Experimental Study on The Extraction of Heavy Metals from Landfill Liner by Electrokinetic Method

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Abstract

Municipal solid waste dumps must be used for the proper disposal of household biodegradable waste. Landfills usually construct liner systems to prevent leachate from contaminating groundwater. Compacted clay is frequently the most basic of the several types of liner systems. Clay's limited permeability is the main argument in favour of utilizing it as a liner. Even though the compacted clay liners are kept for their designated usage, misuse could make leachate (which is a water like substance formed by mixing up of the percolated water and the water from degraded wastes) flow through them more intense. Leachate frequently contains heavy metals including lead, mercury, and cadmium in addition to toxicants, which can eventually seep into the groundwater and soil. Because they harm ecosystems and contaminate drinking water supplies, these toxic metals can pose a serious threat to human health and the environment. Thus, as a cost-effective alternative to conventional landfill liners, this study investigates the feasibility of using locally accessible bentonite and hydrated lime-stabilized clay. The study will examine the clay's geotechnical properties, including compressibility, shear strength, and hydraulic conductivity, to determine whether it is suitable for use as landfill liners. Reducing the heavy metal contamination of the clay liner is the aim of this effort. To avoid contaminating landfill liners, heavy metals will be reduced electrokinetically. This project report gives a summary of the work completed, the methodology, the test setup, and the current state of the project.

Keywords: Landfill liner, Removal of heavy metals, Electrokinetic removal, Clay liner, MSW landfill, Compacted clay liner.

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1. Introduction

In the context of contemporary waste management, landfills are essential. On the other hand, poor landfill management can have detrimental effects on the ecosystem, such as contaminated groundwater and degraded soil. To reduce these risks and stop leachate (a hazardous liquid) produced by decaying waste from migrating into the environment, effective landfill liners are essential. Compacted clay liners or geosynthetic liners have historically served as the main barriers in landfills. Despite their superior functionality, these materials can be expensive and require specific installation methods.

Consequently, an increasing interest is in investigating more economical, eco-friendly, and alternative liner materials. The purpose of landfill liners is to stop nearby soil and groundwater from becoming contaminated by leachate, a liquid that seeps through garbage. While collection systems are designed to prevent heavy metals from escaping the landfill, not all heavy metals are readily removed during treatment. Some metals may be more mobile and soluble than others, making them more difficult to capture or remove. However, heavy metals like lead, mercury, cadmium etc can seep into surrounding ecosystems when these liners deteriorate or break down, posing serious dangers to human health, wildlife, and water quality. Due to their extreme toxicity and environmental persistence, these metals can cause long-term contamination that can upset ecosystems and make their way into the food chain. To safeguard the environment and public health, heavy metals must be removed from landfill liners. To preserve landfill sites, avoid hazardous pollution, ensure sustainable waste management, and protect natural resources, heavy metals must be removed and managed effectively. This research focuses on the potential of locally available clay as a cost-effective and sustainable landfill liner. The primary objective of this study is to remove the heavy metals accumulated on landfill liners by electrokinetic method. This research aims to provide valuable insights into the feasibility of using locally available clay as landfill liners, promoting sustainable waste management practices and reducing the environmental impact of landfills.

Electrokinetic remediation is a promising technology for removal of heavy metal contamination in landfills. This method involves applying a direct current electric field to the contaminated soil, causing heavy metal ions to migrate towards electrodes and be removed. It offers advantages like in-situ treatment, selective removal, and lower energy consumption compared to traditional methods. However, soil type, power consumption, and electrode corrosion can influence its effectiveness. When low-intensity direct current (DC) electricity is applied via electrodes inserted in the ground, cations in the solution phase of the contaminated soil migrate to the cathode while anions migrate to the anode at the attractive force of the established electrical field. Metal contaminants concentrated at the polarized electrodes are subsequently removed by electroplating, (co-) precipitation, solution pumping, or ion exchange resin complexation. The migration of metal ions under a DC electric field is primarily via electroosmosis (movement of water from anode to cathode; even non-ionic species can be transported along with the electroosmosis-induced water flow), electromigration (movement of ions to the counterpart electrode), electrophoresis (movement of charged colloidal particles), and diffusion (transport induced by concentration gradients).

2. Material And Methods

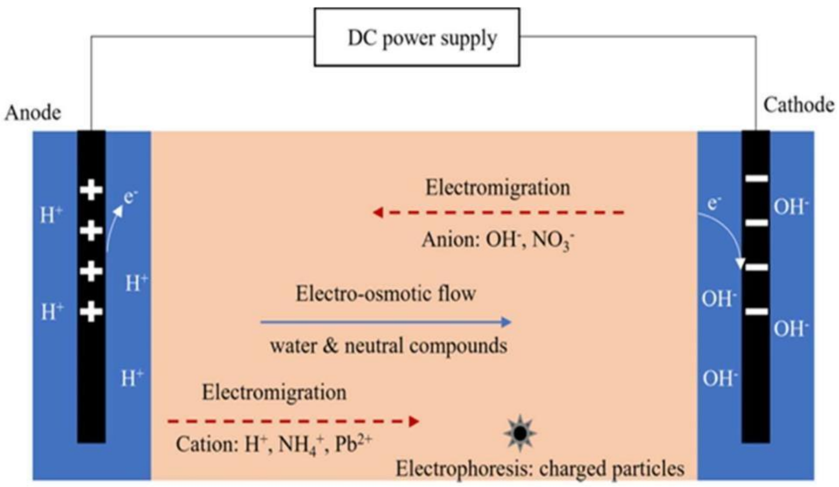

Figure 1: The chemical processes of electrokinetic removal of heavy metals

Clay samples is collected from a paddy field located in Avanoor, Thrissur district, with the objective of evaluating their suitability for use as a clay liner material in landfill applications. Initially, a series of laboratory tests is conducted on the raw clay to determine its geotechnical properties, including parameters such as permeability, unconfined compressive strength (UCC), plasticity, and moisture content.

Figure 2: The lab scale test setup

Test results indicate that the natural clay does not meet the required standards for use as a landfill liner particularly in terms of low permeability and sufficient mechanical strength. The clay is modified by incorporating additives. Varying percentages of bentonite and hydrated lime is blended with the clay to enhance its performance. Bentonite is expected to improve the impermeability of the mix by reducing void spaces, while hydrated lime is intended to increase the UCC strength and reduce plasticity through pozzolanic reactions. The optimum proportions of these additives are determined based on the combination that results in the lowest permeability and highest strength values. Once the optimal mix is identified, a small-scale test setup is constructed, using the modified clay as the liner material. To simulate real landfill conditions and evaluate the liner's resistance to contamination, the clay liner is exposed to a synthetic leachate, prepared by dissolving salts of heavy metals such as cadmium and lead. Given the expected low permeability of the liner, heavy metals may take significant time to infiltrate; therefore, the leachate is premixed with the clay to ensure interaction. After a designated period, the contaminated clay samples are analyzed to determine the extent of heavy metal accumulation. To further investigate the potential for remediation, an electrokinetic extraction process is applied by connecting the setup to a direct current (DC) power supply operating at a fixed voltage of 36 volts. The leachate for the present study is synthesized by mixing various salts of heavy metals such as cadmium and lead. Here the leachate is prepared by mixing cadmium sulphate and lead nitrate salts. The concentration of heavy metal, cadmium and lead are fixed as per the study conducted by Munirah et.al (2021). The cadmium concentration was taken as 20 ppm and lead concentration was taken as 100 ppm. Then this leachate is mixed into the clay liner. Then this is removed by the Electrokinetic method. Only 2 grams of cadmium sulphate and 3.5 grams of lead nitrate was required to contaminate the soil.

3. Result & Discussions

The laboratory works are conducted to find out the index properties as well as the engineering properties of the soil sample. It includes Specific gravity, Particle size distribution, Atterberg Limits, Swell test, Light compaction test, Unconfined Compressive Strength test and Permeability test. The atomic absorption spectroscopy was done in KFRI, Peechi, Thrissur. Table 1 shows the properties of the raw soil sample.

Properties	Values
Specific Gravity	2.61
Particle size distribution Fine Gravel Sand Fines	3%

	45%
	52%
Liquid Limit	34%
Plastic Limit	22%
Plasticity Index	12%
Swell Index	20%
Optimum Moisture	17.2%
Maximum Dry Density	1.71 g/cc
UCC Strength	115 kN/m2
Permeability	5.63 × 10-4 cm/s

Table 1: Properties of the raw soil sample

To guarantee the efficacy and environmental safety of the liner system, specific requirements must be fulfilled in accordance with USEPA rules for landfill liner materials. In order to stop leachate from migrating into the nearby soil and groundwater, one of the main criteria is that the liner material be able to be compacted to obtain a very low permeability. This is made possible by the soil having a enough amount of fine particles, like silts and clays, which fill in vacuum spaces and lower permeability. Additionally, the material's physical composition is tightly regulated; no boulders or stones larger than 1 inch (25.4 mm) in diameter should be present in the liner soil, and the total weight of the sample should not contain more than 10% of these coarse fragments. This limitation stops fluid flow routes from forming and helps guarantee uniform compaction. In order to reduce the possibility of obstruction of the drainage system and preserve the liner's consistent function, the maximum permitted clog size is likewise restricted to 1 inch in diameter. A minimum unconfined compressive strength (UCC) of 200 kilopascals (kPa), or 200,000 newtons per square meters (N/m^2), is required by the USEPA for mechanical strength. This degree of strength is required to make sure the liner doesn't rupture or distort under the weight of the waste on top of it and other loads, which could jeopardize its containment function. The overall goal of these strict requirements is to guarantee that landfill liners are mechanically and hydraulically robust, offering the environment long-term protection.

Table 2 shows the comparison of the raw sample properties with the USEPA limits. It clearly shows that the unconfined compressive strength and permeability of the soil sample is not within the limits. These two properties are the major and important for an effective landfill liner. So, there is a need for stabilization of the raw sample. The stabilizing agents adopted here are bentonite and hydrated lime. Varying percentage of bentonite and hydrated lime are added to the soil sample, then compaction test and unconfined compressive strength test were conducted in varying percentage of the additive and the optimum dosage of the mix was found out.

Properties	**Obtained Values**	**USEPA Limits**
Liquid limit	34 %	**≥ 30 %**
Plasticity index	12 %	**≥ 10 %**
Unconfined compressive strength	**115 kPa**	**≥ 200 kPa**

Permeability	**5.63 × 10^{-4} cm/s**	**≤ 1 × 10-7 cm/s**
%Fines	52 %	**≥ 30 %**
%Passing 1 inch sieve (25 mm IS Sieve)	100 %	**100 %**

Table 2: Comparison of the test results with USEPA regulations

3.1 Stabilization of clay

Stabilization of clay using bentonite and hydrated lime is a common technique to enhance the performance of clay liners used in applications like landfills, waste containment systems, and ponds. Bentonite, particularly sodium bentonite, is added for its high swelling capacity and very low permeability, effectively sealing pores and reducing water movement through the liner. Hydrated lime, on the other hand, improves the clay's strength and durability by initiating pozzolanic reactions that form cementitious compounds, which also help reduce shrink-swell behavior. Typically, 5– 15% bentonite and 2–8% lime (by weight) is mixed with the clay, then moisture-conditioned and compacted. The treated clay is cured for several days to allow the chemical reactions to strengthen the structure. This combined stabilization method significantly improves the liner's hydraulic sealing ability and long-term stability.

Sl. No	**Bentonite added (%)**	**OMC (%)**	**MDD ($^{g}/_{cc}$)**	**UCS Strength, qu(kPa)**
1	0%	17.2	1.71	115
2	2.5%	15.8	1.76	120
3	5%	14.8	1.79	150
4	7.5%	14.4	1.81	185
5	10%	16.1	1.7	175

Table 3: Variation of OMC, MDD and UCS strength of clay with varied percentage of Bentonite

The optimum percentage of bentonite was fixed at 7.5% and then added 1% - 4% of hydrated lime to stabilize the soil. Then the optimum mix was identified and then the permeability of the mix was identified. Table 4 shows the variation of OMC, MDD and UCS Strength of the soil sample with 7.5% of bentonite and varying percentage of hydrated lime. It clearly shows the optimum mix will be obtained as 7.5% bentonite and 3% hydrated lime.

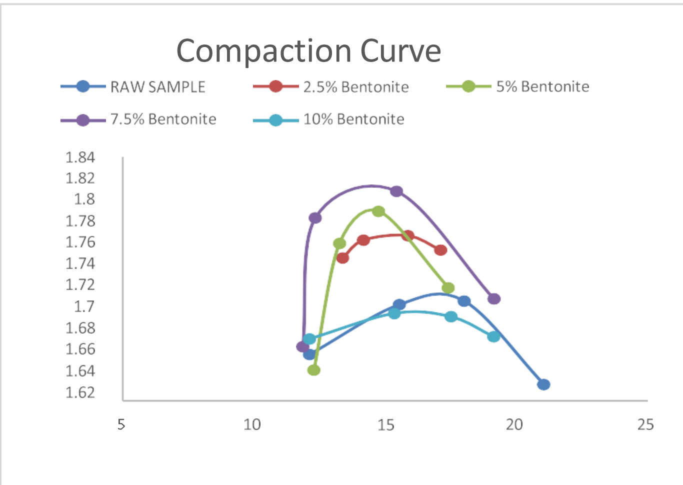

Figure 3: Compaction curves of the soil sample with varying percentage of bentoni

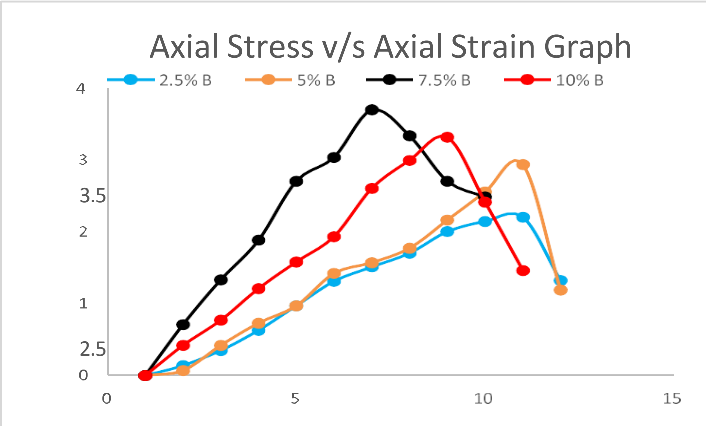

Figure 4: UCS curves of the soil sample with varying percentage of bentonite lime.

Sl. No	Bentonite added (%)	HL added (%)	OMC (%)	MDD ($^{g}/_{cc}$)	UCS Strength, qu(kPa)
1	7.5	1%	24	1.8	125
2	7.5	2%	22	1.9	160
3	7.5	3%	17	2	225
4	7.5	4%	20	1.95	220

Table 4: Variation of OMC, MDD and UCS strength of clay with 7.5% of Bentonite and varied percentage of hydrated

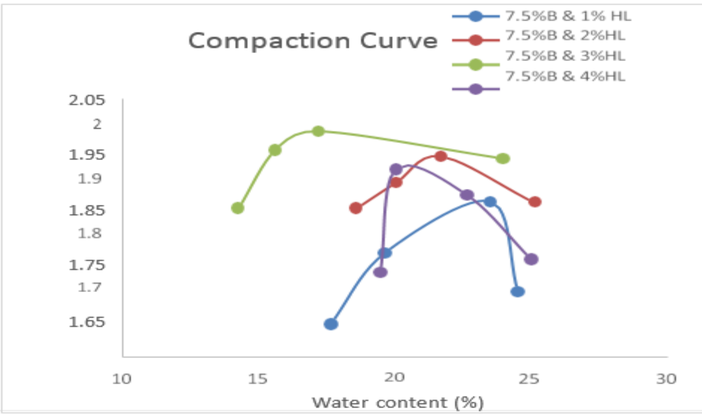

Figure 5: Compaction curve of soil sample with 7.5% bentonite and varying percentage of hydrated lime

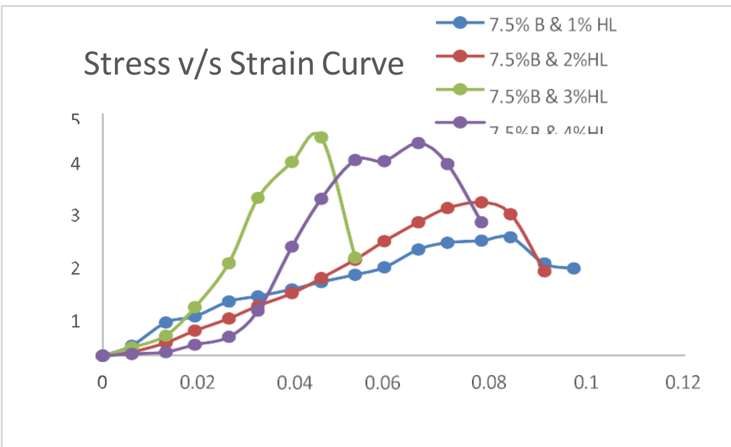

Figure 6: UCS curves of soil sample with 7.5% of bentonite and varying percentage of hydrated lime.

Properties	Obtained Values	USEPA Limits
Liquid limit	54 %	≥ 30 %
Plasticity index	20 %	≥ 10 %
Unconfined compressive strength	225 kPa	≥ 200 kPa
Permeability	1×10^{-7} cm/s	$\leq 1 \times 10^{-7}$ cm/s
% Fines	52 %	≥ 30 %
% Passing 1 inch sieve (25 mm IS Sieve)	100 %	100 %

Table 5: Comparison of properties of soil after stabilization with USEPA regulations

By comparing the results with USEPA regulations the soil sample now satisfies the criteria for using it as a landfill liner. At the optimum dosage of hydrated lime and bentonite the permeability was decreased from 5.63×10^{-04} to 1×10^{-07}. Lime induces cation exchange in the clay particles, especially montmorillonite in bentonite. This causes clay particles to flocculate (group together), creating a denser and more compacted microstructure. Bentonite, being highly fine and plastic, fills in even smaller pores. As a result, smaller pore channels reduce the space for water flow.

3.2 Removal of heavy metals

In order to mobilize and remove heavy metals like lead, cadmium, arsenic, and chromium from contaminated soil, an in- situ soil remediation approach called electrokinetic extraction is used. It uses a low direct current across electrodes positioned in the soil. Contaminants are transported towards the electrodes for collection or additional treatment by means of processes including electromigration, electroosmosis and electrophoresis. In fine-grained, low-permeability soils, such as clays, where traditional remediation procedures are less successful, this approach works very well. Electrokinetic extraction may need pH control, have significant energy requirements, or alter the chemistry of the soil, despite its benefits, which include minimum excavation and applicability to a variety of metals. It is a viable option for cleaning up polluted mining, landfill, and industrial sites in spite of these obstacles. The test result of initial concentration of heavy metals in clay sample is obtained as 20 ppm cadmium and 100 ppm lead. This particular concentration of heavy metals is similar with the initial concentrations of cadmium and lead in landfills.

Heavy Metal	Concentration (ppm)			
	0^{th} day	5^{th} day	10^{th} day	15^{th} day
Cadmium (Cd)	20	11	5	BDL
Lead (Pb)	100	65	36	6

Table 6: Removal of heavy metals from the contaminated landfill liner

4. Conclusion

Paddy field clay, a locally accessible clay soil, was chosen for this study's assessment as a possible landfill liner material in a municipal solid waste (MSW) landfill system. Its cost-effectiveness and local availability were the deciding factors. However, early geotechnical testing showed that the raw clay's permeability and inherent strength were insufficient for use as a landfill liner. The untreated clay's permeability was measured at 5.63×10^{-4} cm/s and its unconfined compressive strength (UCC) was determined at 115 kPa.

Both of these values were below the permitted thresholds needed for landfill lining applications. Bentonite and hydrated lime were used in a soil stabilisation technique to improve the clay's engineering qualities. While bentonite was added in different amounts of 2.5%, 5%, 7.5%, and 10% and hydrated lime was tested at 1%, 2%, 3%, and 4% by weight of the dry soil. 7.5% bentonite and 3% hydrated lime were found to be the ideal combination after a number of experimental trials and performance evaluations. This combination produced the best outcomes in terms of strength growth and permeability decrease. The modified clay's UCC strength increased from 115 kPa to 220 kPa as a result of stabilisation, signifying a 91% increase in mechanical strength. Concurrently, the permeability experienced a dramatic 99% reduction, going from 5.63×10^{-4} cm/s to 1×10^{-7} cm/s. These findings verified that the treated clay's strength and hydraulic conductivity satisfied the requirements for landfill liner materials.

An electrokinetic test setup was used in the following heavy metal migration investigation to assess the clay's ability to contain and immobilise hazardous elements. There were noticeable alterations in the cathode side compartment from the first day of the test itself, as the initially clear solution started to take on a faint yellowish hue. As the days went by, this discolouration became more intense and eventually turned a vivid orange, which most likely meant that certain ions or metal precipitates had been mobilised or changed inside the system. 20 ppm of cadmium and 100 ppm of lead were the starting concentrations of heavy metals added to the system. To track the concentration of heavy metals over time, soil samples were taken from the setup on the fifth, tenth, and fifteenth days. According to the analysis, the metal level gradually decreased, and by the fifteenth day, all of the cadmium had been eliminated (100%) from the soil matrix. With a final removal effectiveness of 94%, lead also shown a significant decrease, indicating that the combined effects of soil stabilisation and electrokinetic therapy effectively immobilised or controlled the migration of the heavy metals. All of these results show that stabilised clay treated with the ideal combination of bentonite and hydrated lime and together with electrokinetic removal technique, not only satisfies the permeability and structural requirements for landfill liners, but also shows great promise for heavy metal containment, making it more suitable for environmentally safe landfill construction and operation.

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