Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam
Visakhapatnam Chapter

Effect of Synthetic Leachate on Volume Change Behavior of Compacted Clay Liners

R. Shanmugapriya [1]and T. Thyagaraj[2]

[1] Research student, Department of Civil Engineering, IIT Madras, Chennai, India,
priya.gte@gmail.com
[2] Professor, Department of Civil Engineering, IIT Madras, Chennai, India,
ttraj@iitm.ac.in

Abstract. Compacted clay liners (CCLs) are widely used as hydraulic barriers below the leachate collection systems of municipal solid waste (MSW) landfills as they reduce the rate of contaminant migration by advection owing to their low hydraulic conductivity and molecular diffusion. The main requirement of liner materials is to minimize the pollutant migration into the soil and groundwater. Apart from the low hydraulic conductivity, the compacted liners should possess enough shear strength to withstand the load of waste over them and volume stability for preventing desiccation cracking. Field studies have shown that compacted clay liners placed at shallow depths undergo swell-shrink movements due to seasonal moisture fluctuations. The swell-shrink volume change in turn affects the hydraulic conductivity of CCLs as complete healing of desiccation cracks does not occur instantaneously. Also, the concentration of leachate has a great impact on the hydraulic conductivity of CCLs. However, most of the literature was focused on bringing out the physico-chemical effects on CCLs using inorganic solutions such as 0.1-0.4M NaCl solutions. The characteristics of the chemically aggressive municipal landfill leachate cannot be demonstrated effectively using distilled water or inorganic simple solutions. To yield a reasonable worst-case scenario, actual leachates obtained from three different MSW dumpsites are characterized. Then the synthetic leachates (SLs) were prepared based on the maximum concentrations of each element obtained from the actual leachates collected from the MSW dumpsites. In this study, SLs are prepared and used as inundating solutions to understand the volumetric behavior of CCLs.

Keywords: Compacted clay liners, synthetic leachate, swell-shrink movements.

1 Introduction

India generates about 960 million tons (Central Pollution Control Board, 2017) of solid waste annually as by-products during agricultural, industrial, municipal, mining, and other processes. Out of this, the organic waste (agriculture), inorganic waste (industrial and mining) and hazardous waste account about 350, 290 and 4.5 million tons, respectively. In metro cities, the average waste produced by an individual in a day is 0.8 kg. The estimated total municipal solid waste (MSW) produced in urban habitat of India is about 69 million tons/year. Out of this, about 43 million tons (70%) are collected and about 12 million tons of waste (20%) is treated. Nearly 31 million tons (50%) of the collected waste is dumped in landfills and dumpsites. In recent years, India is adopting the integrated waste management policy which includes source minimization, reuse, recycling, recovery (Incineration, Composting, Bio-methanation) and in the end disposal. Thus, the amount of waste disposed can be minimized. Similarly, in many other countries throughout the world, landfills are the main disposal stream for most wastes. But still, a huge amount of wastes generated are disposed in the open dumpsites. The unsegregated waste collection is the main cause of open dumping. This method of dumping leads to the leachate generation and methane emission. Leachate pollutes the groundwater as well as the soil in the surrounding areas and the methane emission contributes to the global warming. Hence there is a definite need to protect the environment from the migration of leachates and landfill gases. This is generally achieved by providing a combination of a controlled landfill gas extraction system, a capping layer, a leachate collection system, and a base liner. The compacted clay liners forms as a part of the composite liner system and acts as a diffusion barrier in the landfills (Lake and Rowe, 2005).Thus, the locally available low permeability materials like clays, are generally used as barriers in base liners and capping materials as their physical and chemical characteristics make them appropriate for the use in landfills. If the clay is in-situ, its permeability must be necessarily low to prevent the percolation of leachate. In the other case, if the clay is to be engineered, it must be placed and compacted to the desired density to achieve and maintain the low permeability.

Clay liners are subjected to long-term wetting and drying due to seasonal moisture fluctuations. Over the long term, the desiccation of bottom liners is possible due to the generation of heat from the overlying wastes and is showed through modeling studies and laboratory experiments by Southen and Rowe (2005). Thus, the seasonal moisture fluctuations cause swell-shrink movements to the compacted clay. The desiccation cracks are formed as the result of drying, and they act as preferential paths for the leachate. Thus, the indented function of liners may not be satisfied. Swelling, as a result of wetting may decrease the hydraulic conductivity and helps in the sealing of cracks in clay barriers. But in the initial stage of wetting, the cracks developed in the barrier will act as preferential paths before the complete healing of desiccation cracks as swelling is not an instantaneous process (Wang and Benson, 1995).

Further, when the compacted clays encounter the leachate leaking from landfills, they are subjected to changes in pore fluid composition along with the seasonal moisture fluctuations (Melamed and Pitkanen, 1996; Pusch, 2001). Also, the leachate tends to shrink the diffused double layers that surround the clay particles. This promotes flocculation of clay particles and tends the soil skeleton to shrink and leads to the formation of cracks. The degree of suppression of the diffused double layers depend on the cation valence of the pore fluid (Yong and Wankentin, 1966). Thus, the interaction of leachates combined with the swell-shrink behavior of liners results in physico-chemical changes in clay layers. The integrity of the clay liners can be altered by physical, chemical, and biological processes. Numerous studies have been done to understand the effects of the intrusion of organic chemicals on compacted clays. Studies have also focused on wetting and drying of compacted clays using organic solutions without considering the effect of field leachates. But the characteristics of the chemically aggressive municipal landfill leachates cannot be demonstrated effectively using distilled water or by simple solutions, such as 0.1-0.4M NaCl solutions. Field leachates cannot be directly used as an inundating liquid as it is chemically unstable. The composition of leachate varies significantly depending on waste composition, landfill age and the method of disposal. To account this and to yield a reasonable worst-case scenario, synthetic leachate having the maximum concentrations of the aggressive characteristics of the real-world leachates must be developed (Stanforth and Ham, 1979). Studies related to the design of liners considering the effect of the real-world leachate as an inundating fluid with a sustained low hydraulic conductivity 'k' are lacking and needs examination. Therefore, the present work aims at preparing synthetic leachate and bringing out the effect of MSW leachate on the volumetric behavior of compacted clays using synthetic leachate as an inundating fluid.

2 Background review

Swelling and shrinkage of expansive clay soils are interrelated and occur due to changes in soil moisture content from climatic variations. Clay liners are subjected to cyclic wetting and drying due to seasonal moisture fluctuations. Over the long term, the desiccation of the base liners is likely to happen due to the heat generation due to the degradation of the overlying wastes. This is clearly showed through modeling studies and laboratory experiments by Southen and Rowe (2005). Yesiller et al. (2008) showed the temperature variation of four MSW landfills located in different climatic regions for cover liners. British Columbia landfill site had an average temperature of 9.9°C and annual normal precipitation of 137 mm, showed a similar variation of temperature under climatic variations. Further, significant heat is generated by the degradation of organic matter within the waste. Tripathy et al. (2002) showed that at the end of shrinkage cycles, the water content of the specimens was less than the shrinkage limit for full wetting-drying cycles and above the shrinkage limit for partial drying cycles. Lin and Benson (2000) reported a decrease in swell with the wet-dry cycles when $CaCl_2$ solution was used for wetting. Upon further cycles, the bentonite lost their swelling capacity. Also, the swell characteristics of clays are directly related to the ratio of monovalent and divalent cations (RMD) and inversely related to the ionic strength (Kolstad and Benson, 2004). Tripathy et al. (2009) reported that the magnitude of shrinkage of a given soil increases with an increase in the initial water content for the same surcharge pressure and dry density, whereas the magnitude of swell decreases with an increase in the initial water content and overburden pressure. It was also found that 80% of the total volumetric deformation occurred in the primary swell region of the swell curve. Lin and Benson (2000) reported a decrease in plasticity of the bentonite with an increasing number of wet-dry cycles with the usage of water containing a high concentration of divalent cations. Thus, a reduction in efficiency of the hydraulic barriers was reported when subjected to wetting and drying using pore water primarily comprising of divalent cations. Hence, the pore fluid concentration and the valence of the exchangeable ions dominate the swelling behavior of clay. Studies have shown that the increase in concentration of the pore fluid has a detrimental effect on swell potential (Swagatika et al. ,2019)

Several studies were conducted to delineate the effects of field collected leachate samples and organic solutions on the hydraulic conductivity of GCL and expansive clays. Rauen and Benson (2008) showed that the GCLs permeated with synthetic leachates exhibited 50,000 times higher hydraulic conductivities than the GCLs permeated with deionized water. But the variation of hydraulic conductivity of GCLs permeated with field collected leachates and deionized water was not significant. In contrast, adverse effect was not observed on the hydraulic conductivities of natural and bentonite-modified clays when simulated leachate like acetic acid and $CaCl_2$ solutions were used as inundating liquids (Wang et al., 2014). It was also stated that the desiccation cracks have more influence on hydraulic performance than the pore fluid concentration. Francisca and Glatstein (2013) evaluated the relative effect of physico-chemical and biological interactions on the leachate percolation through the CCLs and reported a reduction in the long-term permeability. The increase in hydraulic conductivity with an increase in the concentration of the salt solutions is due to the decrease in the diffused double layer thickness. Hydraulic conductivity in a clay barrier is directly related to pore fluid concentration and inversely related to the RMD (Kolstad and Benson, 2004). Mishra et al. (2005) showed that the divalent cations were more dominant than the monovalent cations in increasing the hydraulic conductivity. Also, Shackelford et al. (2000) reported more than one order increase in the hydraulic conductivity with monovalent cations of high concentration as well as divalent cations of low concentrations during long-term testing.

From the above literature review, it is evident that most of the available theoretical and experimental analyses was focused on the effect of organic chemicals on the volumetric and hydraulic behavior of compacted clays and GCLs. The present work aims at bringing out the influence of local leachate on the volumetric behavior of compacted clay.

3 Materials and methods

3.1 Expansive soil

The expansive soil used for the study was obtained from Wellington lake, Tiruchirappalli, Tamil Nadu. The sample was air-dried, pulverized, and sieved through a 2mm sieve before using it. Table 1 summaries the soil properties obtained from the laboratory tests. Determination of the range of acceptable water contents and the dry unit weight of compacted clay is the critical step in the design of compacted clay liner (CCL). Benson and Daniel (1990) suggested the acceptable zone by considering hydraulic conductivity and shear strength criteria. For developing the acceptable zone, the laboratory tests were conducted for the determination of hydraulic conductivity, unconfined compressive strength, and volumetric shrinkage of compacted specimens with various initial compaction conditions, simulating the various points on the compaction curve. Then the acceptable zone was plotted using the criteria of hydraulic conductivity value of less than 10^{-7} cm/sec, shear strength greater than 200 kPa) and volumetric shrinkage less than 4%.

Table 1. Properties of expansive soil

Sl. No.	Soil property	Value
1	Atterberg limits	
	Liquid limit(oven-dried)	85%
	Liquid limit (air-dried)	94%
	Plastic limit	40%
	Shrinkage limit	10%
2	Specific gravity	2.65
3	Compaction characteristics	
	Optimum Moisture content	36%
	Maximum dry density	1.34 Mg/m^3
4	Grain size distribution (%)	
	% Sand	3
	% Silt	21
	% Clay	76
5	IS Soil classification symbol	CH
6	Free swell (%)	110
7	Organic matter (%)	3-4 %
8	pH	7.83
9	Conductivity	0.327 milli mho
10	TDS	2080 ppm

3.2 Leachate sampling and analysis

Leachate samples were collected and examined to evaluate their characteristics and stability. For the present study, the leachate samples were collected from the dumpsites of Perungudi (PER) and Kodungaiyur (KKR), Chennai, and Kurumampet (PDY), Puducherry. All sampling tubes and equipment used to collect the leachate were cleaned using a detergent and rinsed thoroughly with tap water followed by deionized water and allowed to air dry. The leachate samples were stored in polypropylene bottles to avoid aeration of the samples. The collected samples were transferred to the laboratory and stored at 4ºC until the analysis of the samples was carried out. Sampling was carried out once in three months for one year to get a total of four leachate samples for each dumpsite. These samples were examined according to the standard methods for examination of water and wastewater (APHA). The characteristics of leachate collected from the dumpsites of the chosen sites are shown in Table 2.

Table 2. Leachate characteristics

Element symbol/ Parameters	DL	KKR S1	KKR S2	PER S1	PER S2	PDY S1
		Concn.in ppm/µg/ml (or) mg/l				
Ca	10	65.46	68.29	BDL	BDL	53.69
Fe	1	62.23	60.06	63.41	59.82	29.50
K	100	48.11	46.18	30.26	23.54	39.40
Mg	10	53.63	50.16	BDL	BDL	211.48
Mn	1	2.043	2.043	1.232	0.158	1.087
Na	100	94.47	91.51	-	-	203.1
Ni	1	1.585	1.490	BDL	BDL	1.273
Zn	1	1.263	1.024	2.29	1.20	1.313
As	1	BDL	BDL	BDL	BDL	BDL
Cu	1	0.553	0.503	0.0843	0.0985	0.024
Cr	1	0.647	0.456	0.0751	0.0821	0.091
Hg	1	BDL	BDL	BDL	BDL	BDL
Pb	1	0.063	0.052	1.20	0.0752	0.121
Cd	1	0.008	0.008	0.019	BDL	0.018
Cl		3652.2	1701.6	UD	2694.2	189.56
TS		24490	24100	6750	17450	2760
TSS		650	700	400	850	450
TDS		25231	24842	5700	16550	3210
Ph		7.2	7.1	7.5	7.25	6.9
EC(MS/cm)		23.60	22.56	12.45	30.6	16.89
Temperature (°C)		30.6	30.8	30	30	30

EC in (MS/cm) and Temperature in (°C)
*(Note: BDL – Below Detection Limit, UD – Under Diluted, S1 – Sample1, S2 – Sample 2

In the present analysis, the above deviation in different parameters of the leachate may be due to the variations in the composition of waste, waste compaction, cover design, sampling procedures, pre-treatment before disposal, amount of precipitation, site hydrology and landfilling conditions.

3.3 Preparation of synthetic leachate

The field-collected leachates have several constraints to be used in laboratory research. They are site-specific with unstable solution chemistry and are difficult to reproduce. To overcome the above limitations of actual MSW leachates, the representative synthetic leachate was developed in the laboratory. However, synthetic solutions cannot fully replace the actual MSW leachates when the site-specific parameters are required for the engineering design (Ghazizadeh et al., 2018). The following procedure was used to develop the synthetic leachate solution. First, the actual field-collected leachates were analyzed to determine the type of chemical species and their relevant concentrations. Then the concentration of the desired synthetic leachate representing the worst condition (maximum concentration) was established. Chemical reagents were chosen to meet the target concentrations of cations and anions. Table 3 shows the various chemical reagents used for the preparation of synthetic leachate. The synthetic leachate was prepared, and the concentrations of the chemical species were verified with the desired concentrations.

Table 3. Composition of synthetic leachate

Sl. No.	Salts used	Required concentration (mg/l)	Amount of salt to be taken (g)
1	Zinc chloride	2.29	0.0048
2	Cadmium chloride	0.02	0.0000
3	Nickel chlorides	1.585	0.0035
4	Chromium chloride	0.647	0.0020
5	Copper sulphate	0.553	0.0009
6	Lead nitrate	1.2	0.0019
7	Ferrous sulphate	63.41	0.1725
8	Sodium chloride	20310	51.6275
9	Potassium chloride	4811	9.1735
10	Manganese chloride	2.043	0.0047
11	Magnesium chloride	2314	9.0647
12	Calcium chloride	682.9	1.8909

3.4 Free swell tests

The free swell index test was used as a short-term compatibility test and to determine the swelling characteristics of compacted clay. The standard test was done as per IS 2720 (Part XL) using deionized water as a control. To study the swell behavior of expansive clay when exposed to site-specific leachate, the three field leachates and the synthetic leachate was used as a dispersive medium. To carry out the tests, a 10 g sample of oven dried soil passing through a 425 µm sieve was dispersed into a 100 ml graduated cylinder containing leachate. The sample was then kept undisturbed for a period of 24 hours and the swell volume was noted. To study the effect of concentration of leachate on the free swell index of expansive clay, the leachates were diluted to 10, 50 and 100 dilutions.

3.5 Swell potential tests

The swell potential of soil indicates its ability to swell upon wetting. Swell tests were conducted in the conventional oedometer using a soil specimen of diameter 75 mm and thickness 20 mm under a surcharge pressure of 12.5 kPa as per ASTM D 4546 – 03 (2010). The specimens were prepared at the respective water content and dry density as obtained from the acceptable zone plots. The swell potential of the compacted clay specimens was determined by varying the inundating fluids.

4 Results and discussion

4.1 Effects of leachate dilution on free swell index

The variation of the free swell index with dilutions of leachate is shown in Fig. 1. It can be observed from Fig. 1 that the free swell index of soil increases with an increase in dilution of leachates. The free swell value of the soil under the study using deionized water as the medium of dispersion was found to be 110%. Results show that the free swell values reduced to a large extent when synthetic leachate was used as a dispersive medium. The percentage increase in the free swell values for the Perungudi and Kodungayiur leachates were approximately the same. The response of the expansive soil to Puducherry leachate and synthetic leachate was significantly different from the other two leachates.

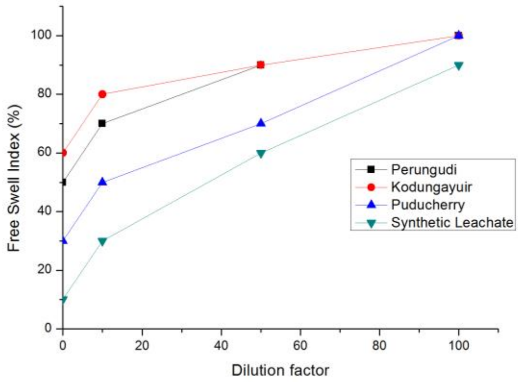

Fig. 1. Variation of free swell index with dilution factor

4.2 Effects of inundation fluids on swell potential

The swell potential was reported as the ratio of the increase in the thickness of the sample upon inundation to its initial thickness. Fig. 2 shows the influence of various inundation fluids on the swell potential of expansive soil. Results show that the swell potential of compacted clay specimens reduced due to the intrusion of leachate. The swell potential reduced from 5% to 2- 3% when inundated with leachates.

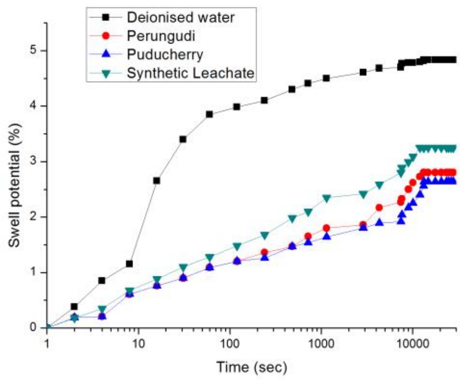

Fig. 2. Variation of swell potential with different inundating fluids

5 Conclusions

The purpose of this study was to develop a synthetic leachate using the desired concentrations of field leachate and to investigate its effect on the volumetric behavior of expansive soil. The following conclusions were drawn based on the experimental results:

1. The free swell index was reduced from 110% to 90% with the addition of field leachate and to 80% with synthetic leachate solution.
2. The inundation of leachates resulted in a considerable reduction in the swell potential of the expansive soil sample. The swell potential was reduced from 5% to 2% while inundating with field leachate and to 3% with synthetic leachate.
3. Thus, the prepared synthetic leachate solution was found to yield comparable results with that of field leachates.

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