Geotechnical and Hydraulic Performance of Liners Constructed using Locally Available Soils

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ABSTRACT: This study aims to investigate geotechnical and hydraulic properties of locally available clayey soil and its mixtures with bentonite for use as an impervious liner in sanitary landfills in Sri Lanka. Experiments (swell index and liquid limit tests) were carried out on candidate soils using deionized water and salt solutions of NaCl, KCl, $MgCl_2$ and $CaCl_2$ at different concentrations (0.01 – 1M). Hydraulic conductivity tests were carried out using deaerated water and aqueous solution of 1M $CaCl_2$ on pre-consolidated and non-consolidated samples of candidate soils and compared with bentonite. Results show that the hydrating liquid has an insignificant effect on swell Index and plasticity of the candidate soils. Hydraulic conductivity was found to decrease with an increase in bentonite content and increase in consolidation pressure. At high consolidation pressure, all the candidate soils exhibited much lower values of hydraulic conductivities than the maximum recommended value for base liners.

1 INTRODUCTION

Management of municipal solid waste is a growing problem in urban areas of developing countries. In developing countries, the main waste disposal practice is open dumping without proper measures to prevent environmental problems. Now, awareness is increasing to construct engineered landfills and protect groundwater and surface water from harmful contaminants generated in waste disposal sites. Engineered landfills are equipped with an effective liner system which acts as a barrier for landfill leachate and minimizes the transportation of contaminants to the surrounding pollution-prone environment. The landfill liner generally consists of low permeability natural clay or commercially available materials such as geosynthetic clay liners. Due to economic constraints, engineered landfills equipped with commercially available liners materials are less likely to be feasible in developing countries. In contrast, locally available clays or their mixtures with bentonite component of Geosynthetic Clay Liner (GCL) are less expensive and can be used as bottom liners under the provision that they meet the recommended criteria for the landfill bottom liners.

The minimum recommended criteria for landfill bottom liners depend upon the type of landfill. Most of the international regulatory authorities recommend that the hydraulic conductivity value of a landfill bottom liner constructed using locally available clay must be less than or equal to 1×10^{-9} m/s. To meet this requirement, certain characteristics of soil material should be met. First, the maximum particle size of the soil should be between 25-50 mm. second, it should contain at least 15-20% of silt or clay-sized material. Third, Plasticity Index (PI) should be greater than 10%. Finally, the gravel content of the soil should not exceed 10% (Sivapullaiah and Lakshmikantha, 2004).

The presence of certain chemicals in landfill leachate can affect the geotechnical and hydraulic properties of clay liners. Therefore, it is important to study the chemical compatibility of the liner materials with different pore fluids which a liner is expected to encounter during its service life (Sivapullaiah and Lakshmikantha, 2004).

This study employed single-species salt solutions to investigate the effects of chemicals on swell index, liquid limit and hydraulic conductivity properties of the candidate soils. Swell index and liquid limit tests were carried out on the candidate soils using deionized water and salt solutions of NaCl, KCl, $MgCl_2$ and $CaCl_2$ with concentrations ranging from 0.01M to 1M. Hydraulic conductivity tests were carried out using deaerated water and aqueous solution of 1M $CaCl_2$. The tests were performed under different confining pressures to study the effects of consolidation on hydraulic conductivity of candidate soils.

2 MATERIALS

2.1 *Candidate Soils*

The locally available soil (hereafter referred to as Soil M) used in this study was obtain from Moragahakanda area located in the central wet zone of Sri Lanka. Wet sieve analysis and hydrometer test was done on the soil in accordance with BS 1377-02:1990, clause 09. The particle size distribution is shown in Fig 1. According to this, the soil has 34% clay particles and 60% fines. In addition to Soil M, soil-bentonite mixtures were prepared by mixing Soil M with 5 % and 10 % bentonite. The bentonite used in this study was sodium bentonite extracted in powdered form from commercially available typical geosynthetic clay liner, Bentofix®. The bentonite passing US sieve no. 200 (0.074 mm) was used in this study. The basic physical properties of all the candidate soils were measured and presented in Table 1.

Table 1. Fundamental properties of candidate soils

Test	Bentonite	Soil M	Soil M + 5% bentonite	Soil M + 10% bentonite
Liquid limit (%)	559	68	76	98
Plastic limit (%)	45	34	30	28
Plasticity index (%)	514	34	46	70
Particle density (g/cm^3)	2.61*	2.63	2.51	2.48
Specific surface area (m^2/g)	21.081	27.462	-	-
Specific surface, Am, (m^{-1}) (water permeation)	-	0.066	0.168	0.168
Specific surface, Am, (m^{-1}) (1M $CaCl_2$ permeation)		0.038	0.094	0.112
Swell pressure (kPa) (water permeation)	-	156	256	342
Swell pressure (kPa) (1M $CaCl_2$ permeation)	-	133	172	199
Swell index (mL/2g) (water permeation)	32.7	3.5	3.6	4.9
pH	8.76 (1:10)	8.06	8.2	8.34
EC / (mS/cm)	1.33	0.027	0.161	0.322

Lake and Rowe, 2000

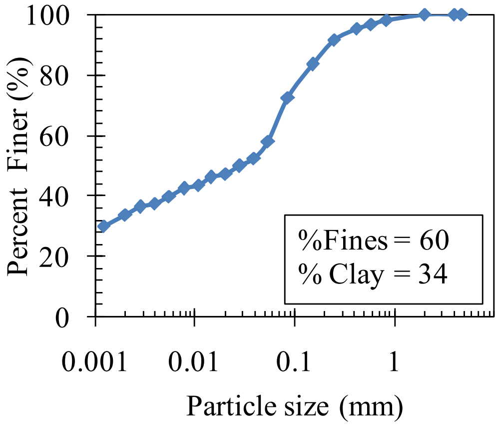

Fig. 1 Particle size distribution of Soil M

X-ray diffraction (XRD) analysis was performed on Soil M and bentonite using a Rigaku Ultima III diffractometer. The main mineral constituent of Soil M was found to be Kaolinite, while minor constituents include Ca-montmorrilonite, quartz and illite. The main mineral constituent of bentonite is Na-montmorillonite and quartz while minor continents include calcite, crystoballite and feldspar.

2.2 *Permeant Liquids*

The permeant liquids used in the swell index and liquid limit tests were deionized water and the salt solutions of NaCl, KCl, $CaCl_2$ and $MgCl_2$. Concentrations of solutions varied from 0.01 to 1 M. For the hydraulic conductivity tests, deaerated water and aqueous solution of 1M $CaCl_2$ were used as permeant.

3 EXPERIMENTAL PROCEDURES

3.1 *Swell Index Tests*

The swell index tests were carried out in accordance with ASTM D5890. According to this, 2g of soil was dusted in 0.1g intervals into a 100 mL graduated cylinder filled with hydrating solution up to 90 mL mark. After the dusting of bentonite was completed, the cylinder was filled up to the 100 mL mark by rinsing the particles adhering to the walls of the cylinder. The cylinder was then covered with plastic wrap and kept undisturbed for 24h prior to take the readings. The measurements were recorded as *ml* of swelled soil per 2g of solids.

3.2 *Atterberg limits*

Liquid limit and plastic limit tests were carried out in accordance with ASTM D4318. The liquid limit tests were carried out in standard Casagerande's apparatus using the multipoint test method. Initially, the soil was mixed with the hydrating liquid in an evaporating dish. The dish was then covered with a plastic wrap and left undisturbed for specified period of time to achieve full hydration.

3.3 *Hydraulic conductivity tests*

In order to evaluate the hydraulic conductivity characteristics of pre-consolidated soils, the Rowe cell apparatus (Rowe et. al., 1966) with a 15 cm internal diameter was used. Rowe cell apparatus can be used to one dimensionally consolidate saturated soil, allowing drainage from both surfaces and then to evaluate the hydraulic conductivity of the consolidated soil sample. In this consolidation cell, the total stress is applied by means of air pressure applied into a convoluted rubber membrane. Initially, the specimen was vertically consolidated up to a constant pressure of 50 kPa. Then, while keeping the applied consolidation pressure, the hydraulic conductivity of the consolidated sample was evaluated by allowing a steady seepage of permeant at the hydraulic heads of 50, 100,150 and 200 kPa. The above procedure of evaluating the hydraulic conductivity was repeated on the same sample after being reconsolidated under increased axial pressures.

The hydraulic conductivity of unconsolidated samples of Soil M was evaluated using a rigid wall constant head hydraulic conductivity setup. Rashid et al (2015) has described the details of apparatus and experimental procedure.

The tests were carried out to obtain several pore volumes of flow to investigate long term hydraulic performance. Pore volume of flow is a dimensionless parameter representing the time elapse. It is defined as the "accumulated flow volume divided by the pore volume of the specimen" (Katsumi et al., 2007)

4 RESUTS AND DISCUSSION

4.1 *Swell and plasticity index tests*

The swell and liquid limit tests were carried out using deionized water and salt solutions of NaCl, KCl, $MgCl_2$ and $CaCl_2$ with concentrations ranging from 0.01M to 1M. The results showed that the nature of the hydrating liquid has insignificant effect on swell and plasticity properties of soil M. However, for mixture soils, swell index and plasticity index were found to increase with increase of bentonite content.

Rashid et al. 2015 found that there exists a linear relationship between swell index and liquid limit of bentonite hydrated with inorganic salt solutions. The results of our study were found consistent with their study as shown in Fig. 2.

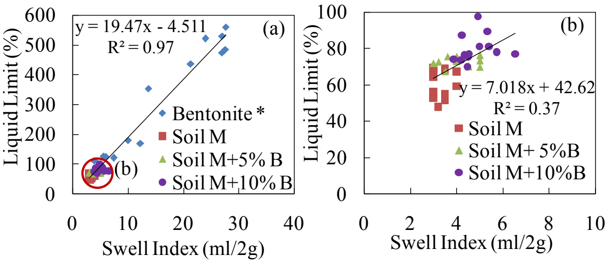

Fig. 2 Correlation between swell index and liquid limit (Rashid et al., 2015)

4.2 *Hydraulic conductivity tests*

Hydraulic conductivity tests on pre-consolidated sample of Soil M and mixture soils were carried out using deaerated water and 1M $CaCl_2$. The tests were continued up to 20 pore volumes of flow (PVF) to confirm that steady hydraulic conductivity is achieved. The tests on non-consolidated samples of Soil M were also carried out using both permeant liquids.

4.2.1 Effect of consolidation pressure

The consolidation pressure was found to have significant effect on hydraulic conductivity as shown in Fig. 3. Hydraulic conductivity decreases with an increase in consolidation pressure. The increase in consolidation pressure causes a decrease in volume of voids which decreases the available pore spaces for the water flow and hence causes a decrease in hydraulic conductivity.

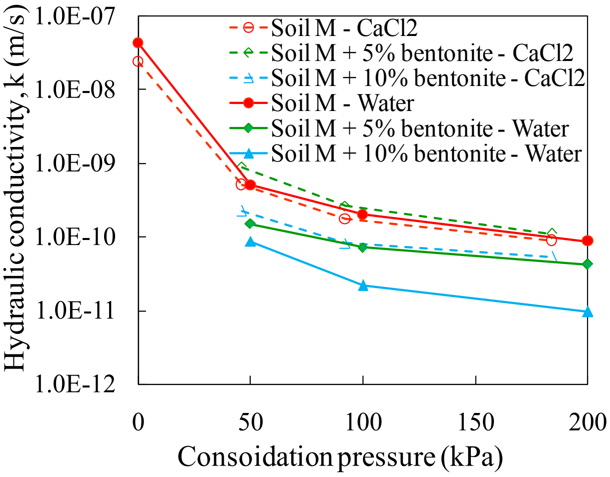

Fig. 3 Effect of consolidation pressure on hydraulic conductivity of candidate soils

Maximum value of hydraulic conductivity was observed with non consolidated samples of unamended Soil M. It can also be observed that soil M showed similar value of hydraulic conductivity for both liquids. However, mixture soil samples hydrated with $CaCl_2$ solution yielded higher value of hydraulic conductivity than the samples hydrated with deaerated water.

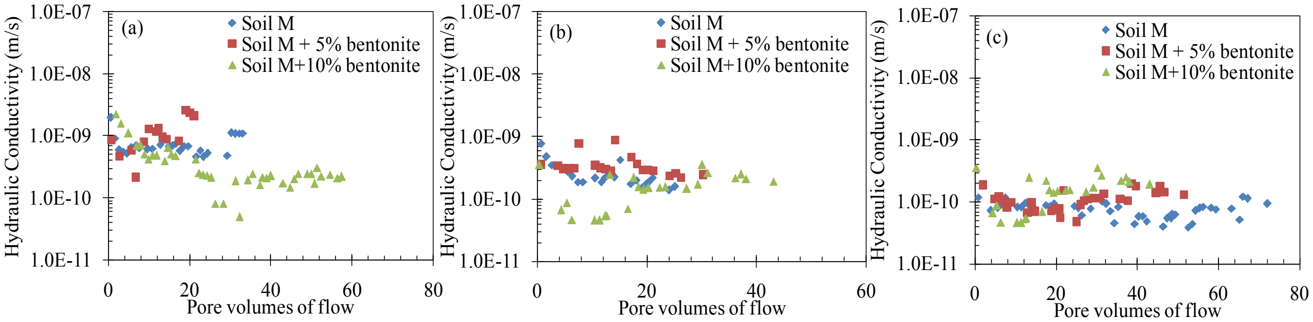

Fig. 4 Effect of bentonite content on hydraulic conductivity under consolidation pressures (a) 46.2 kPa (b) 92 kPa and (c) 184 kPa.

4.2.2 *Effect of bentonite content*

Fig. 4 shows the effect of bentonite content on hydraulic conductivity of the candidate soils under different consolidation pressures. It was observed that the bentonite content has little effect on hydraulic conductivity. The effect becomes insignificant with increase in consolidation pressure. At very high consolidation pressure (184 kPa), the hydraulic conductivity of all the candidate soils is similar.

4.2.3 *Effect of void ratio*

Intrinsic permeability, k_w, was calculated to eliminate the effect of solution density and viscosity. It was observed that intrinsic permeability increase with increase in void ratio as shown in Fig. 5.

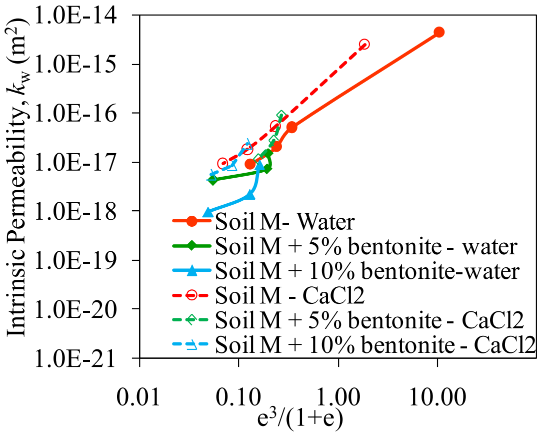

Fig. 5 Effect of void ratio on intrinsic permeability

A linear relationship was observed between void ratio and hydraulic conductivity as predicted by well know Kozeny-Carman equation developed by Kozeney (1927) and modified by Carman (1937).

$$k= (\gamma/u)(1/C_{k\text{-}c})\,(1/A_m^2)[e^3/(1+e)] \qquad (1)$$

where, γ = unit weight of permeant; μ = viscosity of permeant; $C_{k\text{-}c}$ = Kozeny-Carman empirical coefficient; A_m = specific surface area per unit volume of particles (1/cm); and e = void ratio. The equation was used to estimate the specific surface, A_m, of the candidate soils. The estimated values of A_m are shown in Table 1.

5 CONCLUSIONS

Effect of permeant liquid and consolidation pressure on geotechnical and hydraulic properties of candidate soils was investigated. The effect of permeant liquid was found insignificant particularly at high consolidation pressure. It was observed that all the candidate soils, when consolidated, fulfill minimum criteria for hydraulic conductivity of base liners. Therefore, the soils can be recommended as liner materials for municipal landfills of Sri Lanka.

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