EFFECT OF SYNTHETIC LEACHATE ON THE HYDRAULIC CONDUCTIVITY OF CLAYEY SOIL IN URMIA CITY LANDFILL SITE[*]

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Abstract– The effect of synthetic leachate on the hydraulic conductivity of a clayey soil in the Urmia city landfill site, Iran, was investigated using a triaxial permeability apparatus. The bladder accumulators were fabricated for flexible wall triaxial permeability apparatus to facilitate synthetic leachate permeation in the apparatus. The landfill soil was tested and classified as silty clayey sand (SM-SC) and did not fulfill the requirements as a soil for landfill liner. Hence, the landfill soil was mixed with 12% of a clayey soil from a nearby location to bring the index parameters of the mixed soil into a range specified for a landfill liner soil. The synthetic leachate was prepared with three different Ca^{++} concentrations. The mixed soil was compacted wet of optimum water content and permeated with tap water. After equilibrium, the tap water was replaced with synthetic leachate with three different Ca^{++} concentrations. The hydraulic conductivities of 1.33×10^{-8} cm/s, 1.81×10^{-8} cm/s, and 1.77×10^{-8} cm/s were obtained for the soil permeated with synthetic leachate, compared with the average hydraulic conductivity of 1.52×10^{-8} cm/s when permeated with tap water for tests A, B, and C, respectively. The synthetic leachate with a 1000 mg/L Ca^{++} concentration caused about a 13% reduction in hydraulic conductivity in test A which could be due to the decrease in the void ratio because of the consolidation of the sample. The percentages of increase of hydraulic conductivity for tests B and C, in comparison with the values for tap water permeation, were 18% and 20%, respectively, which is attributed to double layer contraction and increased pore space, resulting from the adsorption of divalent cations into the soil matrix.

Keywords– Hydraulic conductivity, landfill liner, synthetic leachate, calcium ion

1. INTRODUCTION

The design of waste disposal facilities typically involves some form of barrier that separates the waste from the general groundwater system. This barrier is intended to minimize the migration of contaminants from the facility, thus the environmental impact of the facility is intimately related to its design and long-term performance. Natural liners, because of their availability, low cost for a relative thick lining, long life, and attenuating ability, are usually the most attractive barriers to use in waste disposal facilities [1-4]. The hydraulic conductivity of soil liners is the most variable, the easiest to misjudge, and too difficult to measure accurately. Interest in soil hydraulic conductivity has increased substantially in recent years because of concern over ground-water contamination. Assessments of the potentially continued or future contamination at a site are only possible if accurate information is available concerning the hydraulic conductivity of subsoil.

A clay liner material used for waste containment should, among other things, possess a low hydraulic conductivity (typically, 10^{-7} cm/s) and a high cation-exchange capacity and should be compatible with the intended waste leachate. Of these properties, however, the hydraulic conductivity has received the most attention [1-3, 5-15].

The objective of this study was to investigate the effect of synthetic leachate with different calcium ion concentrations on the hydraulic conductivity of compacted mixed clayey soil obtained from the Urmia city landfill site and a nearby location.

2. TEST MATERIALS

a) Soil sample

The soil sample obtained from the Urmia city landfill site had a plasticity index of 6% which does not meet the minimum requirement of 10% for the plasticity index for a compacted soil to be used as a landfill liner. Hence 88% of Urmia landfill soil was mixed with 12% of clayey soil obtained from a nearby location. The mixed soil was identified as clayey sand with a plasticity index of 10%. The soils percentages were obtained by trial and error tests on different fractions of soils. Table 1 shows the physical properties of the mixed soil.

Table 1. Physical properties of mixed soil sample

Properties	Values
Liquid limit (%)	24
Plastic limit (%)	14
Plasticity index (%)	10
Fraction passed through No. 200 sieve (%)	48
Clay size fraction ($< 2\mu m$, %)	19
Specific gravity	2.67
Optimum moisture content (%)	12
Maximum dry density ($\rho_{d\,max}$, g/cm^3)	1.98
Void ratio at $\rho_{d\,max}$	0.30

b) Synthetic leachate

Due to the complicating effects of natural leachate on hydraulic conductivity test,s numerous researchers have used synthetic leachate to evaluate the effect of chemical permeants on the hydraulic conductivity of landfill soils [13, 15-20].

Table 2 shows the chemical composition of three synthetic leachates used in this study (leachates A, B, and C which were used in tests A, B, and C, respectively). The chemical species of Na^+, K^+, Ca^{++}, Mg^{++}, Cl^-, and SO_4^{2-} usually constitute the major inorganic components of the most municipal solid waste leachates [21-23].

Considering the predominant role of divalent cations (Ca^{++}, Mg^{++}) among other inorganic chemicals on the hydraulic conductivity of soil, calcium ion was chosen as a variable chemical parameter to investigate the effect of concentration of the calcium ion on the hydraulic conductivity of the mixed soil. The composition of synthetic leachates listed in Table 2 is similar to what has already been reported by Rowe *et al*. [21]. Table 3 shows the concentration of chemical ions and other chemical characteristics of leachates A, B, and C used in the experiments.

Table 2. Chemical composition of three synthetic leachates

Component (mg/L)	Test A	Test B	Test C
NaCl	1440	1440	1440
NaNO$_3$	50	50	50
CaCl$_2$+6H$_2$O	5466	13665	21864
MgSO$_4$+7H$_2$O	320	320	320
K$_2$CO$_3$	324	324	324

Table 3. Concentration of chemical ions and other characteristics of the
synthetic leachates used in Tests A, B, and C

Test No.	Concentration of chemical ions (mg/L)								pH	EC (μs/cm)	Salinity	TDS (mg/L)
	Ca^{++}	Mg^{++}	Na^+	K^+	SO_4^-	Cl^-	CO_3^-	NO_3^-				
A	1000	31.5	580	183	125	2642	140	36.5	7.13	8.03	4.5	6424
B	2500	31.5	580	183	125	5294	140	36.5	7.24	14.35	8.4	12485
C	4000	31.5	580	183	125	7946	140	36.5	6.83	20.85	12.5	18557

3. TEST EQUIPMENT AND METHODS

a) Test equipment

The flexible-wall triaxial permeability apparatus (Tri-Flex 2 permeability test system, ELE Inc.) was used in this study [24]. A pair of bladder accumulators was designed and fabricated to facilitate the synthetic leachate permeation in the test apparatus. Figure 1 shows a fabricated bladder accumulator in disassembled (Fig. 1a) and assembled (Fig. 1b) situations. Figure 2 shows the triaxial permeability apparatus (including the control panels and the test cell with the soil sample installed inside the cell) and the accompanying bladder accumulators.
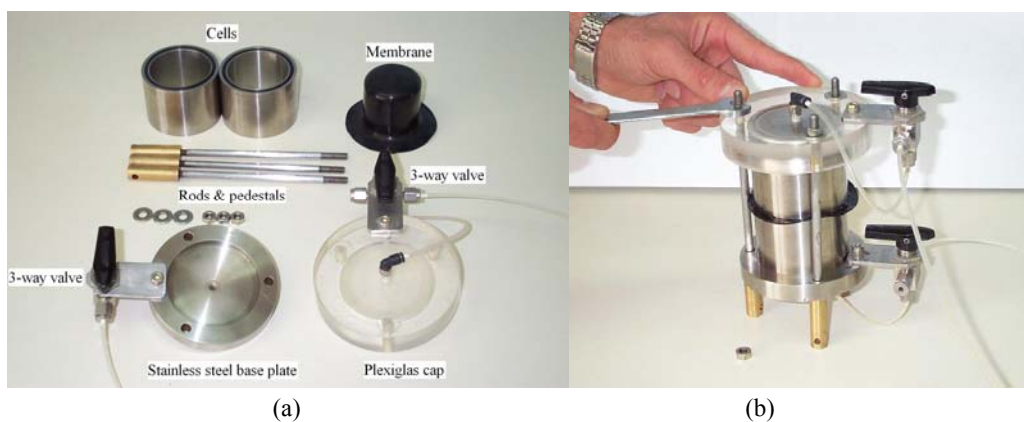

Fig. 1. a) A disassembled bladder accumulator, b) An assembled bladder accumulator

Fig. 2. Triaxial permeability apparatus including the control panels, bladder
accumulators, and test cell containing the soil sample

b) Soil sample preparation

The mixed soil was air dried, passed through a No. 4 sieve, and mixed with tap water to a water content of 14% (2% wet of optimum water content). The wet soil was compacted using a standard Proctor method (ASTM D-698), extruded from the compaction mold, and trimmed to a diameter of 7 cm using a thin walled sharp edge pipe. The trimmed soil had a height to diameter ratio (aspect ratio) of 0.714.

c) Hydraulic conductivity testing

The standard test method of triaxial hydraulic conductivity using a flexible wall permeameter was used in the experiments (ASTM D-5084) [25]. After preparation of the test specimen it was mounted in the permeability cell (Figure 2). The sample was then saturated using a backpressure and the applied pressures were 200 kPa, 175 kPa, and 185 kPa as lateral, upper, and lower pressures, respectively. These pressures were maintained for 24 hours to ensure complete saturation of the sample. The backpressure was then removed and the soil was permitted to rest for about 24 hours. The soil was then permeated with de-aired tap water under the hydraulic gradient of 101 and the average soil effective stress of 65 kPa. This test configuration was identical for all three tests. The volumes of inflow and outflow were recorded and plotted against the elapsed time. When the rates of inflow and outflow became equal, the final hydraulic conductivity values were calculated based on Darcy's law and using the following equations [24]:

$$K = \frac{aL}{2At} Ln\left[\frac{P_B + h(t_1)}{P_B + h(t_2)}\right] \tag{1}$$

$$h(t_1) = V_u(t_1) - V_L(t_1) \tag{2}$$

$$h(t_2) = V_u(t_2) - V_L(t_2) \tag{3}$$

where, a is the inside area of burette (0.906 cm^2), L is the height of soil sample, A is the area of soil sample (cm^2), $t = t_2 - t_1$ is the elapsed time between the readings in the burettes (Seconds), P_B is the Bias Pressure [psi × 70.37 cm/psi (cm – H$_2$O)], h is the difference between the height of water in the lower and upper burettes (cm), $V_u(t_i)$ is the volume reading of the upper burette at t_i (cm^3), and $V_L(t_i)$ is the volume reading of the lower burette at t_i (cm^3). Test durations for tests A, B, and C were 5, 7, and 8 days, respectively.

After completion of the hydraulic conductivity test with tap water, the synthetic leachate was replaced with tap water as a permeant. The bladder accumulators were used in this stage of the operation. Samples from the effluent solution were regularly collected for concentration and other characteristics measurement of the solution. The criterion for termination of the tests with synthetic leachate was when the effluent concentrations reached the influent concentrations when a certain volume of synthetic leachate, equivalent to a certain number of soil pore volumes, passed through the soil sample [3]. The values of calculated soil pore volumes for tests A, B and C were 53 cm^3, 50 cm^3, and 49 cm^3, respectively. For synthetic leachate permeation the number of pore volumes for tests A, B, and C were 4.5, 5, and 4.7, respectively. The total test durations (including tap water and synthetic leachate permeation) for tests A, B, and C were 49 days, 53 days, and 54 days, respectively. All tests were performed at a room temperature of 24±2 °C and the measured hydraulic conductivities were corrected for the room temperature.

d) Effluent samples analysis

The effluent samples were analyzed for the concentrations of chloride, sodium, calcium, and potassium ions. Samples were also tested for pH, Total dissolved solids (TDS), Electrical conductivity (EC), and salinity.

4. RESULTS AND DISCUSSION

a) Hydraulic conductivity

The hydraulic conductivity values along with other data for tests A, B and C are given in Table 4. The change in hydraulic conductivity values against permeated pore volumes are shown in Fig. 3.   The following conclusions were made:

Table 4. Hydraulic conductivity values along with other data in tests A, B, and C

| Properties	Test A	Test B	Test C
Hydraulic gradient	101	101	101
Inflow pressure, u_1 (kPa)	70	70	70
Outflow pressure, u_2 (kPa)	20	20	20
Cell pressure, σ_3 (kPa)	110	110	110
Effective stress at inflow, $\sigma_3\text{-}u_1$ (kPa)	40	40	40
Effective stress at outflow, $\sigma_3\text{-}u_2$ (kPa)	90	90	90
Hydraulic conductivity for water ($\times 10^8$ cm/s)	1.538	1.527	1.484
Hydraulic conductivity for leachate ($\times 10^8$ cm/s)	1.335	1.809	1.766
Elapsed time for water test (day)	5	7	8
Elapsed time for leachate test (day)	44	46	46
Estimated pore volume (cm^3)	53	50	49
Initial water content at compaction (%)	14	14.3	13.8
Final water content at the end of test (%)	13.8	14.1	13.8
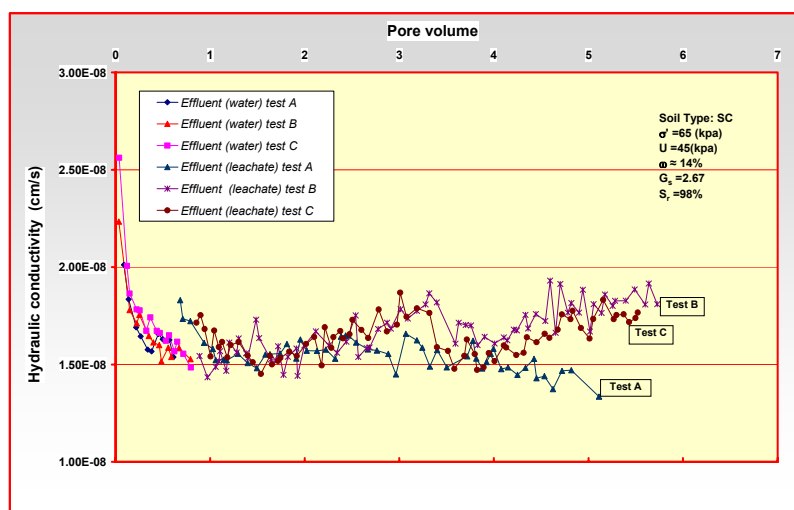
Fig. 3. Hydraulic conductivity versus pore volume in tests A, B, and C

1.   The soil sample in test A experienced 13% reduction in hydraulic conductivity. The decreased hydraulic conductivity could be attributed to a slight consolidation of the soil sample and small reduction of the void ratio during the test [26]. The effect of the low concentration of Ca^{++} (1000 mg/L) in the synthetic leachate, in a slight change of the hydraulic conductivity of the soil sample, was not pronounced in this test.

2. The synthetic leachates that were intentionally made rich in calcium (2500 mg/L and 4000 mg/L) caused an 18% and 20% increase in hydraulic conductivity in tests B and C compared to water permeation, respectively. This could be explained by double layer contraction and an increase in pore space, resulting from the adsorption of divalent cations (Ca^{++} and Mg^{++}). The range of Ca^{++} concentrations used in the tests (1000 mg/l to 4000 mg/l) was low and was not strong enough to cause flocculation of the soil samples which already had a dispersed structure due to the compaction wet of optimum water content (before permeation with synthetic leachate) [27, 28].

3. As indicated above, the effect of synthetic leachate with calcium concentrations up to 4000 mg/L on the hydraulic conductivity of the soil samples was minimal. It could be concluded that assuming similar properties for the real landfill leachate and using the mixed soil as a liner material, and considering similar physical and chemical conditions at site as the conducted test conditions, the change of soil hydraulic conductivity due to leachate will be minimal and is not considered critical.

b) Chemical properties of effluent samples

Some chemical constituents in the effluent (at the outflow end) were monitored during the tests. The effluent concentrations of chemical ions (C) were divided to the initial concentration of the ion in the synthetic leachate (C_o) and plotted in the vertical axes of the figures as relative concentrations (C/C_o). The results are shown in Figs. 4 to 9 and the following conclusions were made:

1. The relative calcium concentrations in the effluent versus pore volume are shown in Fig. 4. As shown, the relative concentrations of calcium did not reach 1.0, which was due to the adsorption of calcium ion into the soil matrix. The adsorption rates of calcium ion were 18%, 19%, and 21%, for tests A, B, and C, respectively. The calcium concentrations curves are fairly asymmetrical breakthrough curves with the extension of the trailing ends.

2. Figure 5 shows the relative potassium concentrations in the effluent versus pore volume. As shown, the potassium ion was strongly retarded and was totally retained by the soil matrix. This substantial retardation has also been observed in tests conducted by Rowe *et al*. [3] and Yanful *et al*. [14] on similar soils. Potassium retardation was due to interlayer K^+ fixation and not due to adsorption at the clay exchange sites [3, 14]. K^+ retardation increases the time required for the soil sample to reach complete chemical equilibrium with the leachate. As shown in Fig. 5, K^+ relative concentrations were gradually increasing with time and complete chemical equilibrium did not occur during the tests. According to Yanful *et al*. [14], a much longer time is required to reach complete equilibrium.

3. The change of effluent pH values with pore volumes are shown in Fig. 6. The average effluent pH values for tests A, B, and C were 7.83, 7.64, and 7.60, respectively. The effluent values for pH were higher than the influent values. The release of aqueous phase carbon dioxide into the atmosphere resulted in the increase of pH during the tests. Due to respiration by organisms, the carbon dioxide concentration in the soil pore liquid in a relatively closed system may be several hundred times greater than it would be when exposed to the atmosphere [29]. As a result, when a sample is exposed to the atmosphere, $CO_{2\ (aq)}$, H_2CO_3, and H^+ all decrease in accordance with the reactions mentioned above and equilibrium with the atmosphere re-establishes and cause the pH to increase [30].
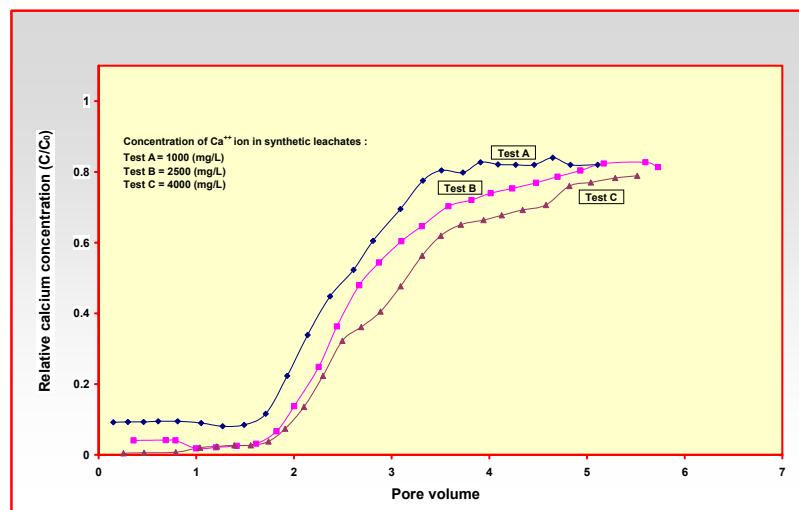

Fig. 4. Relative calcium concentrations in effluent versus pore volume in tests A, B, and C
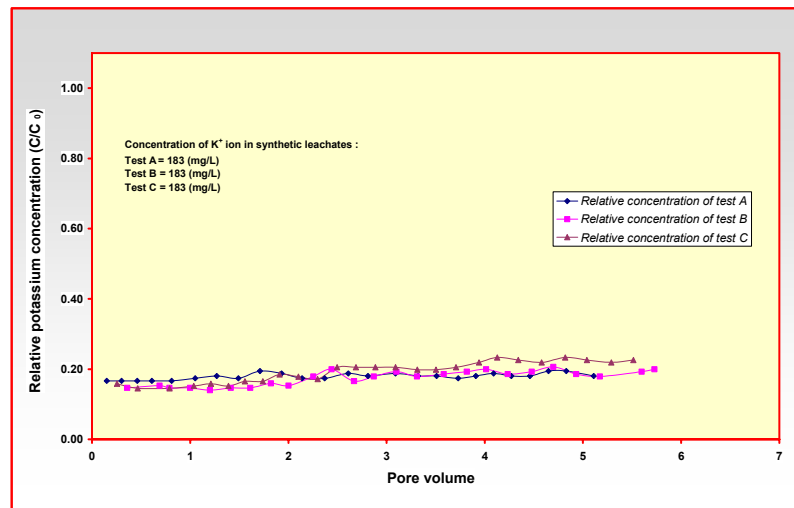
Fig. 5. Relative potassium concentrations in effluent versus pore volume in tests A, B, and C
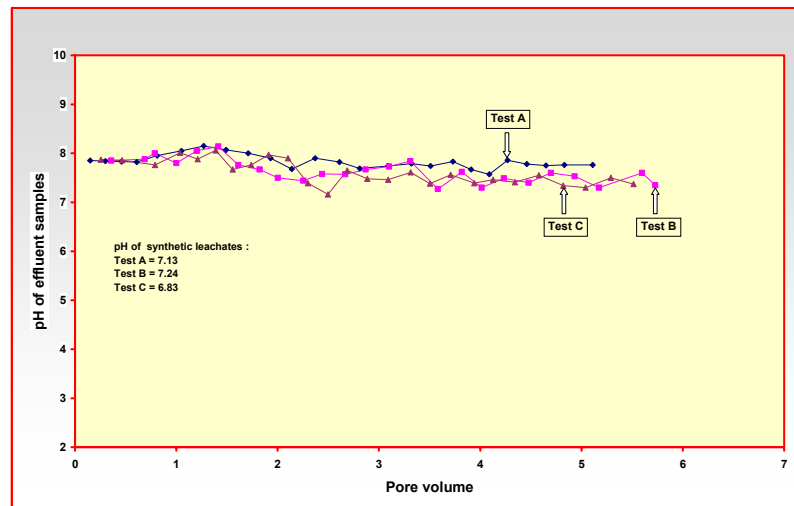

Fig. 6. Effluent pH values versus pore volume in tests A, B, and C.

4. Figure 7 shows the change of electrical conductivity (EC) with pore volume in tests A, B, and C. As shown in Fig. 7, by increasing Ca^{++} concentration, the electrical conductivity of samples was increased. A similar conclusion has also been deduced by Ouhadi and Goodarzi [31]. The electrical conductivity of effluent and influent samples became equal after permeation of about 5 pore volumes of synthetic leachate through samples in all three tests.

5. Figures 8 and 9 show the change in salinity and TDS values versus the number of pore volumes of synthetic leachate passed through soil samples in tests A, B, and C. As shown in both figures, the salinity and TDS values of test C are greater than test B, and similarly in test B are greater than test A. This is attributed to the increase of Ca^{++} concentration (salt concentration) in permeated synthetic leachate in test A compared to test B and in test B compared to test C. The salinity and TDS values of effluent and influent samples became equal after permeation of about 5 pore volumes of synthetic leachate through samples in all three tests.
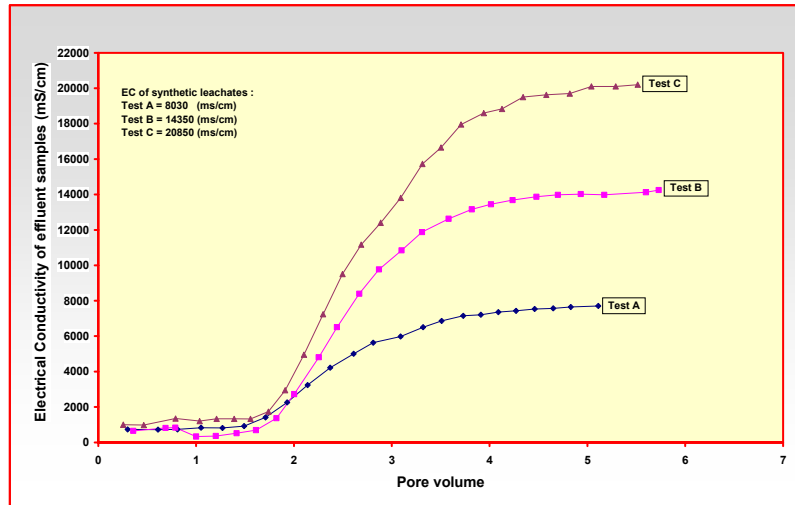
Fig. 7. Electrical conductivity of effluent samples versus pore volume in tests A, B, and C
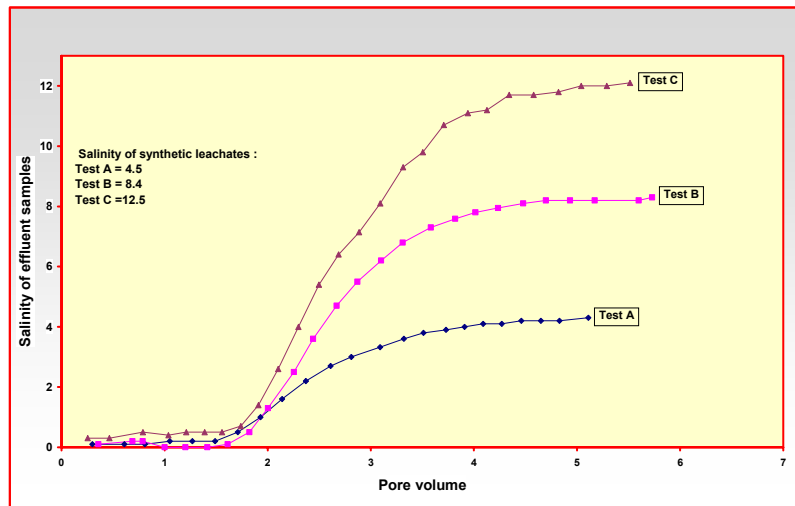

Fig. 8. Salinity of effluent samples versus pore volume in tests A, B, and C
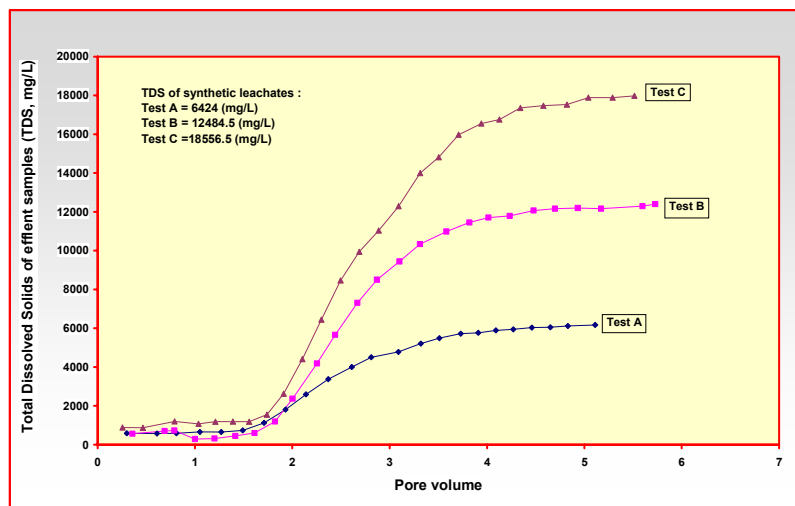

Fig. 9. Total dissolved solids (TDS) of effluent samples versus pore volume in tests A, B, and C

5. SUMMARY AND CONCLUSIONS

Three hydraulic conductivity tests were performed on compacted mixed clayey soil samples from the Urmia city landfill site using tap water and synthetic leachate. The tests examined the effect of different calcium concentrations in the permeated synthetic leachate on the hydraulic conductivity of soil samples. Flexible wall hydraulic conductivity apparatus and accompanying bladder accumulators were used as testing equipment. The hydraulic conductivity values for tap water were first recorded for the soil samples and then synthetic leachate with three different concentrations of calcium ion was permeated through the samples and the hydraulic conductivity values were recorded and compared with similar values with tap water permeation. In test A with 1000 mg/L calcium concentration in the synthetic leachate, about 13% reduction in hydraulic conductivity was observed after about 5 pore volumes of leachate permeation, compared with tap water permeation. The decreased hydraulic conductivity could be attributed to slight consolidation of the sample and reduction of the void ratio during the test and a small change of the hydraulic conductivity of the sample is not believed to be due to the effect of the Ca^{++} ion. In tests B and C, with 2500 mg/L and 4000 mg/L Ca^{++} concentrations in the permeated synthetic leachates, about 18% and 20% increase in hydraulic conductivity values (respectively) were observed after permeation of about 5.5 pore volumes of synthetic leachate compared with tap water. This could be explained by double layer contraction and increase in pore space, resulting from the adsorption of divalent cations (Ca^{++} and Mg^{++}). The range of Ca^{++} concentrations used in the tests (1000 mg/l to 4000 mg/l) was low and was not strong enough to cause flocculation of the soil samples which already had a dispersed structure due to compaction wet of optimum water content. Although slight reduction (test A) and increase (tests B and C) of hydraulic conductivity was observed when soil samples were permeated with synthetic leachate, this effect is minimal.

Effluent samples were collected and tested for chemical properties. On average about 20% of calcium ion was adsorbed into the soil matrix during synthetic leachate permeation in three tests. Potassium ion was strongly retarded and was totally retained by the soil matrix in all tests. The effluent values for pH were higher than the influent values in all tests. The release of aqueous phase carbon dioxide into the atmosphere resulted in an increase of pH during the tests. The values of electrical conductivity, salinity, and TDS for the effluent samples became equal to the influent samples after about 5 pore volumes of synthetic leachate permeation in all tests. The values of these parameters in the effluent samples were increased by increasing salt concentration (Ca^{++} concentration) in the permeated synthetic leachates.

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