldspar	Chlorite, Illite, Montmorillonite, Hematite, Muscovite	Montmorillonite, Biotite, Feldspar, Quartz, Muscovite	Illite, Montmorillonite, Hematite Feldspar, Muscovite

Table IV Sorption characteristics of clayey soil

Heavy Metal	L/S	Sorption characteristics					R ²		
		K _d	K (×10 ²)	n	K ₁	b (×10 ³)	LR	FH	LM
		(l/kg)	(mg/kg)	(kg/l)	(l/mg)	(mg/kg)			
Cu	10	21.58	9.86	4.01	0.07	4.12	0.854	0.984	0.970
	20	34.76	9.95	2.88	0.04	7.03	0.871	0.995	0.954
	50	39.89	12.19	2.70	0.01	14.03	0.953	0.980	0.919
	100	28.70	8.24	2.37	0.10	11.05	0.974	0.992	0.917
	200	32.14	2.91	1.60	0.00	24.51	0.989	1.00	0.944
Mn	10	17.31	4.18	2.70	0.03	3.57	0.967	0.993	0.961
	20	20.87	5.64	2.69	0.02	4.95	0.884	0.997	0.967
	50	14.10	11.03	4.10	0.02	5.42	0.959	0.983	0.986
	100	12.93	4.18	2.44	0.01	6.70	0.975	0.992	0.979
	200	12.87	17.06	2.62	0.02	5.44	0.927	0.994	0.999
Zn	10	9.23	8.04	4.49	0.03	3.42	0.845	0.992	0.980
	20	7.81	12.46	6.31	0.03	3.66	0.819	0.978	0.987
	50	6.90	11.56	5.86	0.02	3.71	0.860	0.984	0.995
	100	7.09	11.97	5.49	0.02	3.86	0.870	0.991	0.997
	200	7.25	10.86	5.28	0.01	4.20	0.961	0.985	0.991
Pb	10	97.93	7.84	1.81	0.04	12.69	0.934	0.999	0.948
	20	70.35	7.03	1.67	0.02	21.98	0.886	0.990	0.982
	50	53.48	13.60	2.03	0.01	34.71	0.910	0.995	0.970
	100	35.29	8.49	1.93	0.00	34.60	0.950	0.997	0.944

200 31.57 4.38 1.61 0.00 47.39 0.961 0.994 0.964

Table V Sorption characteristics of moorum

Heavy Metal	L/S	Sorption characteristics					R^2		
		K_d (l/kg)	K ($\times 10^2$) (mg/kg)	n (kg/l)	K_1 (l/mg)	b ($\times 10^3$) (mg/kg)	LR	FH	LM
Cu	10	256.2	7.87	1.63	10.0	0.067	0.988	0.996	0.864
	20	118.1	19.45	2.86	10.0	0.115	0.870	0.999	0.975
	50	86.76	26.61	3.03	18.1	0.036	0.906	0.996	0.960
	100	68.72	31.33	3.19	23.8	0.017	0.928	0.994	0.962
	200	48.10	19.52	2.76	22.2	0.009	0.937	0.993	0.970
Mn	10	52.68	10.51	3.17	4.44	0.131	0.807	0.989	0.993
	20	28.55	14.12	3.98	5.00	0.083	0.677	0.994	0.992
	50	21.47	16.48	3.62	6.63	0.091	0.805	0.990	0.998
	100	22.25	14.83	3.61	9.26	0.013	0.985	0.992	0.986
	200	22.57	14.52	3.39	10.1	0.013	0.916	0.988	0.999
Zn	10	28.43	14.12	3.77	5.69	0.123	0.749	0.992	0.991
	20	18.02	14.59	3.89	7.14	0.037	0.778	0.990	0.990
	50	16.70	27.63	6.16	7.88	0.039	0.751	0.990	0.996
	100	15.56	25.34	5.98	7.92	0.021	0.858	0.997	0.995
	200	14.66	27.25	6.58	7.69	0.020	0.895	0.998	0.996
Pb	10	156.8	10.00	1.74	15.35	0.046	0.859	0.993	0.972
	20	110.8	11.40	1.72	23.81	0.028	0.809	0.984	0.988
	50	90.86	13.97	1.88	34.48	0.014	0.927	0.993	0.971
	100	58.59	20.72	2.26	47.62	0.006	0.866	0.991	0.983
	200	64.53	14.81	1.91	66.67	0.004	0.971	0.997	0.926

Table VI Sorption characteristics of quarry dust with fifteen percent bentonite

Heavy Metal	L/S	Sorption characteristics					R^2		
		K_d (l/kg)	K ($\times 10^2$) (mg/kg)	n (kg/l)	K_1 (l/mg)	b ($\times 10^3$) (mg/kg)	LR	FH	LM
Cu	10	170.2	10.07	2.15	6.83	0.113	0.955	0.996	0.921
	20	73.55	19.99	3.56	7.98	0.126	0.862	0.992	0.972
	50	48.90	17.22	2.85	14.66	0.021	0.885	0.998	0.965
	100	56.34	4.54	1.58	31.25	0.039	0.965	0.996	0.963
	200	43.89	8.26	2.02	25.32	0.005	0.979	0.996	0.931
Mn	10	21.44	7.52	3.42	3.45	0.075	0.775	0.986	0.997
	20	13.13	10.37	5.04	3.33	0.058	0.697	0.991	0.990
	50	10.96	9.97	4.46	4.33	0.018	0.967	0.991	0.990
	100	10.40	11.79	5.06	4.41	0.019	0.981	0.994	0.994
	200	11.11	4.94	2.77	5.72	0.008	0.961	0.998	0.995
Zn	10	16.38	14.87	5.48	4.27	0.100	0.663	0.990	0.994
	20	15.25	21.21	7.08	5.00	0.083	0.705	0.992	0.998
	50	14.31	18.70	4.93	7.14	0.024	0.824	0.994	0.994
	100	14.01	12.14	3.58	8.10	0.011	0.896	0.995	0.991
	200	13.14	10.22	3.33	8.33	0.008	0.954	0.997	0.986
Pb	10	131.7	8.78	1.74	13.16	0.046	0.928	0.997	0.960
	20	89.42	9.95	1.85	22.72	0.017	0.957	0.994	0.898
	50	60.52	16.09	2.09	33.33	0.013	0.864	0.992	0.985
	100	41.25	10.57	1.97	38.46	0.006	0.909	0.995	0.980
	200	50.76	10.43	1.83	55.55	0.003	0.965	0.992	0.928

Table VII Sorption characteristics of bentonite

Heavy Metal	L/S	Sorption characteristics					R^2		
		K_d (l/kg)	K ($\times 10^2$) (mg/kg)	n (kg/l)	K_1 (l/mg)	b ($\times 10^3$) (mg/kg)	LR	FH	LM
Cu	10	390.59	13.77	2.05	0.34	5.77	0.938	0.994	0.995
	20	519.16	20.37	1.91	0.20	16.95	0.961	0.998	0.968
	50	601.13	32.96	2.16	0.18	17.00	0.855	0.992	0.983
	100	317.67	47.57	2.39	0.04	42.02	0.917	0.999	0.960
	200	161.52	68.08	3.22	0.04	40.32	0.776	0.991	0.989
Mn	10	78.61	13.27	3.32	0.20	4.74	0.865	0.991	0.994
	20	108.77	14.70	2.57	0.09	8.95	0.927	0.998	0.967
	50	210.61	34.77	2.62	0.07	22.27	0.921	0.992	0.992
	100	89.51	38.15	3.20	0.03	23.87	0.908	0.978	0.994
	200	79.38	22.60	2.43	0.01	33.26	0.968	0.988	0.976
Zn	10	200.15	13.37	2.98	0.30	4.74	0.902	0.996	0.795
	20	86.34	20.99	2.51	0.03	21.33	0.905	0.997	0.957
	50	135.47	32.35	2.58	0.04	25.08	0.747	0.983	0.993
	100	104.94	31.65	2.42	0.02	40.45	0.890	0.986	0.978
	200	121.05	23.59	2.05	0.01	67.25	0.980	0.993	0.967
Pb	10	423.19	15.03	1.63	0.08	17.46	0.979	0.998	0.880
	20	671.86	22.37	1.59	0.06	31.87	0.989	0.991	0.777
	50	1372.73	23.32	1.15	0.01	167.50	0.983	0.997	0.988
	100	431.73	40.78	1.74	0.01	132.28	0.987	0.990	0.835
	200	458.75	27.11	1.40	0.01	240.38	0.936	0.989	0.984

Table VIII Input parameters for numerical analysis using POLLUTE v6.3

Parameters	Value
Dry density of clayey soil (g/cc)	1.7
Effective porosity, n	0.4
Effective porosity of aquifer, n_b	0.3
K_d (mL/g)	28.7 ¹ , 12.9 ² , 7 ³ , 35.3 ⁴
Infiltration of rain water, q_o (m/yr)	0.15
Leachate collected, q_c (m/yr)	0.14
Reference leachate height, H_r (m)	6
Initial concentration C_o (mg/l)	100
Hydraulic conductivity of clayey soil, k (m/s)	6×10^{-11}
Darcy velocity, v_a (m/s)	0.0024
Effective diffusion coefficient, D_e (m ² /s)	0.02
Thickness of clay barrier, H (m)	0.9, 1.5, 3, 4.5, 6
Thickness of aquifer, h (m)	3
Width of landfill, W (m)	100
Length of landfill, L (m)	100
Outflow Darcy velocity in aquifer, v_b (m/yr)	1.08

¹Cu, ²Mn, ³Zn, ⁴Pb

Table IX Drinking water quality guidelines in (mg/l) [46]

Contaminant	Guide lines (WHO)	BIS, 1998	
		Permissible limit	Excessive limit
Iron	0.3	0.3	1
Copper	1	0.05	1.5
Cadmium	0.005	0.01	0.01
Lead	0.05	0.05	0.05
Manganese	0.1	0.1	0.5

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