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Performance assessment of amended laterite soil as liner material in ash pond structures

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The aim of the present study was to examine the effectiveness of locally available laterite soil (LS) as primary liner material in ash ponds to restrict subsurface migration of heavy metals such as Cd, Ni, and Zn etc. present in the leachate generated from ash ponds of Thermal Power Plants. Due to its high permeability (3.74×10^{-5} cm/s) and moderate shear strength, laterite soil was further amended with commercially procured bentonite (B) and fly ash (FA) in the ratio of 8(LS):1(B):1(FA) to enhance its contaminants attenuating potential as liner material. The metal removal efficiency of the amended laterite soil was observed around 96% in case of cadmium metal. The results of fixed bed column experiment exhibit excellent heavy metal adsorption potential of amended laterite soil. The breakthrough curves (BTCs) generated by using HYDRUS-1D solute transport software shows good fitting with experimentally observed data.

Keywords: Ash pond, heavy metal, groundwater pollution, amended laterite soil, liner material, HYDRUS-1D.

Introduction

Fly ash (FA) disposal is a potential threat to the environment and mankind surroundings the coal fired thermal power plant. In India, dominance of coal as the prime energy source will continue for next few decades. The ash content of Indian coal is significantly very high and is in the range of around of 25 to 45%, thus generating large quantity of fly ash. To cater to the disposal of huge quantity of coal fly ash of around 112 million tons, a substantial area of land about 65000 acres has been occupied by ash ponds[4]. Even after significant increase in utilization of fly ash from 6.64 million-ton in 1996-97 to a level of 102.54 million-ton in 2014-15[3], disposal of fly ash remains a matter of concern for thermal power plants. But only a small quantity (56%) of the total ash produced in India is currently utilized in construction materials, building engineering, road sub-base, backfill, agriculture etc.[3]. Thus, a substantial quantity of fly ash produced is disposed of with greater environmental risk. For National Clean Air Programme (NCAP), Ministry of Rural Development, Government of India has issued notification no. M-12016/06/2017-RH(M&T) dated 12th September 2018 to maximize the usage of fly ash in a time bound manner, so as to combat the adverse impact of fly ash on the environment.

It was observed that the trace elements such as Cu, Cr, Hg, As, Cd, Zn and Pb etc. present in the fly ash generated on coal combustion, which on disposal or utilization, may percolate through subsurface media and be a potential environmental threat[1,4]. Quality of fly ash primarily depends on type of coal, fineness of coal particle, percentage of ash in coal, combustion technique, air/fuel ratio, type of burners and boiler[11]. The physical and chemical properties of fly ash and mobility of its constituents significantly depend on environmental conditions[10].

In view of above, it was necessary to explore locally available less permeable soil to act as a protective barrier material to retard the transmission of trace elements present in ash pond leachate through the adsorptive mechanism[6,12,13] that has motivated the authors to carry out the present study. Batch absorption test results conducted by earlier researchers showed that the adsorption capacity of the soil for Pb, Cd and As increases with the increase in the adsorbate concentration[5]. Also, utilization of red soils and amended soils as a liner material was investigated by earlier researchers[14] for attenuation of copper from aqueous solution with the addition of 3% cement to red soil gave maximum adsorption with a pH range of 6 to 8. It was also reported that the addition of bentonite improve the Geotechnical properties of fly ash, and a 20% bentonite-fly ash mix can be used as liner material[9]. It was also observed that in a bentonite-fly ash mixture the plasticity, hydraulic conductivity, swelling and shrinkage properties decreases and the dry unit weight and shear strength increases with the increase in fly ash content[2]. Furthermore, as per EU directives[15] for suitability of landfill liner materials for hazardous waste, the hydraulic permeability k should be $\leq 10^{-7}$ cm/s and thickness of at least 5 m, whereas for non-hazardous waste permeability remains same and thickness $\geq$ 1 m. However, in case of inert waste hydraulic permeability $k \leq 10^{-5}$ cm/s and thickness of at least 1 m. The present study was undertaken to ascertain the efficacies of low cost and moderate permeable laterite soil (LS) amended with bentonite (B) and Class-"C" fly ash (FA), in the selected proportion of 8(LS):1(B):1(FA) as a composite liner material for impeding migration of trace elements present in ash pond leachate into the surrounding lithosphere thereby to attenuate risk of health hazards. Comparison of experimental results with standard adsorption isotherms and numerical solute transport modelling of leachate migration in subsurface soil media was also carried out to study the concentration pattern of heavy metals leaching using HYDRUS-1D software.

Materials and methods:

The ash samples were collected from three different ash pond sites located in and around the industrial city of Durgapur, West Bengal, India. Locally available laterite soil was collected from Kamalpur, Durgapur, West Bengal, India and was further amended with commercially procured bentonite and fly ash in the selected ratio of 8:1:1 to enhance its engineering properties to be used as a liner material in ash pond site.

The background concentration of heavy metals in ash samples was determined as per protocol depicted in the USEPA 3050B using Atomic Absorption Spectrophotometer (AAS). Batch absorption tests were performed with synthetically prepared leachate as adsorbate and amended laterite soil as adsorbent to examine the heavy metal removal efficiency of the later. The pH of the solution was maintained in between 7 and 8. The supernatant was centrifuged and filtered through Whatman no. 41 filter paper prior to analysis using AAS. The physical properties of soil and fly ash samples were determined as per the BIS guidelines[7,8]. Four different initial concentrations of the heavy metals cadmium (Cd) were taken from the range of values obtained from the acid digestion test. Although in ash ponds, the pH heavily varies from highly acidic to highly alkaline conditions, in this present study, the pH of the mixed leachates are maintained in and around 7 as suggested by earlier researcher[14]. Four batch setups were made for seven different reaction time intervals viz. 30 min, 1 h, 2 h, 4 h, 8 h, 16 h and 24 h. The percentage removal of the heavy metals was calculated using eq. (1)

$$\% \text{ removal} = (C_0 - C_e)/C_0 \times 100 \quad (1)$$

where, C_0 and C_e being the initial and equilibrium concentrations (in ppm) respectively.

The adsorption isotherm experiments was carried out varying the adsorbent dosages in two different cases and maintaining the fixed values of concentrations of the heavy metals in each case. After the equilibrium is reached in each case, the adsorption capacity value, q_e (mg/gm), is calculated using eq. (2).

$$q_e = (C_0 - C_e) \times V/(M \times 1000) \quad (2)$$

where, V (ml) is the volume of the leachate solution taken for each of the batch setups and M (grams) is the mass of the adsorbent used.

Linear, Langmuir, Freundlich and Temkin isotherm models were used to derive the isotherm constants.

Linear isotherm using eq. (3),

$$q_e = K_d \times C_e \quad (3)$$

Langmuir isotherm using eq. (4),

$$q_e = K_l \times C_e/(1 + K_l \times C_e) \quad (4)$$

Freundlich isotherm using eq. (5)

$$q_e = K_f \times C_e \,(1/n) \quad (5)$$

Temkin isotherm using eq. (6),

$$q_e = K_T \times \ln (A_T \times C_e) \quad (6)$$

where, K_d, K_l, K_f and K_T are the Linear, Langmuir, Freundlich and Temkin isotherm constants respectively which were analysed using non-linear regression analysis.

Numerical models have been prepared using HYDRUS-1D which solves the Richard's equation, simulating both the water flow and the standard solute transport modules together. The column study experiments have been developed using different combination of input parameters and initial and boundary conditions with the help of HYDRUS-1D software. Also, real scale models were prepared for obtaining the results.

Results and discussion

The physical properties of soil and ash samples were determined as per BIS guidelines and depicted in Table 1.

Table 1. Physical properties of soil and ash samples

Parameters	Unit	Laterite soil	Amended soil	Fly ash
Saturated hydraulic conductivity of soil (k_s)	cm/s	3.74×10^{-05}	1.3×10^{-08}	–
Average true density of the ash (ρ_{ash})	g/cc	–	–	2.10
Specific gravity (*G*)	–	2.60	2.55	1.9–2.3
pH	–	6.51	5.8	6.2
Particle size distribution				
Sand	%	49	39.2	6
Silt	%	39	41.2	94 silt +
Clay	%	12	19.6	clay
Optimum moisture content	%	14	14	15.4
Maximum dry density	g/cc	1.85	1.875	1.29
Cohesion	kN/m^2	48	57	–
Angle of internal friction	deg.	26	11	–

Acid digestion test results:

The concentrations of the heavy metals were observed in the ash samples in the range of 0.004–0.215 ppm for zinc, 0.132–0.37 ppm for cadmium, 0.037–0.332 ppm for nickel, 0.002–0.057 ppm for chromium and 0.213–1.145 ppm for antimony respectively, as depicted in Tables 2 and 3.

Table 3. Permissible limits of heavy metals in drinking water (IS 10500: 2012)

Metal	Acceptable Limit (mg/L)	Permissible limit in absence of alternate source (mg/L)
Cadmium	0.003	No relaxation
Chromium	0.05	No relaxation
Antimony[a]	0.1–0.2	No relaxation
Nickel	0.02	No relaxation
Zinc	5	15

[a]The permissible limit of antimony is provided according to WHO standards.

Batch adsorption test results:

Within the range of values found from the acid digestion test, four values were chosen as the values of initial concentrations of heavy metals in solution, for the batch adsorption test. For cadmium, the concentrations chosen were 0.1 ppm, 0.2 ppm, 0.3 ppm and 0.4 ppm. The equilibrium concentration values showed a steady decline in the concentrations of the heavy metals in the solution, thus indicating the strong absorption property of the laterite soil. It is seen that in almost all the cases the equilibrium concentrations are same for 16 and 24 h (Fig. 1(a)). The heavy metal removal efficiency of the amended laterite soil was observed at 96% for the cadmium (Fig. 1(b)). It is observed that in the case of amended soil, the saturation comes much earlier. This is due to the fact that the overall fineness of the soil increases in

Table 2. Background concentrations of heavy metals in ash samples (mg/L)

Sample No.[a]	Cadmium	Chromium	Nickel	Zinc	Antimony
1A	0.267	0.002	0.098	0.024	0.297
1B	0.266	0.048	0.153	0.156	0.213
2A	0.148	0.040	0.202	–	0.330
2B	0.132	0.002	0.037	–	0.256
3A	0.127	0.003	–	–	0.326
3B	0.167	0.045	–	–	0.582
4A	0.370	0.056	0.332	0.198	1.068
4B	0.370	0.057	0.314	0.215	1.145
5A	0.259	0.012	0.177	0.004	0.803
5B	0.261	0.012	0.274	0.016	0.695
6A	0.141	0.014	–	–	0.627
6B	0.134	0.006	–	–	0.407

[a]Sample no. 1, 2 and 3 are from DPL, 4 and 5 are from NSPCL and sample 6 is from MTPS.

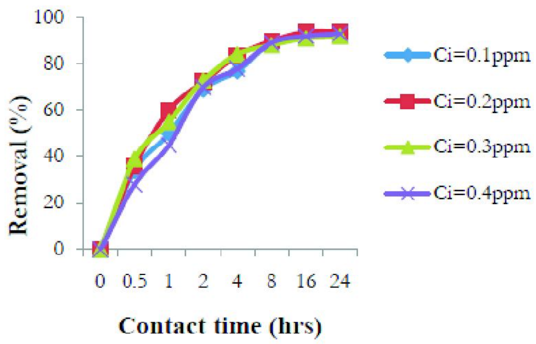

Fig. 1(a). Plot between % removal of heavy metals vs contact time – Laterite soil.

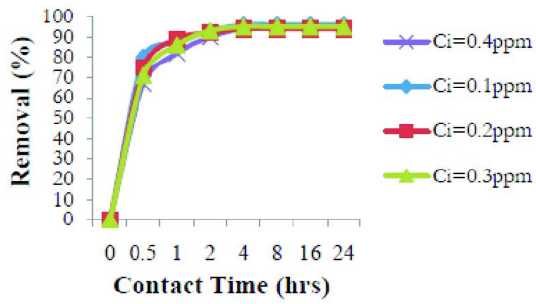

Fig. 1(b). Plot between % removal of heavy metals vs contact time – Amended soil.

case of the amended soil. Therefore, increased surface areas are available for adsorption of heavy metals.

Isotherms: For amended soil, the equilibrium concentration and the adsorption capacity values of 4th hour is taken to plot the adsorption isotherms, viz. linear, Langmuir, Freundlich, Temkin, as depicted in (Fig. 2(a), 2(b), 2(c) and 2(d)). Ergo, it may be seen that for cadmium, the best fitting adsorption isotherm is Langmuir, which exhibits monolayer adsorption, signifying all the adsorbed molecules are in contact with the surface layer of the adsorbent and there is no stacking of adsorbed molecules.

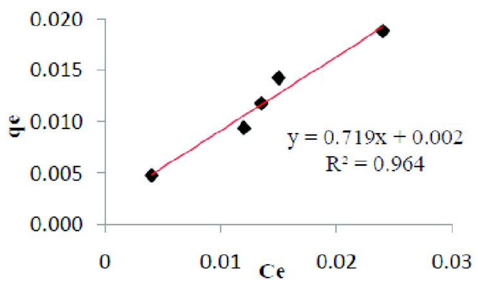

Fig. 2(a). Linear isotherm – Amended soil.

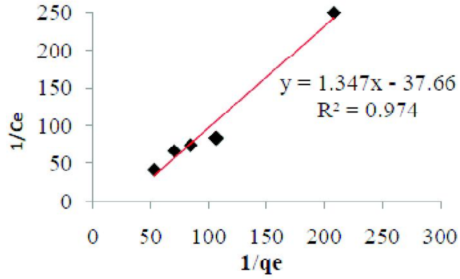

Fig. 2(b). Langmuir isotherm – Amended soil.

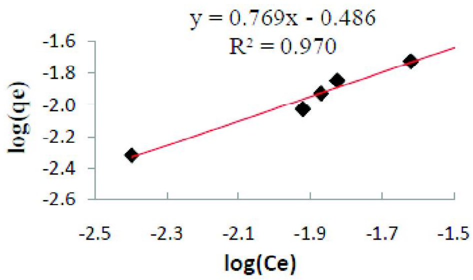

Fig. 2(c). Freundlich isotherm – Amended soil.

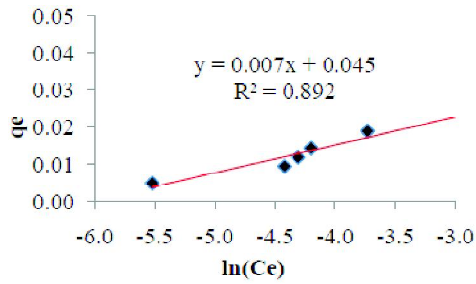

Fig. 2(d). Temkin isotherm – Amended soil.

Vertical column test results and HYDRUS-1D modelling: The column test experiments were conducted successfully with amended laterite soil and the setup was simulated in HYDRUS-1D to validate the results. Experimental result almost matches with HYDRUS-1D simulated results as depicted in Fig. 3.

Through numerical modelling performed using HYDRUS-1D solute transport software, it is seen that in both cases, the amended soil is much more effective than the laterite soil, in terms of the permeability as well as adsorption capacity of the soil. The useful life of the liner will be much more in case of amended soil compare to laterite soil for the same thickness of liner (Fig. 4(a) and 4(b)). Hence, amended soil is the better choice of liner material for ash pond structure.

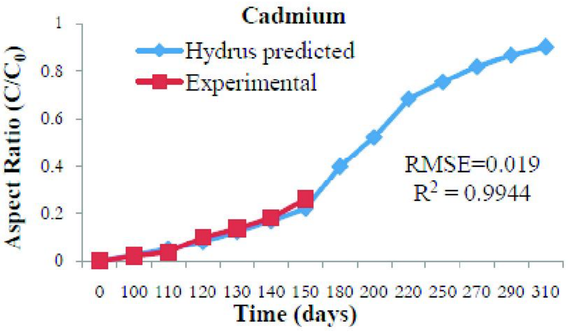

Fig. 3. Solute transport through 3 cm thick amended laterite soil.

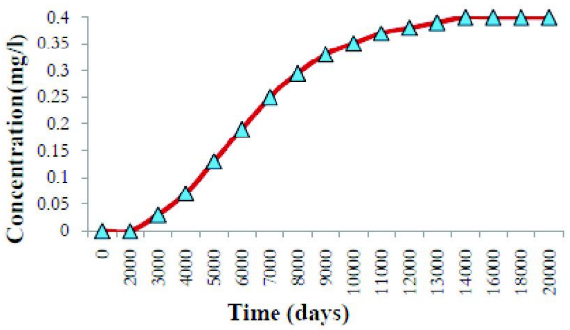

Fig. 4(a). Solute transport through 1 m thick laterite soil.

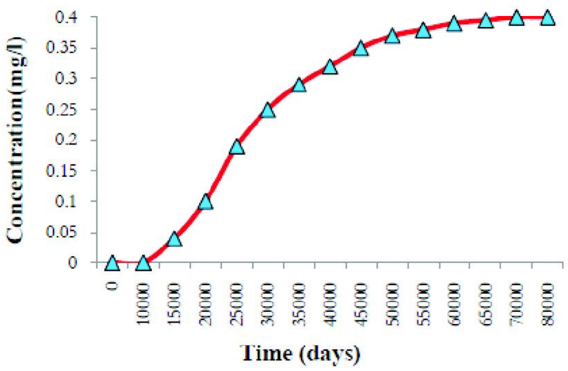

Fig. 4(b). Solute transport through 1 m thick amended soil.

Conclusions

Hazardous and toxic heavy metal pollution of groundwater is one of the most key environmental problems throughout the world. The present paper deliberates the metal removal efficiency of the laterite soil amended with bentonite (B) and fly ash (FA), in the selected proportion of 8(LS): 1(B):1(FA) to be used as a composite liner material in ash pond site. Further, numerical modelling, in HYDRUS-1D finite difference solute transport software, was performed to determine the useful life of the composite liner. Based on the experimental and numerical modelling results, the following conclusions were drawn:

The amended laterite soil has very good potential to be considered as liner material in the ash ponds due to its reasonably higher metal adsorption capacity and very low hydraulic conductivity.

The experimental results show that metal removal efficiency of the amended laterite soil is around 96% for cadmium metal. Moreover, isotherm studies on amended laterite soil exhibits Langmuir isotherm is best fitting for cadmium.

Numerical modelling using HYDRUS-1D finite difference solute transport software shows the efficiency of amended soil over the laterite soil to be the better choice of liner material. The useful life of the composite liner material is nearly 4 times more than the laterite soil for same liner thickness 1 m.

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