DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DETERMINING THE HYDRAULIC CONDUCTIVITY BEHAVIOR OF GEOSYNTHETIC CLAY LINERS (GCLs) PERMEATED WITH DIFFERENT LEACHATES

by
Havva DEMİRKIRAN

September, 2014
İZMİR

DETERMINING THE HYDRAULIC CONDUCTIVITY BEHAVIOR OF GEOSYNTHETIC CLAY LINERS (GCLs) PERMEATED WITH DIFFERENT LEACHATES

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DETERMINING THE HYDRAULIC CONDUCTIVITY BEHAVIOR OF GEOSYNTHETIC CLAY LINERS (GCLs) PERMEATED WITH DIFFERENT LEACHATES"** completed by **HAVVA DEMİRKIRAN** under supervision of **ASSIST. PROF. ALİ HAKAN ÖREN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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DETERMINING THE HYDRAULIC CONDUCTIVITY BEHAVIOR OF GEOSYNTHETIC CLAY LINERS (GCLs) PERMEATED WITH DIFFERENT LEACHATES

ABSTRACT

This study covers the results of the hydraulic conductivity tests on four GCLs using deionized water, tap water and landfill leachates as the permeant solutions.

In this study, eight hydraulic conductivity tests were conducted using DIW and TW. Only two tests were carried out on non-prehydrated GCLs to see whether hydrating the GCL before the test has an influence on the hydraulic conductivity. Hydraulic conductivity tests were performed on prehydrated GCLs as well (11 tests). Long term hydraulic conductivity tests were carried out on a selected GCL of which had the lowest hydraulic conductivity to DIW among others (i.e. GCL-4) (3 tests). Thus, total of twenty four hydraulic conductivity tests were performed with flexible-wall permeameters.

The results are discussed into two parts. In the first part, the hydraulic conductivities of GCLs to DIW and TW are considered. The relationships between the hydraulic conductivities and the physico-chemical properties in terms of index properties, clay content, activity, smectite content, final void ratio, specific surface area and cation exchange capacity of bentonite were investigated. The relationships showed that the hydraulic conductivity correlated well with free swell, final void ratio and cation exchange capacity.

In the second part of experiments, the free swell and hydraulic conductivity results were evaluated in terms of hydration condition and leachate type. The results show that the free swell of bentonites decreased remarkably when the tests conducted with landfill leachates. This behavior confirmed that the hydraulic conductivity of non-prehydrated GCLs increased by three orders of magnitude in comparison with the hydraulic conductivity of prehydrated GCLs. This increase can be attributed to chemical interactions between the bentonite and landfill leachates. The results demonstrated that there was no considerable effect of landfill leachates on the hydraulic conductivity of prehydrated GCLs, although the tests were terminated in 0.5 and 1.5 years.

Keywords: Free swell, geosynthetic clay liners, hydarulic conductivity, physico-chemical properties, prehydration.

DEĞİŞİK SIZINTI SULARINDAN GEÇİRİLMİŞ GEOSENTETİK KİL ÖRTÜLERİN (GKÖ) HİROLİK İLETKENLİK DAVRANIŞININ BELİRLENMESİ

ÖZ

Bu çalışma, süzdürme sıvısı olarak deiyonize su, çeşme suyu ve sızıntı suları kullanılarak yapılan dört adet GKÖ'nün hidrolik iletkenlik deney sonuçlarını kapsamaktadır.

Bu çalışmada, deiyonize su ve çeşme suyu kullanılarak sekiz adet hidrolik iletkenlik deneyi yapılmıştır. Ön ıslatmanın hidrolik iletkenliğe etkisinin varlığını incelemek amacıyla sadece iki adet ön ıslatmasız hidrolik iletkenlik deneyi yapılmıştır. On bir adet de ön ıslatmalı hidrolik iletkenlik deneyi yapılmıştır. Deiyonize su ile yapılan hidrolik iletkenlik deneylerinde en düşük hidrolik iletkenliğe sahip olan GKÖ seçilerek uzun dönem hidrolik iletkenlik deneylerine tabi tutulmuştur (GKÖ-4) (3 adet deney). Böylece, esnek duvarlı permeametre kullanılarak yirmi dört adet hidrolik iletkenlik deneyi yapılmıştır.

Sonuçlar iki bölümde incelenmiştir. İlk bölümde, deiyonize su ve çeşme suyu ile yapılan hidrolik iletkenlikler dikkate alınmıştır. Hidrolik iletkenlikle bentonitin fiziko-kimyasal özellikleri; indeks özellikleri, kil içeriği, aktivite, smektit içeriği, nihai boşluk oranı, özgül yüzey alanı ve katyon değişim kapasitesi açısından ilişkileri incelenmiştir. Sonuçlar, hidrolik iletkenlik ile serbest şişme, nihai boşluk oranı ve katyon değişim kapasitesi arasında iyi korelasyon olduğunu göstermiştir.

Deneylerin ikinci kısmında, hidrolik iletkenlik ile serbest şişme sonuçları ıslatma durumu ve sızıntı suyu tipi açısından değerlendirilmiştir. Sonuçlar, deneyler sızıntı suları ile yapıldığında serbest şişme değerlerinin önemli derecede azaldığını göstermiştir. Bu davranış, ön ıslatmasız GKÖ'lerin ön ıslatmalı GKÖ'lere göre hidrolik iletkenliğinin 3 mertebe arttığını doğrulamaktadır. Bu artış bentonit ve sızıntı suları arasındaki kimyasal etkileşime dayandırılabilir. Sonuçlar, deneylerin 0,5 ile 1,5 yılda sonlandırılmasına rağmen, sızıntı sularının ön ıslatmalı GKÖ'lerin hidrolik iletkenliklerine önemli bir etkisinin olmadığını da göstermiştir.

Anahtar kelimeler: Serbest şişme, geosentetik kil örtü, hidrolik iletkenlik, fiziko-kimyasal özellikler, ön ıslatma.

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CHAPTER ONE
INTRODUCTION

1.1 Background

It is significant to design landfill area by controlling the interaction between groundwater and contaminants. In order to prevent the leaks of contaminants to groundwater, landfill liners consist of clay and synthetic membranes are used. Landfill liners are required to serve as a barrier against contaminants and leachates. Compacted clay liners (CCLs), which are one of the landfill liners, were preferred to use as barriers because of their low hydraulic conductivity. However, if the size of the landfill area is concerned, it is difficult to get homogeneous compaction on the area. Furthermore, CCLs are vulnerable freeze-thaw and wetting-drying cycles thanks to clay which result in severe cracks on the barriers. Thus, the hydraulic conductivity of CCLs undesirably increases. With the development of the technology, geosynthetic clay liners (GCLs) are commenced to use in liner and waste containment facilities.

Geosynthetic clay liners (GCLs) are factory-manufactured hydraulic barriers containing a thin layer (~ 5-10 mm) of natural or treated bentonite sandwiched between two geotextiles or glued to a geomembrane (Benson, Ören & Gates, 2010; Jo, Katsumi, Benson & Edil, 2001; Ruhl & Daniel, 1997). General view of the GCL is shown in Figure 1.1. Primary differences between GCLs are related to the chemical and physical properties of bentonite such as mineralogical composition (eg., high vs. low montmorillonite content), the particle size (eg., powdery vs. granular) and the type of exchangeable cations (eg., sodium vs. calcium). Moreover, the bonding methods, the hydration condition (eg., prehydrated or non-prehydrated), and the type of geotextile (eg., woven vs. nonwoven geotextiles) or addition of a geomembrane used during manufacturing allow GCLs to have different characteristics (Bouazza, 2002; Shackelford, Benson, Katsumi, Edil & Lin, 2000).

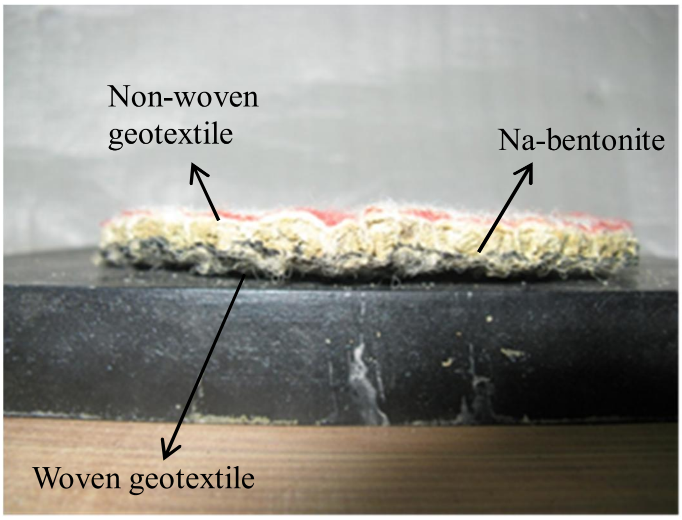

Figure 1.1 General view of the GCL

GCLs, which are alternative materials to traditional compacted clay liners, are used as hydraulic barriers in liner and waste containment facilities due to several advantages such as their low hydraulic conductivity to water (i.e.< 10^{-8} cm/s), relatively low cost, quick and easy installation and invulnerability of environmental damage (Benson et al., 2010; Guyonnet et al., 2005; Jo et al., 2001; Katsumi, Ishimori, Onikata & Fukagawa, 2007; Kolstad, Benson, & Edil, 2004).

1.2 Scope of This Study

The primary aim of this study is to evaluate short term and long term hydraulic conductivity behavior of GCLs permeated with waters and real leachates. Although these studies have increased in the last two decades, they are rather limited in Turkey. This study bridges the gaps and involves lots of innovation in order to research the factors which were not examined in prior studies. These innovations could be listed as the following:

- First of all, four different GCLs, three of which are native and one of which is import, are used in this study. Therefore, comparison of native and import GCLs in term of hydraulic behavior is researched.

- As one of the native GCLs is polymer treated, the effect of polymer is examined in terms of hydraulic behavior and chemical properties. In Turkey, this study is the first study in which the hydraulic conductivity behavior of GCLs using three different landfill leachates (LL) is determined. When considered from this point of view, it is thought that this study would contribute to the literature.

1.3 Outline of Thesis

This thesis consists of eight chapters.

Chapter two reports the geotechnical properties of materials used in this study and depicts the experimental program.

Chapter three states the physico-chemical and mineralogical properties of bentonites obtained from four different GCLs. This chapter contains the index properties, mineralogy (the results of XRD analysis) and chemical properties (specific surface area, cation exchange capacity, soluable salts and bound cations) of each bentonite.

Chapter four gives the results of free swell and the hydraulic conductivity of GCLs with deionized water and tap water. This chapter also explains the termination criteria established for the hydraulic conductivity tests.

Chapter five correlates the results of the hydraulic conductivity of GCLs when permeated with water and the physico-chemical properties of bentonites such as index properties, free swell, mineralogy, specific surface area, soluable salts, bound cations and cation exchange capacity.

Chapter six discusses the results of the free swell and the hydraulic conductivity of GCLs with three different landfill leachates. This chapter also investigates the pre-hydration effect on the hydraulic conductivity behavior of the GCLs.

Chapter seven presents the posttest changes on GCLs when permeated with landfill leachates. This chapter also reveals the relationships between the hydraulic conductivity of GCLs and physical properties.

Finally, chapter eight summarizes the results and lines up with the conclusions.

CHAPTER TWO
MATERIALS AND METHODS

2.1 Materials

2.1.1 Geosynthetic Clay Liners

Four types of geosynthetic clay liners (GCLs) were used in this study. These GCLs are manufactured as consisting of a layer of sodium bentonite sandwiched between woven and non-woven geotextiles that is held together by needle-punching. GCLs, three of which were local productions (GCL-1, GCL-2 and GCL-4), one of which was imported production (GCL-3) were used in tests. The GCL rolls used in this study were consigned to Dokuz Eylül University, Department of Civil Engineering, Soil Mechanics Laboratory by the manufacturer. General views of GCL rolls are shown in Figure 2.1. GCL-4 that is one of the native products was manufactured with polymer. The GCLs were about ~5-6 mm thick in air dry condition.

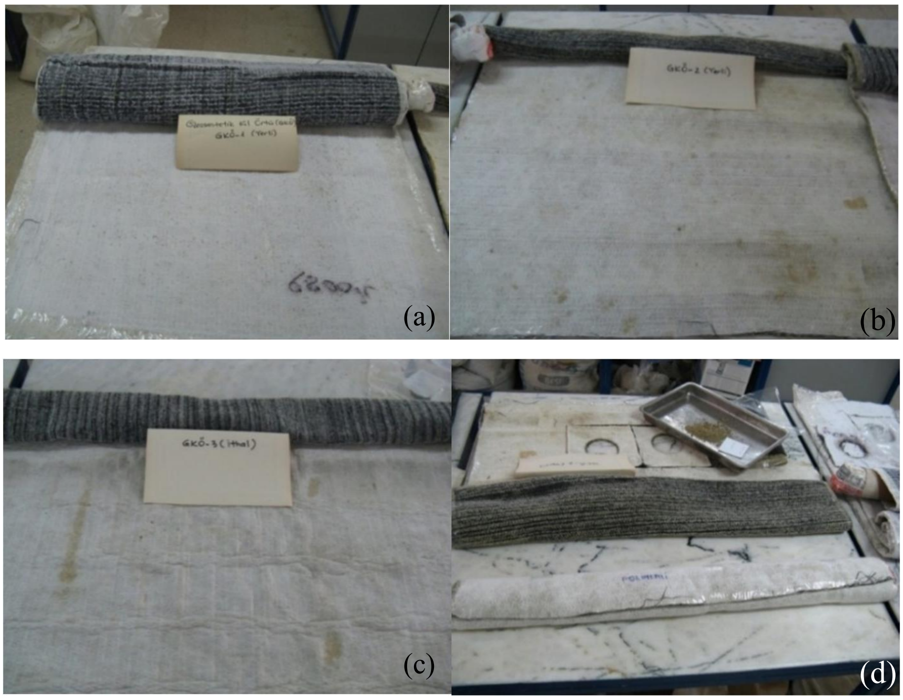

Figure 2.1 General views of GCLs. a) GCL-1, b) GCL-2, c) GCL-3, d) GCL-4.

2.1.2 Permeants

The permeant waters used in this study were deionized water (DIW) classifies as Type II water per ASTM D 1193 (ASTM 2002c), and tap water (TW) which was taken from network of Izmir, Buca.

Municipal solid waste (MSW) leachates, which were obtained from three different landfills, were used as well. These leachates were denoted as LL-1, LL-2 and LL-3 in this study and were procured from Kuşadası, Harmandalı-İzmir, and Aydın landfills, respectively. These landfill leachates were decided to represent the age of the waste containment areas. Landfill leachates used in the study are shown in Figure 2.2.

Figure 2.2 Keeping condition of landfill leachates

The pH values of LL-1, LL-2 and LL-3 were 8.7, 7.5, and 8.4; whereas electrical conductivity (EC) values were measured as 13.1 mS/cm, 20.9 mS/cm and 20.3 mS/cm, respectively. According to chemical analysis, leachates, involve Na^+≈1700-2500 mg/L, K^+≈1800-3500 mg/L, Ca^{++}≈50-300 mg/L, Mg^{++}≈150-350 mg/L.

2.1.3 Chemicals

Chemicals were used to determine the chemical properties of bentonite. Methylene blue was used to determine the specific surface area (SSA) of bentonite samples. To analyze soluble cations, boundary cations and cation exchange capacity (CEC) of the bentonites in this study; 1 M KCl, 1 M ammonium acetate (NH_4OAc), isopropanol and nitric acid were used. Reaction cells and NH1-1K reagent were also used for determining the CEC. In addition, 10% nitric acid was used to clean all the materials and the test equipments.

2.2 Methods

2.2.1 Index Properties

In order to obtain particle size distributions of the bentonites, sieve analysis and hydrometer analysis were performed according to ASTM D 421 and ASTM D 422, respectively. The specific gravity of each bentonite was obtained based on ASTM D 854. The GCL components (i.e. geotextiles) were separated from each other by tearing. Then, adequate bentonites were gathered from GCLs in order to determine the physico-chemical characteristics and mineralogical compositions of bentonites (Figure 2.3).

Figure 2.3 General views of the bentonites. a) GCL-1, b) GCL-2

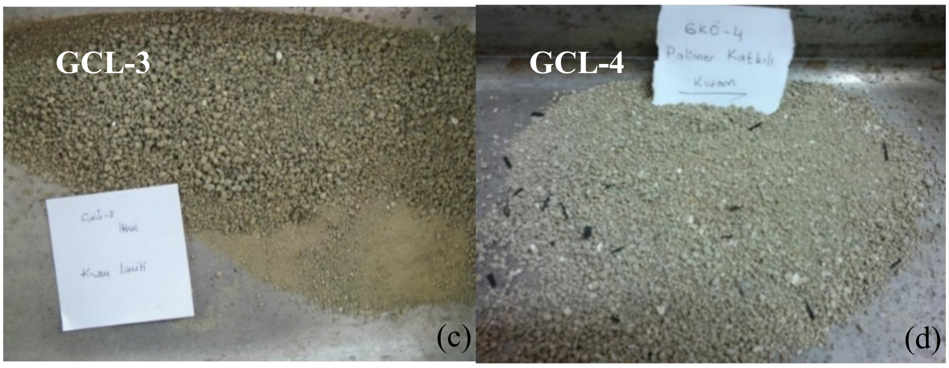

Figure 2.3 General views of the bentonites. c) GCL-3, d) GCL-4 (Continue)

The consistency limits (the liquid limit and the plastic limit) of the bentonites were determined in accordance with ASTM D 4318. Both Casagrande and fall cone method were used to ascertain the liquid limit of the bentonites. Although Casagrande method is more eligible for high plasticity clays, fall cone method was also preferred to perform since this method are widely used to determine the liquid limit of clays in Turkey.

2.2.2 Free Swell Test

Swell index tests were conducted by following the procedures described in ASTM D5890 using each DIW, TW and the permeant liquids. Before the tests, bentonites stripped off from the GCLs were kept in oven at 55 °C for ~5-6 days. Then, bentonites were grinded in a mortar in order to get powdered bentonites. Powdered bentonites were sieved from No.200 (75 µm) sieve and 2 g of sieved bentonites were preserved for each test. 90 ml of each testing liquid (DIW, TW or one of landfill leachates) was added to the 100 ml graduated cylinder (Figure 2.4a). 0.1 g dried bentonite were poured into the graduated cylinder by tapping in a period of approximately 30 seconds (Figure 2.4b-c). After each pouring, it was awaited for minimum10 minutes as required by ASTM D 5890. This process was maintained until 2 g bentonite was fully poured. Then, the cylinder was filled with the same testing liquid to the 100 ml mark (Figure 2.4d). The top part of the graduated cylinder was closed with a parafilm and it was preserved for swelling. The free swell values in mL were recorded after 24 hours by reading the value on the graduated cylinder at clay/water interface.

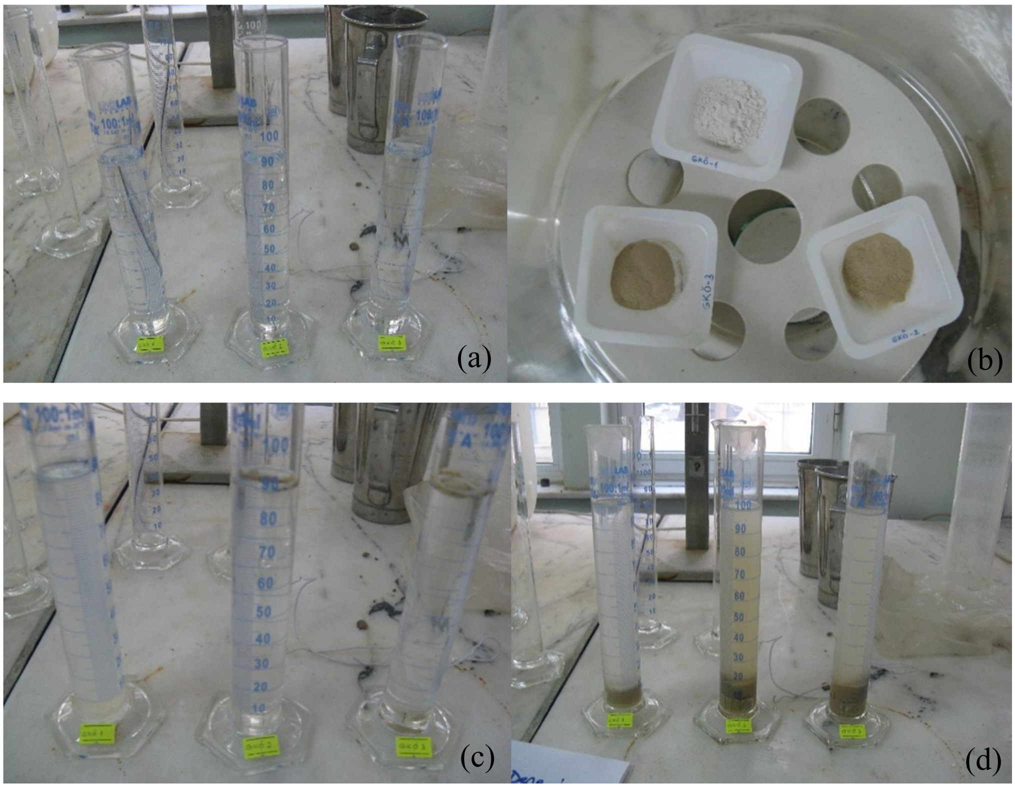

Figure 2.4 The steps of the free swell test. a) Adding 90 ml of water, b) Weighing the bentonites, c) Pouring the bentonites into the graduated cylinder, d) Recording the free swell value after 24 hours.

2.2.3 Specific Surface Area

Specific surface area (SSA) of the bentonites was determined with methylene blue spot test. The methylene blue spot test procedure is described by Yukselen & Kaya, 2008. For this purpose, 1 g dry powder methylene blue was mixed with 200 ml DIW to prepare a methylene blue solution. Then, 10 g oven dried bentonite was mixed with 30 ml DIW, and methylene blue solution was added into bentonite with 0.5 ml increments carefully. After each addition, bentonite suspension was mixed by magnetic stirrer for 1 minute and a drop was removed from suspension and placed onto Fisher brand filter paper. Since montmorillonitic clays have high SSA, greater drop steps, such as 2 ml and 5 ml, were used in this study. This process is continued to get a permanent blue halo around the soil aggregate spot onto the filter paper (Figure 2.5). This halo means that methylene blue has replaced cations in bentonite and coated the entire surface of bentonite (Yukselen et al., 2008).

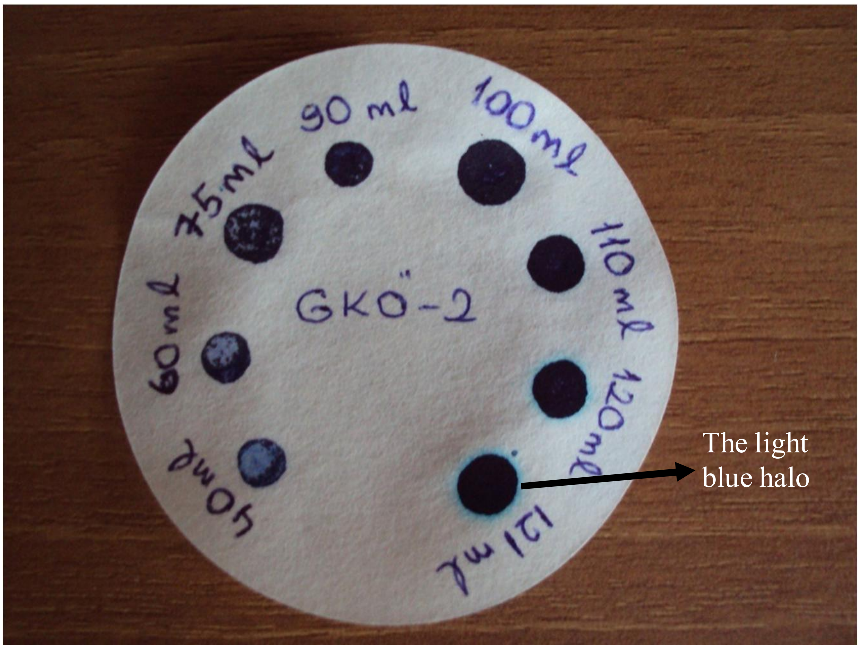

Figure 2.5 The light blue halo in methylene blue spot test

Specific surface area (SSA) is calculated as with the following equation:

$$SSA = \frac{1}{319.87}\frac{1}{200}(0.5N)A_v A_{MB}\frac{1}{10} \tag{2.1}$$

where N is the number of methylene blue increments added to the bentonite suspension, A_v is Avogadro's number (6.02×10^{23} / mol), and A_{MB} is the area coated by one methylene blue (typically assumed to be 130 Å^2).

2.2.4 Soluble Salts, Exchangeable Cations, Cation Exchange Capacity

Soluble salts, exchangeable cations and cation exchange capacities of bentonites were determined according to ASTM D7503.

In order to determine soluble salts in the bentonite, 2 g air dry soil solid passed from No.10 sieve and 100 ml of Type II deionized water were placed into a covered plastic container that fits firmly into the end-over-end shaker. The plastic container was shaken for 1 hour at 30 rpm. Then, 2.5 μm ashless filter paper was placed on the Buckner funnel and the mixture was filtered to a filtering flask by applying vacuum

(Figure 2.6). Then the filtrate was transferred to 100 ml volumetric flask, which was previously washed with 10% nitric acid. Then, 1 ml nitric acid was added into the filtrate to preserve the eluent. Finally, this eluent was analyzed to determine the cation species in the solution using inductively coupled plasma spectrometry (ICP).

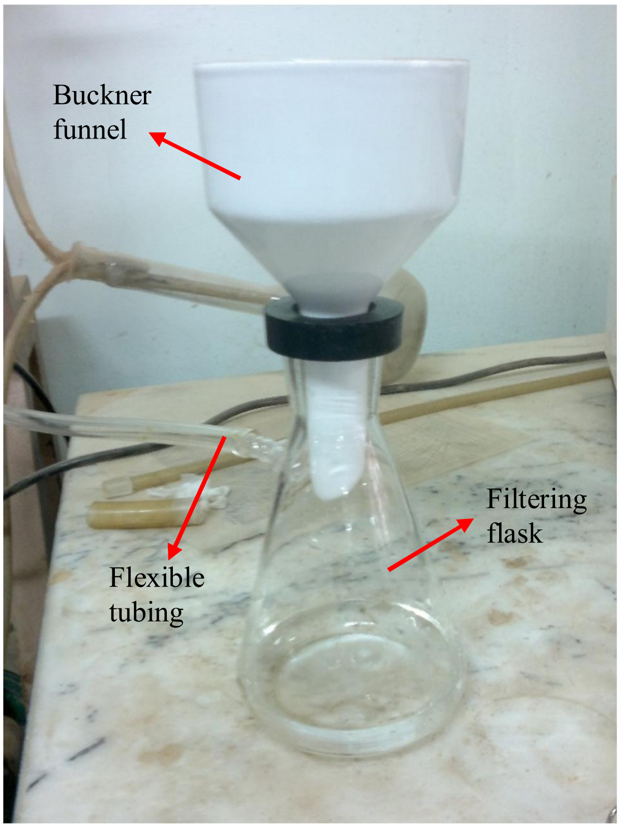

Figure 2.6 Experimental setup for vacuum filter

To determine bound cations in the bentonite, 100 ml deionized water, 10 g air dry soil solid passed from No.10 sieve and 40 ml ammonium acetate solution were placed into a plastic container that fits firmly into the end-over-end shaker. The plastic container was placed in the shaker and shaken for 5 minutes at 30 rpm. The mixture was led to stand for 24 hours. After 24 hours, the mixture was shaken for 15 minutes at 30 rpm again. Buckner funnel and 500 ml filtering flask (Figure 2.6) were rinsed with 1 M ammonium acetate. The filtering flask was placed over the Buckner funnel and 2.5 µm ashless filter paper was lined the Buckner funnel. The bentonite mixture was transferred to the Buckner funnel. The plastic container and the cap were rinsed with ammonium acetate solution through the Buckner funnel. The filtering flask was applied low suction (<10 kPa). The bentonite in the Buckner funnel was washed with four 30 ml portions of 1 M ammonium acetate. The filtered aqueous solution was transferred into the 250 ml volumetric flask, which was washed with 1 M ammonium acetate before and the solution was preserved to pH of 2. Volumetric flask was filled to volume with ammonium acetate. The aqueous solution was analyzed for cation concentration using ICP. Some steps of determining soluble cations, boundary cations and CEC are shown in Figure 2.7.

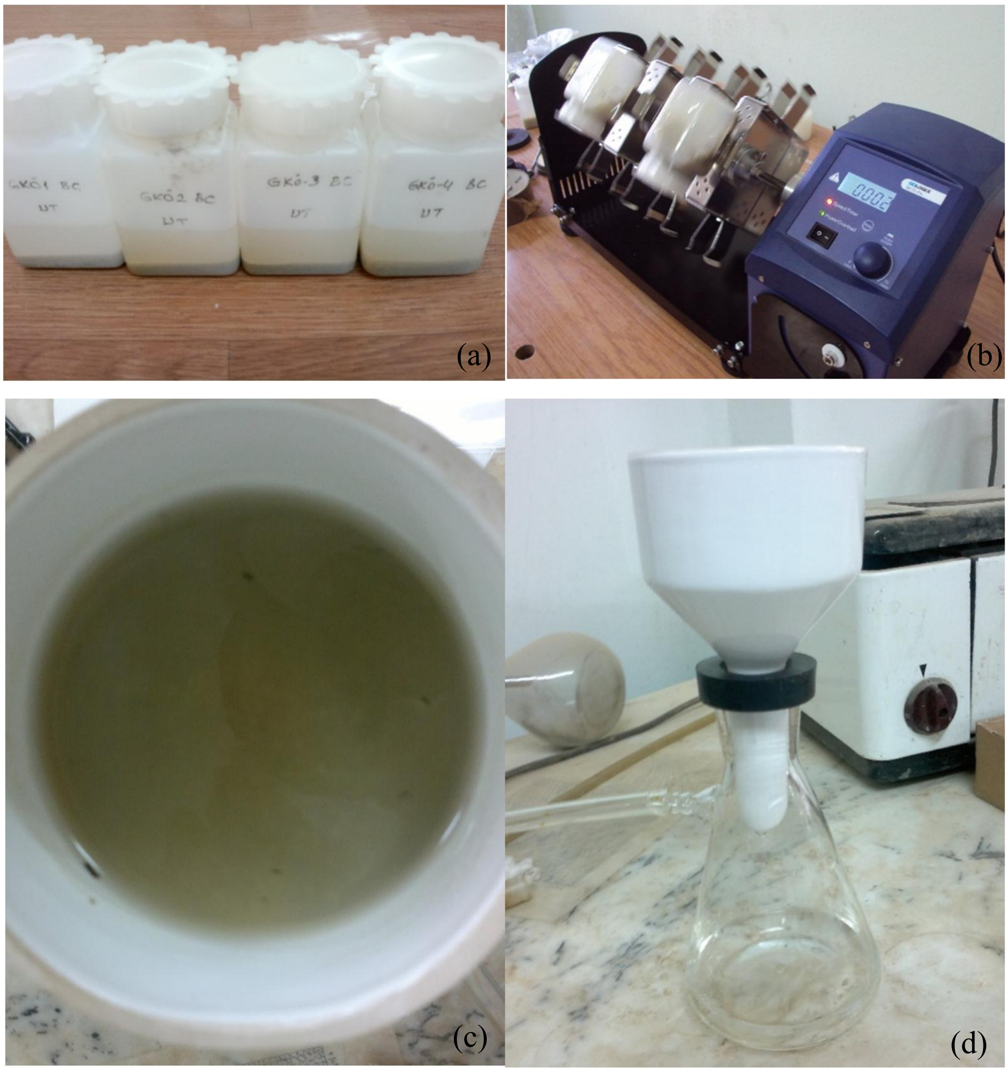

Figure 2.7 Some steps of determining CEC, a) Placing bentonite and DIW into plastic container, b) Shaking sample with shaker at 30 rpm, c) Filtering process, d) Applying vacuum to ease filtering.

Bentonite, which was washed with ammonium acetate was used for determining the cation exchange capacity (CEC). To determine the bound cations, filtering flask

(500 ml) was rinsed with 10% nitric acid and then washed with isopropanol. The Buckner funnel with 1 M ammonium acetate washed bentonite place onto the 500 ml filtering flask and low suction (<10 kPa) was applied to the filtering flask. The bentonite onto the filtering flask was washed with three 40 ml portions of isopropanol. Therefore, residual ammonium acetate was removed by washing with isopropanol. The isopropanol collected in the 500 ml filtering flask was discarded and the flask was washed with DIW three times. The bentonite onto the Buckner funnel was then washed with four 50 ml portions of the 1 M potassium chloride solution. A 250 ml volumetric flask was rinsed with 1 M potassium chloride and the extract was transferred into this flask. The volumetric flask was then filled to volume with water.

For the CEC analysis, 0.1 ml of this potassium chloride extract (Figure 2.8a) and one dose of NH_4-1K reagent (Figure 2.8b) were dropped into reaction cell (Figure 2.8b). Reaction cell was shaken until the reagent dissolved. Before the CEC analysis in the spectrophotometer the sample was kept for 15 minutes. After 15 minutes, the solution (Figure 2.8c) was analyzed for nitrogen concentration using Photolab S12 brand spectrophotometer (Figure 2.8d).

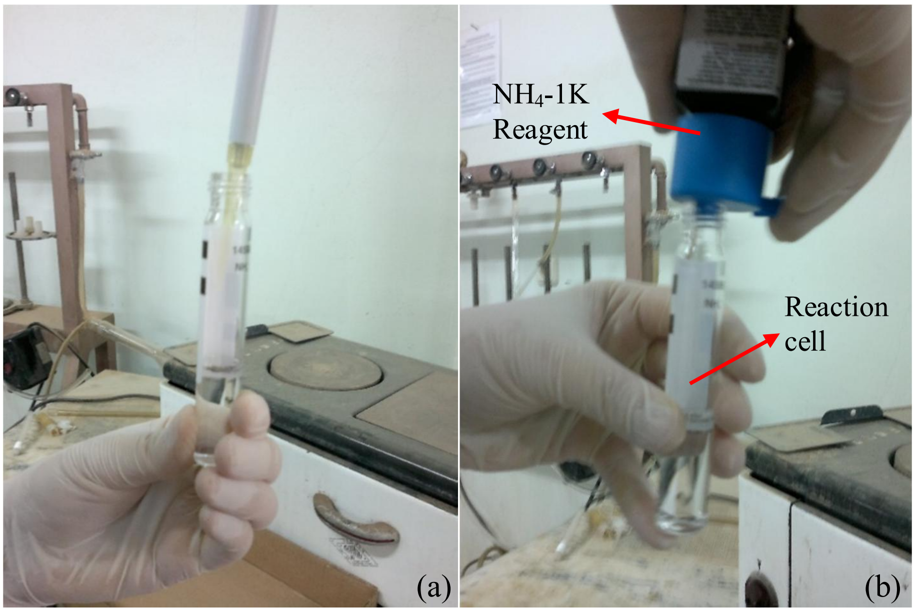

Figure 2.8 Preparation for measurement of CEC. a) Dropping 0.1 ml KCL extract, b) Adding one dose of reagent

Figure 2.8 Preparation for measurement of CEC. c) Solution will be analyzed, d) Analyzing. (Continue).

2.2.5 Mineralogical Analysis

The mineralogical compositions of the bentonites were determined by X-ray diffraction (XRD). Samples of the powdered bentonites were prepared by passing the bentonite through the No.200 (75 µm) sieve for XRD. Samples were sent off to Atılım University to have the mineralogical composition of the bentonites determined. GE Seifert XRD 3003-PTS machine with Cu-Kα radiation was used in order to estimate the quantitative amounts of mineral phases in the bentonite samples. Quantitative amounts of minerals were obtained from the results of the measurement has completed for four hours using AutoQuanR software.

2.2.6 Sample Preparation for Hydraulic Conductivity Tests

To prepare the GCLs for the hydraulic conductivity test, square (200×200 mm) samples were cut from each roll of GCL. Then, the middle sections of these squares were pointed with a pen to prepare circular samples in 100 mm diameter and were cut carefully using a razor knife. To prevent loss of bentonite during cutting, a small amount of DIW applied along the inner circumference of the sample using squirt bottle. After cutting, excess geotextile fibers were cut with scissors. The initial thicknesses of the specimens were measured with calipers at four equidistant points around the GCLs and the masses of the specimens were weighed. Bentonite paste hydrated in DIW was applied to the perimeter of the specimens to prevent the side-wall leakage. Then, the sample was placed into the permeameter cell. For each GCL specimen, two non-woven geotextiles were used instead of porous stones.

2.2.7 Hydraulic Conductivity Tests

Falling head hydraulic conductivity tests were conducted using flexible wall permeameters on GCL specimens (ASTM D5084). The permeameters were eligible to measure the hydraulic conductivity of the samples having 100 mm diameter. Even though Petrov et al. (1997) concluded from their experiments that the type of permeameter did not have a significant effect on hydraulic performance of GCLs, flexible wall permeameter is the most suitable device for testing GCLs to prevent side-wall leakage.

Instead of pre-hydration, the specimens were initially exposed to DIW or TW for 48 h by opening the influent valve only (i.e., keeping effluent valve closed). The flow is accomplished downward. The hydraulic conductivity tests were lasted at least 6 months for the pre-hydrated GCLs. The test duration for non-prehydrated GCLs was one week. Once the hydraulic conductivity tests were terminated, the permeameters were dismantled and the GCLs were removed from the permeameters for subsequent analysis on bentonites.

Cell pressure of 100 kPa, which is considered to expose average stress in waste containment facilities, and an average hydraulic gradient of 200 were applied. Although the hydraulic gradient is considered to be high, hydraulic gradient is preferred to be 200 by taking into consideration the duration of tests. On the other hand, Shackelford et al. (2000) reported that the hydraulic conductivity of GCLs is significantly influenced by average effective stress than by the magnitude of hydraulic gradient when hydraulic gradient is less than 500. No backpressure was applied during the hydraulic conductivity tests to represent the field condition. Average effective stress was applied in the tests is calculated as 90 kPa in accordance with the following equation:

$$\sigma_{av}' = \sigma_{cell} - \frac{\sigma_{in} - \sigma_{out}}{2} \tag{2.2}$$

where σ_{av}' is average effective stress, σ_{cell} is cell pressure, σ_{in} and σ_{out} are the pressures at the inflow and outflow, respectively.

Hydraulic conductivity values of GCLs are calculated with the following equation:

$$k = \frac{a \times \mathrm{H_{GCL}}}{A \times \Delta t} \times \ln \frac{h_0}{h_1} \tag{2.3}$$

where k is hydraulic conductivity of GCL, a is the cross-sectional area of the reservoir (i.e. burette) containing the influent liquid, $\mathrm{H_{GCL}}$ is the thickness of GCL, A is cross-sectional area of GCL specimen, Δt is interval of time which is the difference between start and end of permeation, h_0 is the head loss across the permeameter/specimen at the start of permeation, and h_1 is the head loss across the permeameter/specimen at the end of permeation.

Hydraulic conductivity results are expressed in terms of pore volume of flow (PVF). PVF was defined as the volume of flow into the test specimen divided by the volume of voids in the bentonite (ASTM D5084; Ruhl et al., 1997). The volume of voids was calculated from the following equation (Petrov et al., 1997):

$$V_v = H_v \times A = (H_{GCL} - H_s) \times A = [H_{GCL} - (H_{bentonite} + H_{geotextile})] \times A =$$

$$\left[H_{GCL} - \left(\frac{M_{bentonite}}{\rho_{bentonite} \times (1+w)} + \frac{M_{geotextile}}{\rho_{geotextile}} \right) \right] \times A \tag{2.4}$$

where V_v is volume of voids in bentonite, H_v is height of voids, H_s is height of solids in the GCL, $H_{bentonite}$ is height of bentonite, $H_{geotextile}$ is height of geotextile, $\rho_{bentonite}$ is density of bentonite, $\rho_{geotextile}$ is density of polypropylene geotextile (is taken as 0.91 Mg/m^3 (Petrov et al., 1997)), w is initial bentonite water content, $M_{bentonite}$ and $M_{geotextil}$ are reference mass of bentonite and geotextile per unit area in the GCL, respectively. From this equation, the volume of voids in the GCLs is determined around 30 cm^3 and the results are evaluated according to this determined value.

2.2.8 pH and Electrical Conductivity Measurements

Landfill leachate samples were taken from inlet and outlet periodically during the hydraulic conductivity tests. The pH and EC values were measured with these samples. These samples were filled in 50 ml plastic centrifuge tubes and kept in the refrigerator in order to not decay the composition of the samples. Afterwards, pH and EC measurements of these samples were monitored using a pH meter (Accumet® XL50, Fisher Scientific Co., Pittsburgh, PA), and EC probe (Accumet® XL50, Fisher Scientific Co., Pittsburgh, PA), respectively. Before the measurements, the probes were calibrated. Three buffer solutions for pH (pH=4, pH=7, pH=10) and two buffer solutions for EC (0.1 M KCl and 0.01 M KCl) were prepared for the calibrations of pH probe and EC probe, respectively. pH ratio (pH_{out}/pH_{in}) and EC ratio (EC_{out}/EC_{in}) were considered whether the requirement of chemical stability was ensured or not during the hydraulic conductivity tests. In these ratios, pH_{out} and EC_{out} represent the pH and EC values of outflow landfill leachates whereas pH_{in} and EC_{in} stand for the pH and EC values of inflow landfill leachates. According to ASTM D7100 and ASTM D6766, the chemical termination criteria for the hydraulic conductivity tests are dependent on the pH and EC equilibrium (pH_{out}/pH_{in} and EC_{out}/EC_{in}) which is defined as 1.0±0.1. This termination criteria was considered during the tests in this study.

CHAPTER THREE
PHYSICO-CHEMICAL AND MINERALOGICAL PROPERTIES OF BENTONITES

3.1 Index Properties of Bentonite

Particle size distribution curves of bentonites were obtained according to sieve and hydrometer analysis and depicted in Figure 3.1. Particle size distribution of three GCLs (GCL-1, GCL-2, GCL-3) were observed quite similar to each other. However, a bit different grain size distribution was observed for GCL-4. It was believed that the difference resulted from polymer treatment. Because, while the sieve analysis was being performed it was observed that bentonite of GCL-4 had gelatinous form and in consequence it could not pass through No.200 (75 μm) sieve.

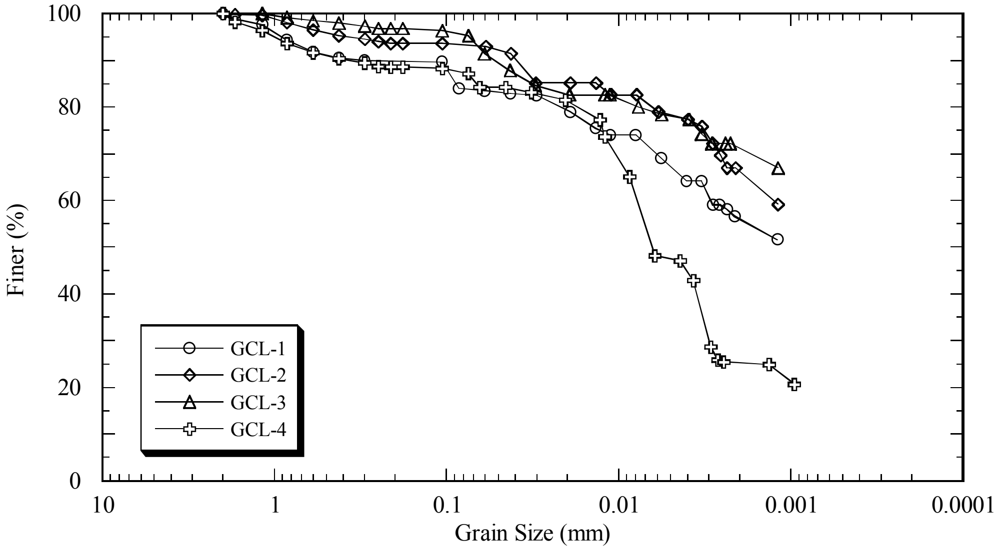

Figure 3.1 Grain size distribution curves of bentonites

Index properties of bentonites (specific gravity, initial water content, clay content, activity and consistency limits) are given in Table 3.1. Initial water content of GCL-1 and GCL-4 was obtained as 11%. For GCL-1 and GCL-4, the initial water content was determined as 18% and 22%, respectively. If clay content is considered, it can be observed that the clay content was 25% for polymer treated GCL-4 and the clay contents of other GCLs ranged from 67% to 72% (Table 3.1). The specific gravity of GCLs were within the range of 2.70 and 3.04. It seems that the specific gravity of GCL-1 is out of the range of specific gravities reported in the literature (i.e. 2.7-2.8). However, the test was tripled for GCL-1 and the specific gravities were obtained as 3.04, 3.06, and 3.06. The value represented in Table 3.1 is the average of these three values. Note that the reason for the greater specific gravity for GCL-1 is not known.

Table 3.1 Index properties of bentonites

Bentonite Type	Specific Gravity	Initial Water Content (%)	Clay Content (%)	Activity	Liquid Limit (%)		Plasticity Index (%)	
					Fall Cone	Casagrande	Fall Cone	Casagrande
GCL-1	3.04	11	57.0	0.8	99	108	39	48
GCL-2	2.79	22	67.0	4.2	232	310	206	284
GCL-3	2.79	18	72.0	4.0	236	320	206	290
GCL-4	2.70	11	25.0	44.4	800	1163	748	1111

Liquid limit of GCL-4 is higher than those of other GCLs. Since GCL-4 was polymer treated, it was observed that GCL-4 had porous structure and this structure held excess water in the texture. For this reason, liquid limit, plasticity index and activity of GCL-4 were rather high.

Although Casagrande method was more eligible for high plasticity clays (Sridharan & Prakash, 2000), fall cone method was also used to determine liquid limit of bentonites due to popularity in Turkey. The results of these two methods are compared and illustrated in Figure 3.2. Based on this figure, it is seen that the liquid limits obtained from Casagrande method is greater than the liquid limits obtained from fall cone method. This conclusion is consistent with the literature (Sridharan & Prakash, 2000). The mechanisms that control the liquid limit behavior of bentonites are not discussed herein. However, the details can be found in Sivapullaiah & Sridharan (1985) and Sridharan & Prakash (2000).

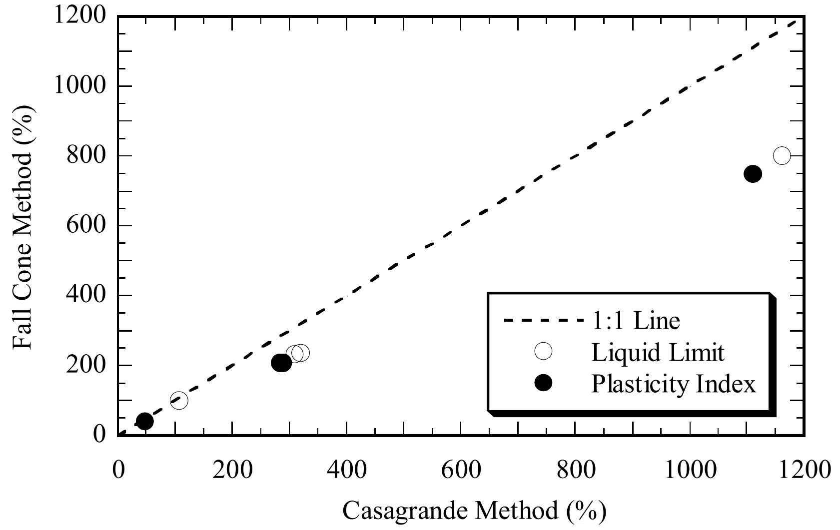

Figure 3.2 Comparison between the liquid limits obtained from the fall cone method and the Casagrande method

3.2 Mineralogy of Bentonite

The XRD patterns of bentonites are illustrated in Figure 3.3. Based on Figure 3.3a-d, the principal mineral in the GCLs are smectite.

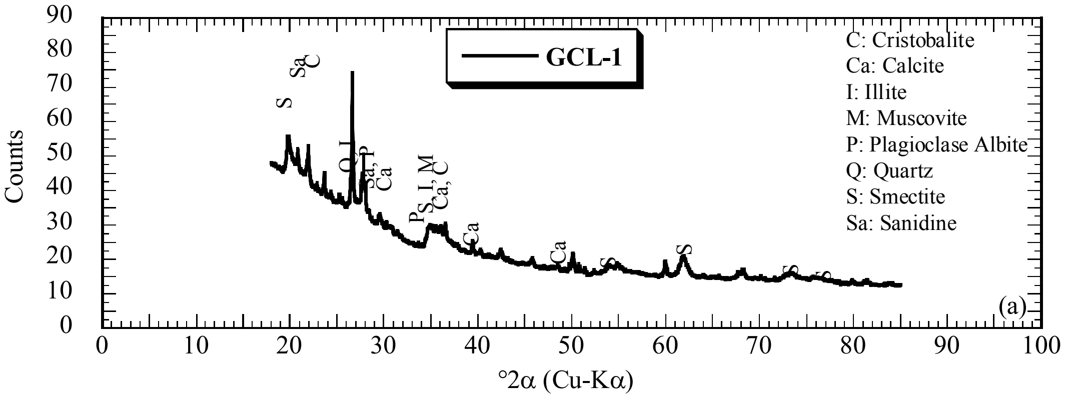

Figure 3.3 X-ray diffraction patterns of GCLs. a) GCL-1

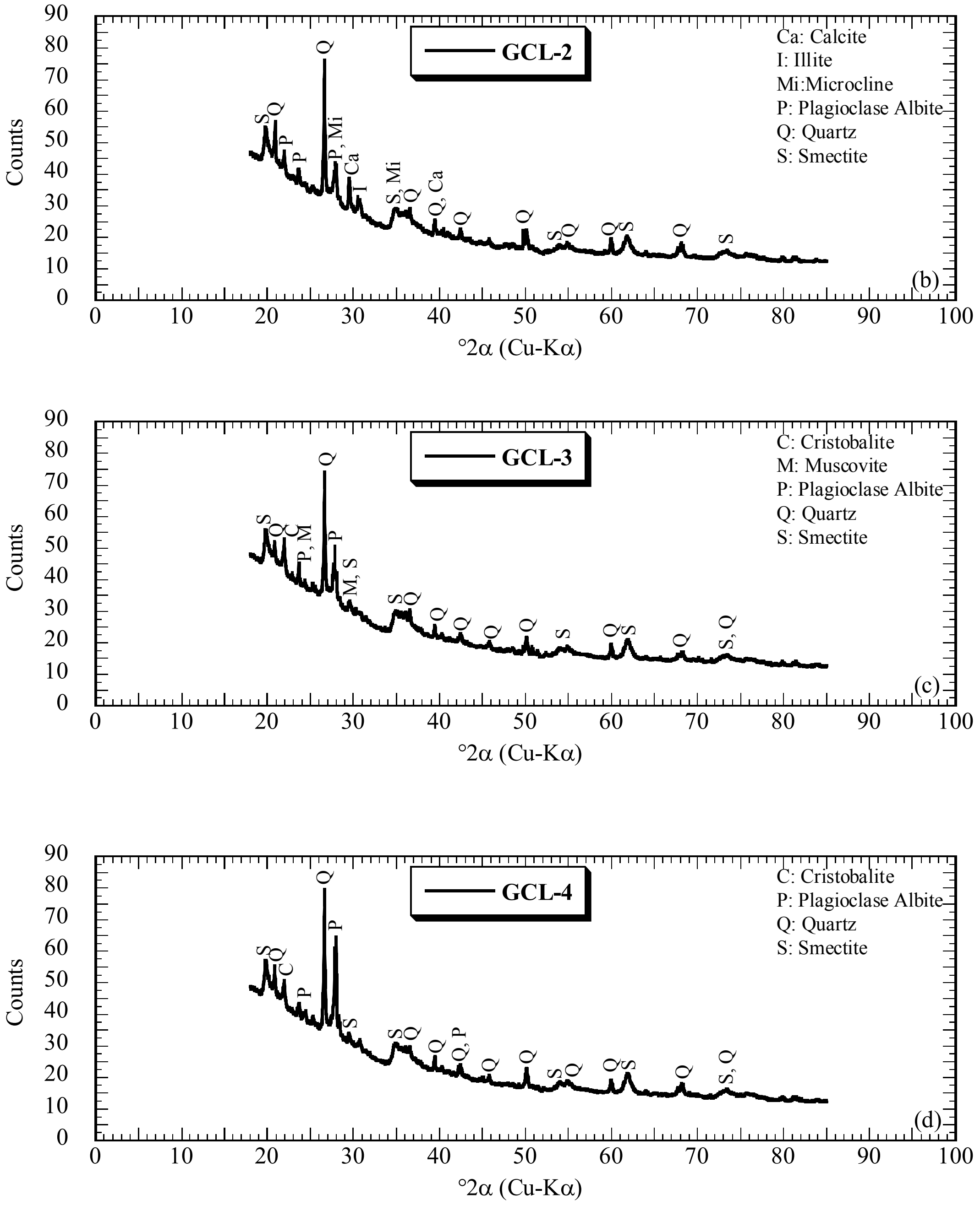

Figure 3.3 X-ray diffraction patterns of GCLs. b) GCL-2, c) GCL-3, d) GCL-4 (Continue)

The mineralogical compositions of bentonites are also reported in Table 3.2. The smectite content of bentonites varies from 64 to 68 %. Bentonites involve other minerals such as quartz, illite, calcite, cristobalite, muscovite, microcline with less amounts.

Table 3.2 The mineral contents of the bentonites

Mineral Content (%)	**GCL Type**			
	GCL - 1	**GCL - 2**	**GCL - 3**	**GCL - 4**
Smectite	68.0	65.3	63.7	66.2
Quartz	2.8	13.5	11.5	13.6
Calcite	4.1	2.6	-	-
Cristobalite	9.2	1.8	4.1	3.1
Muscovite	3.1	1.3	4.0	2.4
PlagAlbite	3.5	8.0	-	-
Illite	3.9	2.7	5.5	5.6
Microcline	-	4.9	3.5	4.7
Sanidine	5.5	-	-	-
Plagioclase Andesine	-	-	7.7	4.4

3.3 Chemical Properties of Bentonite

Some chemical properties such as specific surface area and cation exchange capacity (CEC) are presented in Table 3.3. It was found that the specific surface area of bentonites are ranged from ≈538 to 890 m^2/g. This range is quite high. However, since GCL-4 was polymer treated, specific surface area of GCL-4 could be higher than other bentonites. Cation exchange capacity of GCLs were obtained as between 75 and 80 meq/100 g. Chemical properties of bentonites are consistent with the bentonites used in literature.

Table 3.3 Chemical Properties of Bentonites

Bentonite Type	Specific Surface Area (m^2/g)	Cation Exchange Capacity (meq/100g)
GCL-1	670.37	75.7
GCL-2	592.08	79.5
GCL-3	538.26	80.0
GCL-4	890.57	78.9

CHAPTER FOUR

FREE SWELL AND HYDRAULIC CONDUCTIVITIES OF GEOSYNTHETIC CLAY LINERS WITH DEIONIZED AND TAP WATER

4.1 Background

As GCLs are used to provide the impermeability, determining the hydraulic conductivities of GCLs properly plays a vital role. The results of the several studies have shown the need to perform the hydraulic conductivity tests of GCLs with deionized water (DIW) and tap water (TW). Numerous researchers have used DIW or TW as reference liquid to chemicals (Ashmawy, El-Hajji, Sotelo & Muhammad, 2002; Benson et al., 2010; Jo et al., 2001; Ruhl & Daniel, 1997; Shackelford et al., 2000; Shan & Lai, 2001).

There are some points to take into consideration for determining the hydraulic conductivity of the composite materials like GCLs. The influence of operator is noticeable especially during preparing the sample and placing it into the permeameter. Therefore, it is inevitable that various hydraulic conductivity values can be obtained depending on the sample preparation technique. Since GCLs are in use recently in Turkey, this chapter reports some information about the free swell and hydraulic conductivity of GCLs with DIW and TW.

4.2 Free Swell of Bentonite

Free swell values of bentonites used in this study are displayed in Figure 4.1. It can be seen that the lowest and the highest free swell values were obtained as ≈12 mL/2g (GCL-1) and ≈32 mL/2g (GCL-4). Free swell values for GCL-2 and GCL-3 are almost the same and are around 20 mL/2g (Figure 4.1).

As shown in Figure 4.1, the effect of water type (DIW or TW) is scant on the free swell values of bentonites. In other words, testing water had no significant effect on the free swell values of bentonites. It is expected that the free swell of bentonite in

DIW should be greater than that of bentonite in TW. However, for GCL-1, free swell value in DIW was lower than those in TW. This may be due to the chloride anions that is available in tap water.

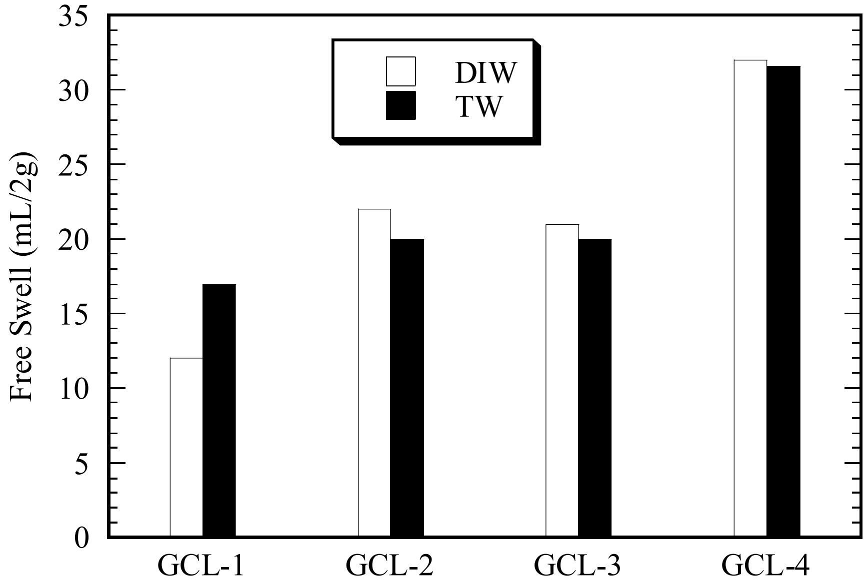

Figure 4.1 Free swell with DIW and TW

4.3 Hydraulic Conductivity of Geosynthetic Clay Liners with Permeant Water

4.3.1 Deionized Water

The hydraulic conductivities of GCLs when permeated with DIW is shown in Figure 4.2. Q_{out}/Q_{in} values, which indicate the rate of effluent to influent of flow, were located on the second y-axes. The dashed lines in this figure represent the boundary conditions corresponding to 1.0±0.25 of $Q_{out}/Q_{in.}$ Henceforth, this ratio will be considered as the physical stability. During the tests, some irregularity of physical stability was observed. For example, some values of Q_{out}/Q_{in} depicted in Figure 4.2 were out of the allowable ranges of physical boundaries. The irregularity, originated from decreasing the cell pressure, can be attributed to the power failure during the hydraulic conductivity tests. When this happened, the valve that provided the pressure to the system was switched off in order to temporarily keep the pressure in the cell. In contrast, the valves that control influent and effluent lines were not closed. The cell pressure valve was switched on again after the end of the power failure.

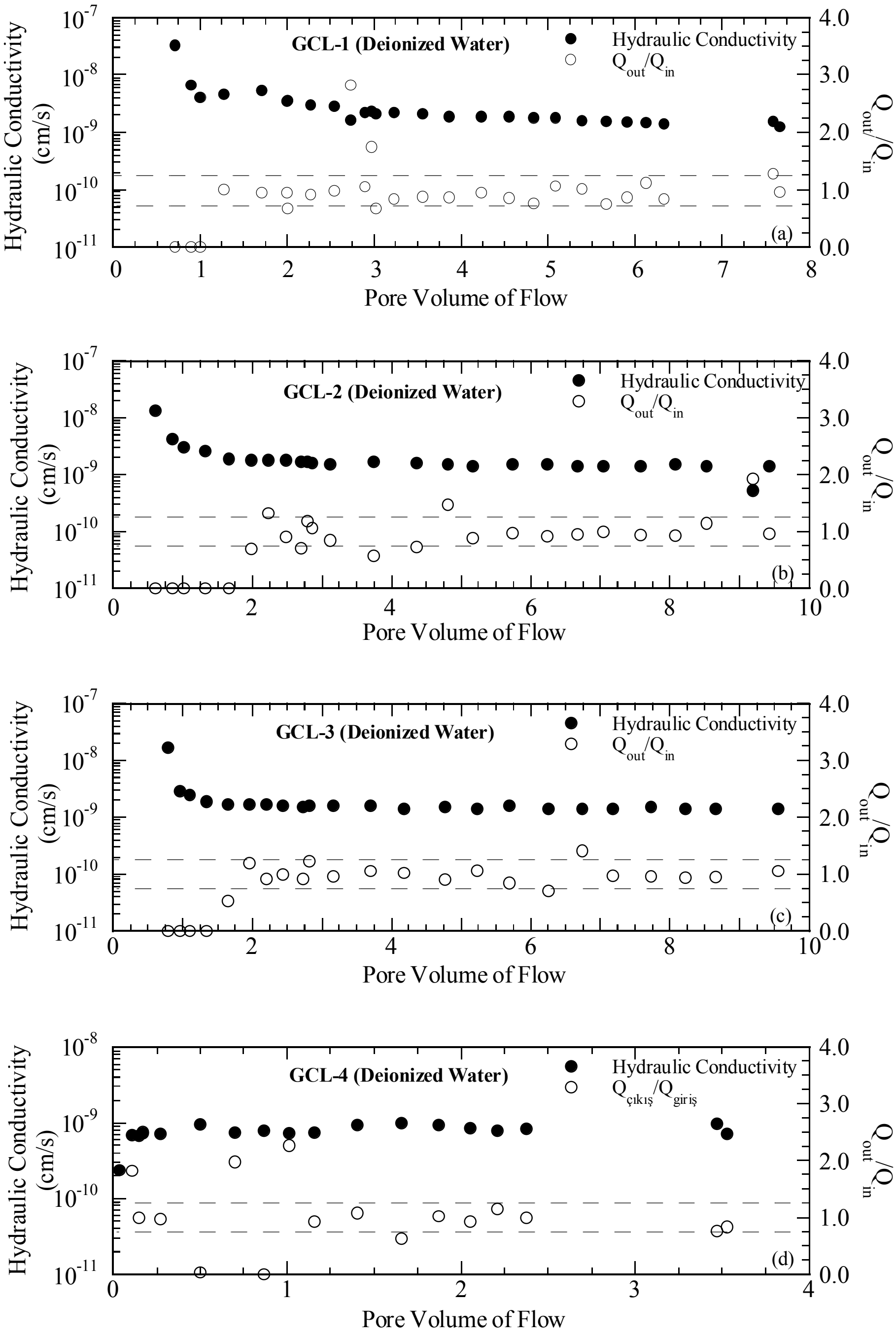

Figure 4.2 The results of hydraulic conductivity tests of geosynthetic clay liners using deionized water as permeant liquid: a) Geosynthetic Clay Liner-1 (GCL-1), b) Geosynthetic Clay Liner-2 (GCL-2), c) Geosynthetic Clay Liner-3 (GCL-3), d) Geosynthetic Clay Liner -4 (GCL-4).

In the case of DIW permeation, the hydraulic conductivity of GCL-1 was 3.3×10^{-8} cm/s at the beginning of the test. Then, this value decreased to 1.2×10^{-9} cm/s when PVF was 8. As it can be seen in Figure 4.2a, although physical stability was achieved at 1.25 PVF, the hydraulic conductivity became barely stable at 5.5 PVF. Similar decrease of hydraulic conductivities were also obtained for GCL-2 and GCL-3 (Figure 4.2b-c). Hydraulic conductivity tests for GCL-2 and GCL-3 were continued till 10 PVF and the physical and hydraulic stabilities were achieved earlier for GCL-2 and GCL-3 when compared to GCL-1(around 2 PVF).It is important to note that GCL-4 has an opposite hydraulic conductivity behavior among the other three GCLs (Figure 4.2d). Hydraulic conductivity was 2.4×10^{-10} cm/s at the beginning, but it further increased to 7.1×10^{-10} cm/s which corresponds to three-fold increase with respect to the initial value.

4.3.2 Tap Water

The hydraulic conductivities of GCLs with TW is shown in Figure 4.3. In the case of TW permeation, the hydraulic conductivity of GCL-1 was similar to that of GCL-1 using DIW as the permeant. The hydraulic conductivity value was obtained as 3.6×10^{-5}cm/s and later, it reduced to 1.7×10^{-10} cm/s at 8 PVF. From this point to the end of the test, there were no significant changes in the physical stability (Figure 4.3a). For GCL-2, however, the hydraulic conductivity values preserved their stability along the test duration. However, physical stability was achieved at 1.5 PVF (Figure 4.3b). As it can be seen in Figure 4.3c, the hydraulic conductivity behavior of GCL-3 was similar in terms of displaying a stepped decrease with the hydraulic conductivity behavior of GCL-1. While the hydraulic conductivity of GCL-4 was 6.2×10^{-10} cm/s at the beginning of the test, it was measured as 1.0×10^{-9} cm/s when test was ceased (Figure 4.3d). This increase in the hydraulic conductivity was almost the same as previously reported hydraulic conductivity behavior of GCL-4 using DIW (Figure 4.2d).

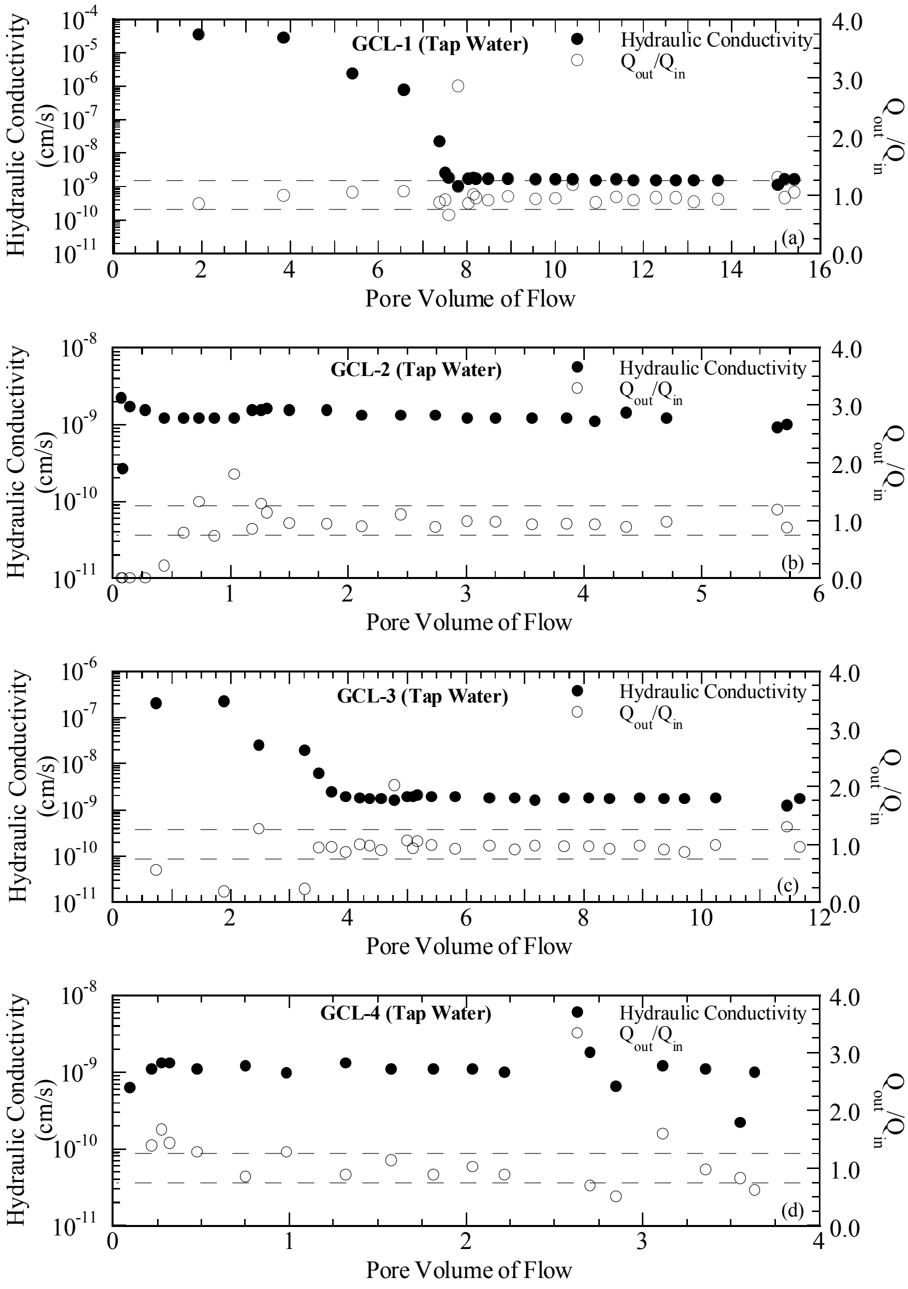

Figure 4.3 The results of hydraulic conductivity tests of geosynthetic clay liners using tap water as permeant liquid: a) Geosynthetic Clay Liner-1 (GCL-1), b) Geosynthetic Clay Liner-2 (GCL-2), c) Geosynthetic Clay Liner-3 (GCL-3), d) Geosynthetic Clay Liner -4 (GCL-4).

4.4 Termination Criteria for the Hydraulic Conductivity Tests

Achievement of steady hydraulic conductivity values and maintaining the tests for a while are required in order to terminate the hydraulic conductivity tests. According to the ASTM D 7100-11, this criteria is stipulated with permeation of 2 PVF. The hydraulic conductivity ratio can be obtained by dividing the hydraulic conductivity values shown in Figure 4.2 and Figure 4.3 to the final hydraulic conductivity values of GCLs. As a result of this normalization, the hydraulic conductivity differences observed along the test duration could be obtained.

The plot of the hydraulic conductivity ratios versus PVF for each permeation water is depicted in Figure 4.4. The hydraulic conductivity ratio was obtained by dividing each value of hydraulic conductivity to final hydraulic conductivity value. For GCL-1, the difference between hydraulic conductivity values at the beginning of the tests and at the end of the tests was observed as roughly 28 times when the permeation liquid was DIW (Figure 4.4a). This difference reduced to less than 1.5 times at 4.5 PVF. For TW permeation, the hydraulic conductivity ratio was considerably high at the beginning (22.5 times). This difference decreased to 1.5 at the end of the test. It was considered that the reason of obtaining the greater hydraulic conductivity values at the beginning can be attributed to the particle size of bentonite (GCL-1 had granular bentonite). It was observed that GCL-1 contains granular bentonites when compared to the others. Thus, the hydraulic conductivity of granular bentonites was quite high at the beginning of the test and the permeability decreased over time due to swelling of bentonite.

In contrast, there was no significant difference on the hydraulic conductivity ratio of GCL-2 throughout the test duration. The difference was fairly high (≈10) at the beginning of the test and then it reduced to 1.5 at 2 PVF (Figure 4.4b). From 2 PVF until the end of the test, there was no significant change observed on the hydraulic conductivity ratio.

The hydraulic conductivity ratio for GCL-3, permeated with DIW, was 1.5 at 1.4 PVF, while it was observed as 12 at the beginning of the test (Figure 4.4c). In the case of permeation with TW, the hydraulic conductivity ratio was observed as 120 at the beginning of the test, and then it decreased to less than 1.5 (Figure 4.4c) at ≈4 PVF.

It is interesting to note that the hydraulic conductivity ratio for GCL-4 was low at the beginning of the test. It was approximately 0.4 at 0.5 PVF. Then, the ratio reached to 1.0 (the hydraulic conductivity value at any time is equal to final hydraulic conductivity value) and maintained this value until the end of the test.

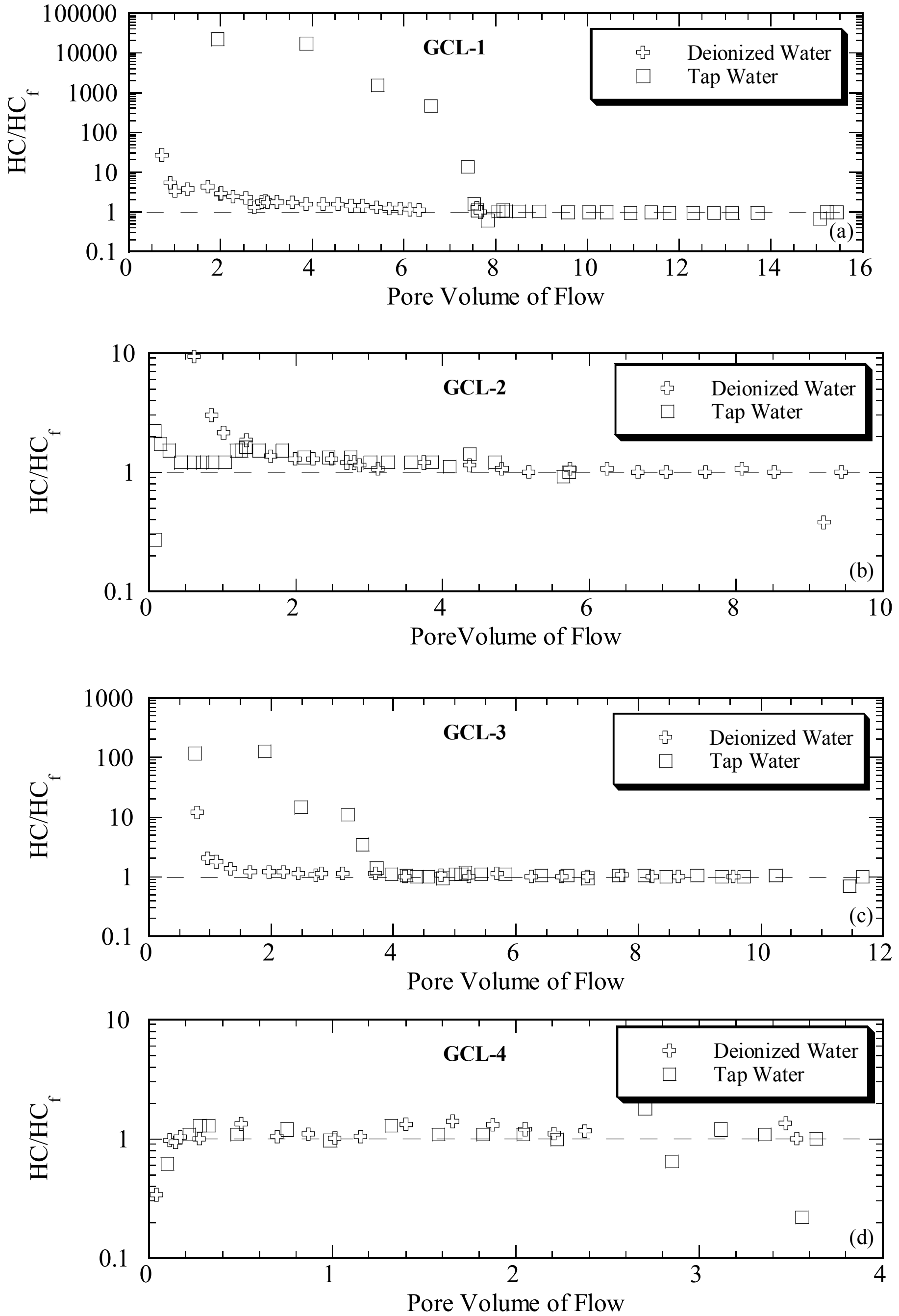

Figure 4.4 The hydraulic conductivity ratio which was obtained by dividing each value of hydraulic conductivity to final hydraulic conductivity value: a) GCL-1, b) GCL-2, c) GCL-3), d) GCL-4.

Figure 4.4 depicts that the termination criteria that should be applied during hydraulic conductivity tests is generally greater than 2 PVF, depending on the bentonite particle size. If GCL contains granular bentonite, the hydraulic stability is generally satisfied at further PVFs. In this study, for example, GCL-1 reached the stability around 8 PVF regardless of permeation water. Thus, it is suggested that the hydraulic conductivity ratio should be taken into consideration along the test duration and the hydraulic conductivity tests should be lasted when hydraulic conductivity ratio is reduced below 1.5.

4.5 Post Tests Changes on Geosynthetic Clay Liners

The GCL properties, such as height and water content, generally change during the hydraulic conductivity tests. This is important while interpreting the results. Thus, the height and water content of GCLs were measured and presented in Table 4.1. The differences between the initial and final GCL heights indicate the swelling amount of bentonites within the GCLs. As can be seen in Table 4.1, the post test GCL heights were within the range of 0.63 – 0.82, whereas final water contents were within the range of 92 – 268 %. The greatest amount of swelling with respect to the initial height was recorded for GCL-4. Similarly, the final water content of GCL-4 was roughly twice the final water contents of other GCLs. It is possibly due to the polymer characteristics of bentonite used in the GCL-4. This also leads the lowest hydraulic conductivities for GCL-4 when compared to GCL-1, GCL-2 and GCL-3.

Table 4.1 Initial and final properties of geosynthetic clay liners

GCL Type	Test Liquid	GCL Height (cm)		Water Content (%)	
		H_i	H_f	w_i	w_f
GCL-1	DIW	0.58	0.82	11	92
GCL-2	DIW	0.52	0.63	22	90
GCL-3	DIW	0.50	0.69	18	109
GCL-4	DIW	0.41	0.76	11	236
GCL-1	TW	0.60	0.79	11	128
GCL-2	TW	0.58	0.77	22	95
GCL-3	TW	0.51	0.65	18	108
GCL-4	TW	0.42	0.75	11	268

CHAPTER FIVE

CORRELATING THE HYDRAULIC CONDUCTIVITIES OF GEOSYNTHETIC CLAY LINERS WITH PHYSICO-CHEMICAL PROPERTIES OF BENTONITE

5.1 Background

The hydraulic conductivities of GCLs used as hydraulic barrier in many facilities should be determined properly in the laboratory before the application. The hydraulic conductivity of GCLs is influenced by many parameters such as particle size of the bentonite (granular or powder bentonite), the montmorillonite content, the void ratio of bentonite, hydration condition, etc. (Shackelford et al., 2000). Besides, the hydraulic conductivity tests are the tests that last months or even years. For this reason, numerous researchers concentrate on the study in which the hydraulic conductivity values are correlated with the parameters obtained from basic and practical tests in order to save time and economy.

For instance, various studies have shown that free swell of bentonite is directly correlated with the hydraulic conductivity of GCLs (Ashmawy et al., 2002; Benson et al., 2010; Jo et al., 2001; Katsumi et al., 2008; Kolstad et al., 2004; Lee et al., 2005; Shackelford et al., 2000). These studies have revealed that increase in the free swell of bentonite led to decrease in the hydraulic conductivity of GCLs. As a result, a strong relationship, which could be used to estimate the hydraulic conductivity for preliminary design, was found to exist between free swell of bentonite and the hydraulic conductivity of GCLs in their study.

Jo et al. (2001) have revealed that two types of expansion could occur and the expansion is affected by montmorillonite content of GCL. In other words, osmotic swelling appears in bentonites which contain monovalent cations and hydration (i.e. crystalline) swelling occurs in bentonite involving polyvalent cations. Bentonites including monovalent cations exhibit an excellent hydraulic barrier performance due to osmotic swelling.

Ashmawy et al. (2002) have revealed that there is a relationship between both free swell and hydraulic conductivity of GCLs and montmorillonite content and hydraulic conductivity of GCLs. They have claimed that greater swelling was observed in conjunction with lower hydraulic conductivity. They have also stated that the hydraulic conductivity decreases with the increase of the montmorillonite content for GCLs permeated with water and prehydrated GCLs with one of the landfill leachates.

In addition, Lee et al. (2005) have used liquid limit test and sedimentation test to find correlation with hydraulic conductivity of GCLs. They used DIW and $CaCl_2$ solutions (5-500 mM) as the permeant in the study. Lee et al. (2005) have indicated that the correlations between hydraulic conductivity and index properties, such as liquid limit, plasticity index, swell volume, solution retention capacity, and grain size, could be separated into three regions. In the first region, with little change in index property, high increase occurs in the hydraulic conductivity of GCL. In the second region, greater increase in the index property correlated with little change in the hydraulic conductivity. In the third region, however, increase in the index property correlated with remarkable decrease in hydraulic conductivity.

Katsumi et al. (2007) have asserted that there is a significant correlation between the hydraulic conductivity performance of bentonite and the crystal interlayer expansion of bentonite. Moreover, Katsumi et al. (2007) indicate that the hydraulic conductivity of GCLs are affected by several factors such as quality of bentonite, which is affected by mineralogical composition, specific surface area, cation exchange capacity and the amount of exchangeable cations, effective confining stress and the chemical properties of permeant liquids.

5.2 Summary of Free Swell and Hydraulic Conductivity Results

The physico-chemical properties and mineralogy of bentonites were aforementioned in Table 3.1, Table 3.2 and Table 3.3. The final hydraulic conductivity and free swell values of bentonites are shown in Table 5.1.

Table 5.1 Free swell and the final hydraulic conductivity values

Bentonite Type	Free Swell (ml/2g)		Hydraulic Conductivity (cm/s)	
	DIW	TW	DIW	TW
GCL-1	12.0	17.0	1.2×10^{-9}	1.0×10^{-9}
GCL-2	22.0	20.0	1.4×10^{-9}	9.8×10^{-10}
GCL-3	21.0	20.0	1.4×10^{-9}	1.7×10^{-9}
GCL-4	32.0	31.6	7.1×10^{-10}	1.0×10^{-9}

5.3 Post Test Correlations between Geosynthetic Clay Liner Properties and Hydraulic Conductivity

The correlations between the hydraulic conductivities of GCLs and some basic physico-chemical properties of bentonite will be discussed under this section. Note that since the index properties and free swell tests were conducted with DIW, only the hydraulic conductivity to DIW was considered for the correlations.

Relationship between the final hydraulic conductivity and final GCL heights are illustrated in Figure 5.1a. According to this figure, the increase of the final GCL heights caused to increase the hydraulic conductivity. The hydraulic conductivity values and the final GCL heights presented in this study were observed to be compatible with the values reported in literature. However, Petrov et al. (1997) have remarked that expressing the hydraulic conductivity of GCLs was more feasible with the final void ratio of GCLs rather than the final GCL height. They have claimed that each GCL has different amount of bentonite ($M_{bentonite}$) which lead to differ the GCL heights. Therefore, the final void ratio of GCLs was calculated by using the following equation and the results were compared with the results of Petrov et al. (1997) and Shan & Lai (2002).

$$e = \frac{V_v}{V_s} = \frac{V - V_s}{V_s} = \frac{\left[H_{GCL} - \left(\frac{M_{bentonite}}{\rho_{bentonite} \times (1+w)} + \frac{M_{geotextile}}{\rho_{geotextile}}\right)\right]}{\left(\frac{M_{bentonite}}{\rho_{bentonite} \times (1+w)} + \frac{M_{geotextile}}{\rho_{geotextile}}\right)} \qquad (5.1)$$

where V_s is volume of solids and e is the void ratio of GCL, respectively. Other terms were expressed in Equation 2.4. The hydraulic conductivity and the final void ratio values of GCLs obtained from Equation 5.1 are shown in Figure 5.1b.

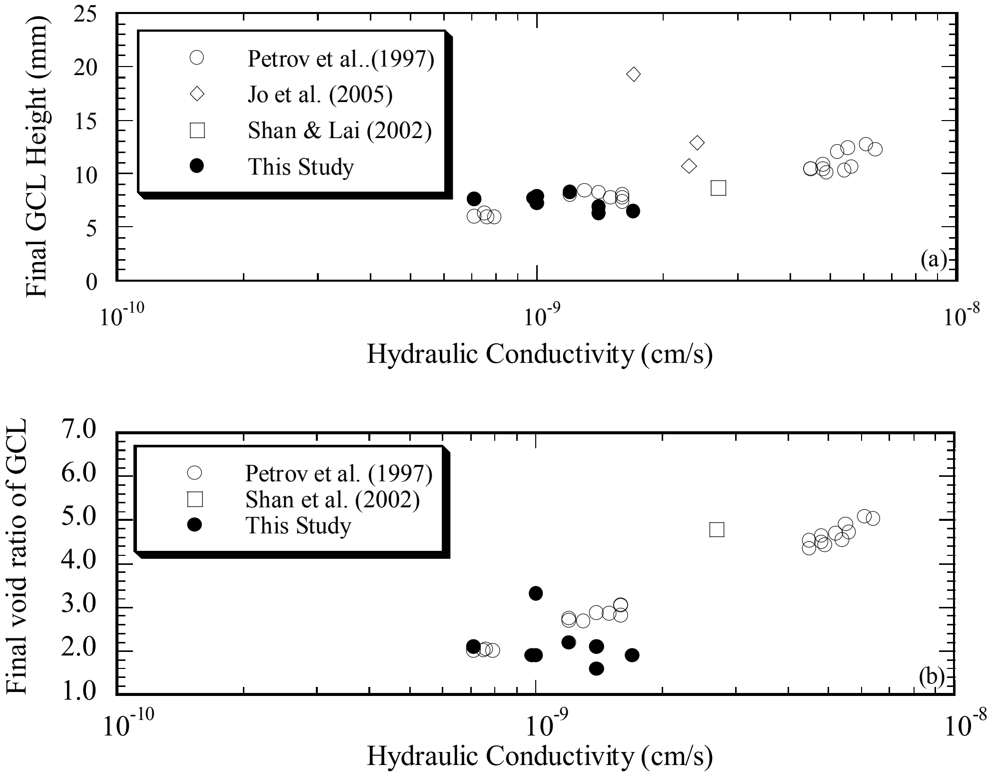

Figure 5.1 The changes of the hydraulic conductivity of GCLs with a) final GCL height, b) Final void ratio of GCL

As it can be seen from Figure 5.1b that low void ratio was obtained due to high effective stress applied in this study. In addition, since Petrov et al. (1997) performed their tests by using one type of GCL, the correlation of the hydraulic conductivity and void ratio of GCL was almost linear. However, since four different types of

GCLs were used in this study, the final void ratio values were scattered at the same effective stress. Besides, when Figure 5.1b was considered, it can be realized that the results of this study were consistent with the behavior reported in the literature. That is; the hydraulic conductivity decreases as the void ratio of GCL decreases.

5.4 Relationship between Index Properties of Bentonite and Hydraulic Conductivity of Geosynthetic Clay Liners

There are several studies investigating the correlation of liquid limit of bentonites and hydraulic conductivity of GCLs in the literature. In these studies, the chemical liquids were used when liquid limit and hydraulic conductivity tests were carried out. It was reported that hydraulic conductivity values increased when aggressive liquids were used as the permeant liquid. In contrast, if these aggressive liquids were used in liquid limit test, the liquid limit values decreased with respect to the liquid limit values obtained using DIW (Gleason et al., 1997; Lee at el., 2005). In this study, it was aimed to find the required liquid limit value by associating the liquid limit values of bentonites with the final hydraulic conductivity of GCLs (Figure 5.2). According to Figure 5.2, the hydraulic conductivity increased up to liquid limit value of 400%, thereafter the hydraulic conductivity decreased with the liquid limit. It is interesting to note that there was no considerable influence of the liquid limit of polymer treated bentonite (GCL-4) on the hydraulic conductivity of GCLs, although the liquid limit of GCL-4 was obtained as 1163%.

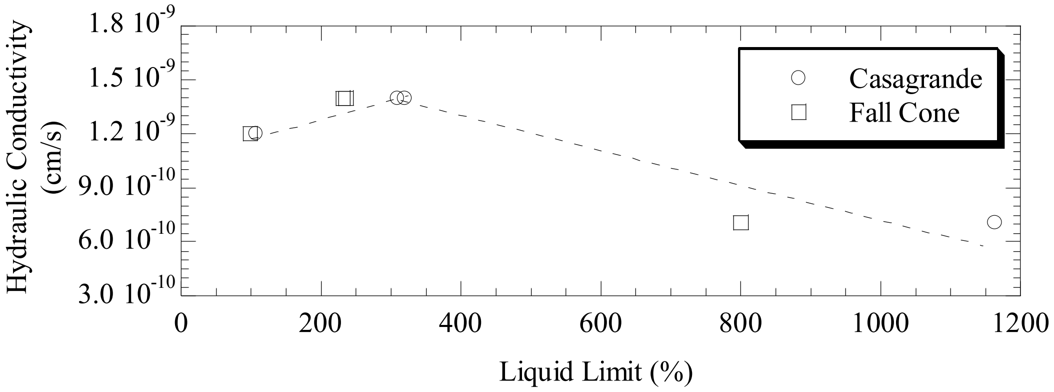

Figure 5.2 Hydraulic conductivity vs liquid limit of bentonite

Like liquid limit, the plasticity index affected the hydraulic conductivity. As it can be seen in Figure 5.3, if the plasticity index increased up to plasticity value of 300%, the hydraulic conductivity increased whereas if the plasticity index increased up to 1000%, the hydraulic conductivity decreased.

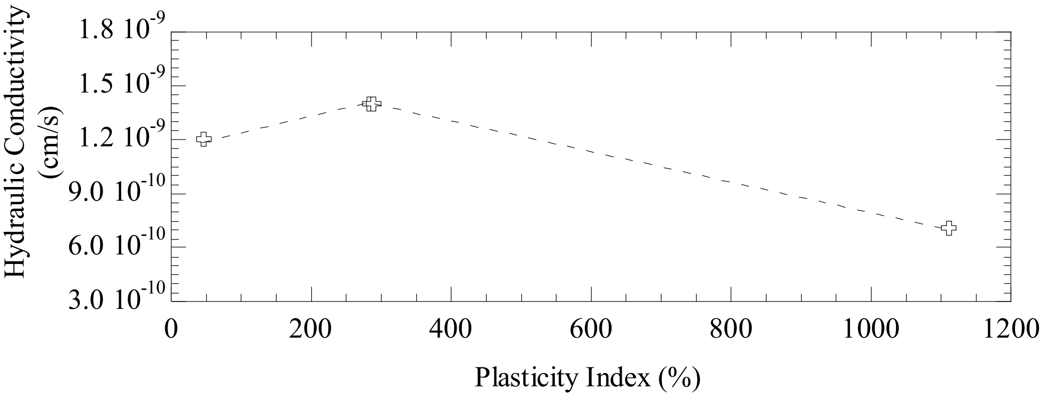

Figure 5.3 Hydraulic conductivity vs plastic limit and plasticity index of bentonite

Correlating the myriad properties of clays with clay content is a simple method. The clay content of bentonites was examined in order to correlate with the hydraulic conductivity of GCLs (Figure 5.4).

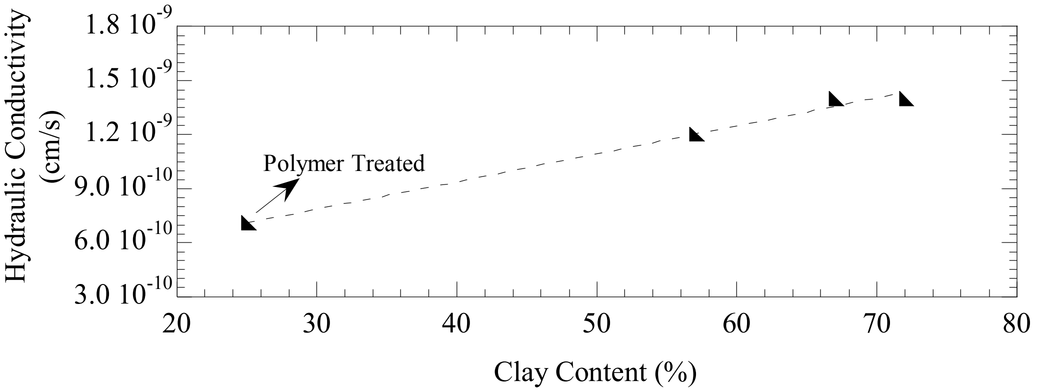

Figure 5.4 Hydraulic conductivity vs clay content of bentonite

When the clay content increased, the hydraulic conductivity of GCLs except GCL-4, which is polymer treated, changed negligibly. However, GCL-4 exhibited different behavior. The structure of bentonite particles were affected by polymer additive. Therefore, GCL-4 demonstrated a flocculated and spongy structure.

Actually, the relatively high liquid limit value for GCL-4 (1163%) was caused due to the entrapped water in the flocculated structure formed by bentonite particles. Likely, bentonite particles of GCL-4 settled quickly during hydrometer tests like silt and/or sand and this led GCL-4 to have 25% clay content.

The activities of bentonites were calculated by considering the clay contents and plasticity indices of bentonites as previously shown in Table 3.1. The changes in the hydraulic conductivities of bentonites with activity are also illustrated in Figure 5.6. If GCL-4 was thought as an exception, it could be seen that the hydraulic conductivity increased with increasing the activity (Figure 5.5). Although the hydraulic conductivity of GCL-1 was lower, it was determined as 1.2×10^{-9} cm/s. On the other hand, the activity of GCL-4, which was polymer treated, was calculated as 44.4 due to its high plasticity index. This activity value was considerably high if it was compared to other bentonites.

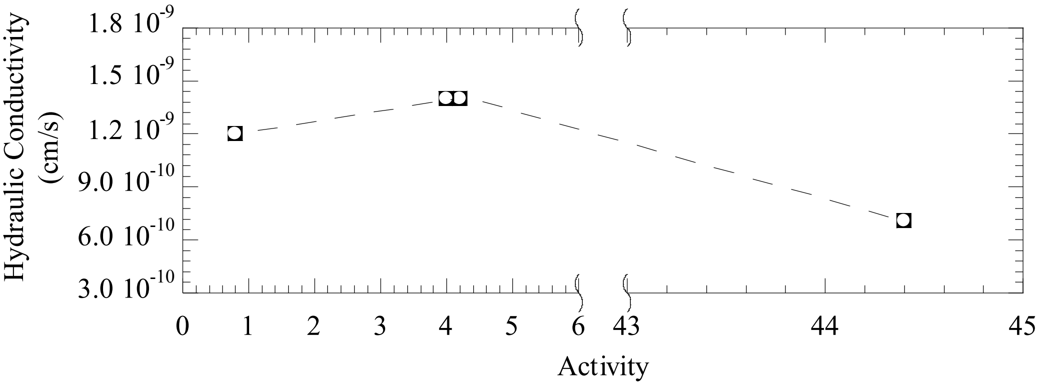

Figure 5.5 Hydraulic conductivity vs activity of bentonite

5.5 Relationship between Free Swell of Bentonite and Hydraulic Conductivity of Geosynthetic Clay Liners

Correlating the hydraulic conductivity of GCLs with the free swell of bentonites is a common process. However, free swell tests is used for estimating the hydraulic conductivity behavior of GCLs against permeant liquids containing different concentrations of chemicals. Therefore, in many studies it is reported that the free swell of bentonites decreased and the hydraulic conductivity of GCLs increased when high concentrations of permeant liquids were used (Ashmawy et al., 2002; Jo et al., 2001; Katsumi et al., 2008; Kolstad et al, 2004; Lee et al. 2005; Shackelford et al., 2000; Shan & Lai, 2002). The similar trend also exist between hydraulic conductivity behavior of GCLs permeated with DIW and/or TW and the free swell of bentonites (Figure 5.6).

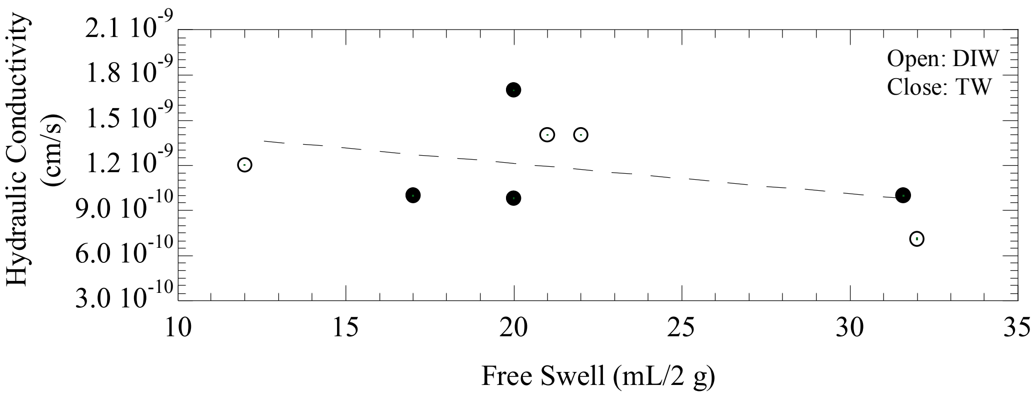

Figure 5.6 Relationship between the free swell and the hydraulic conductivity of GCLs

According to Figure 5.6, although the free swell values of bentonites differed from each other, the hydraulic conductivity behaviors of GCLs permeated with DIW and TW were determined almost the same. On the other hand, in bentonites having similar free swell values, different hydraulic conductivity behaviors were obtained. It is believed that the cause of this behavior proceeded from other factors affecting the hydraulic conductivity such as smectite content, particle size, void ratio, etc. of bentonites.

5.6 Relationship between Mineralogy of Bentonite and Hydraulic Conductivity of Geosynthetic Clay Liners

Smectite was a key component for the hydraulic conductivity behavior of GCLs. In general, barrier performance of GCLs increase with increase in smectite content. For instance, Ashmawy et al. (2002) have indicated that the hydraulic conductivity of GCLs permeated with water decreased from $\approx 1 \times 10^{-7}$ to $\approx 1 \times 10^{-8}$ cm/s when the smectite content in the bentonite increased from 49 to 91%, respectively (Figure 5.7). This behavior has also stated in the study researched by Lee & Shackelford, 2005 (Figure 5.7). As it could be seen from Figure 5.8, the greater the smectite content in the bentonite, the lower the hydraulic conductivity of the GCL.

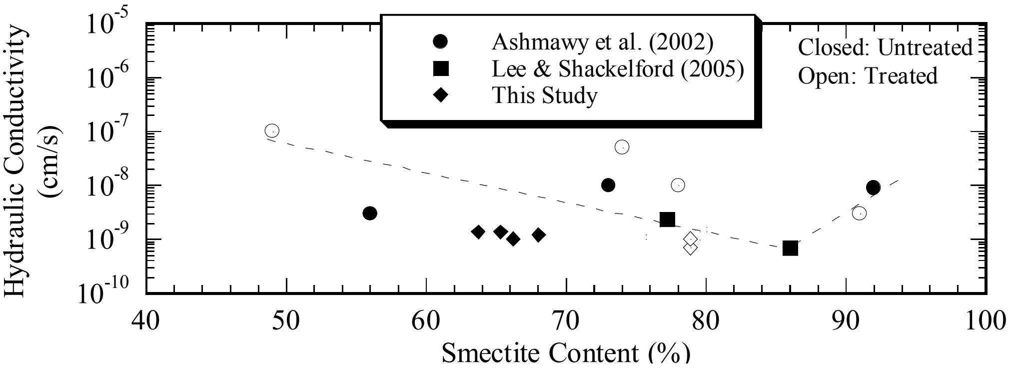

Figure 5.7 Relationship between smectite content and hydraulic conductivity of GCLs.

Additionally, Guyonnet et al. (2009) found that there was a correlation between smectite content and cation exchange capacity of bentonites. The results of the studies demonstrated that this correlation fell within the region shown with cutout dashes in their study (Figure 5.8). Figure 5.8 illustrated that cation exchange capacity was directly related with smectite content of bentonite and the results of this study were compatible with Guyonnet et al., (2009) and Kaufhold et al. (2009).

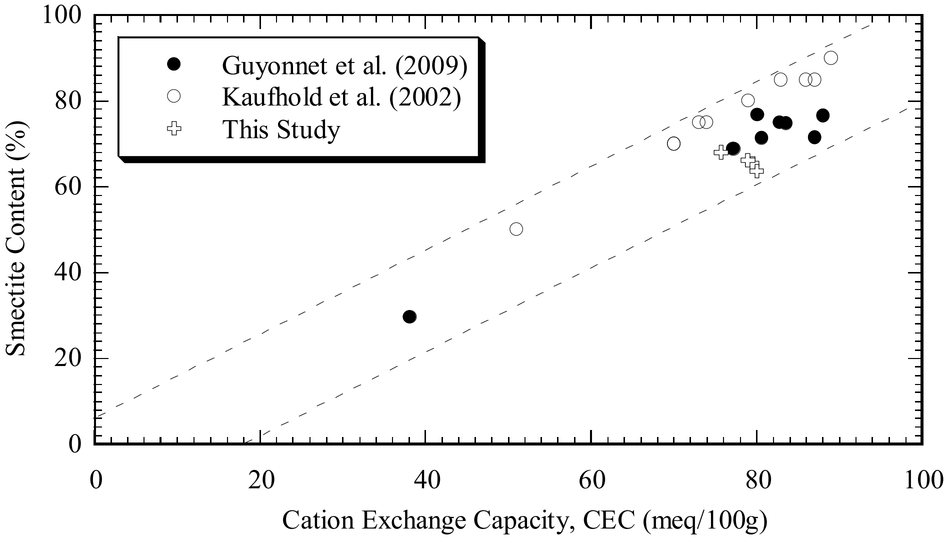

Figure 5.8 Relationship between smectite content and cation exchange capacity of bentonites.

5.7 Relationship between Chemical Properties of Bentonite and Hydraulic Conductivity of Geosynthetic Clay Liners

Addition to physical and mineralogical properties of bentonites such as particle size, smectite content, etc., the chemical properties of bentonites may affect the hydraulic conductivity of GCLs. The influence of specific surface area of bentonites are shown in Figure 5.9. According to this figure, the hydraulic conductivity of GCLs was inversely related to specific surface area of bentonites. In other words, the hydraulic conductivity decreases with increase of specific surface area of bentonite.

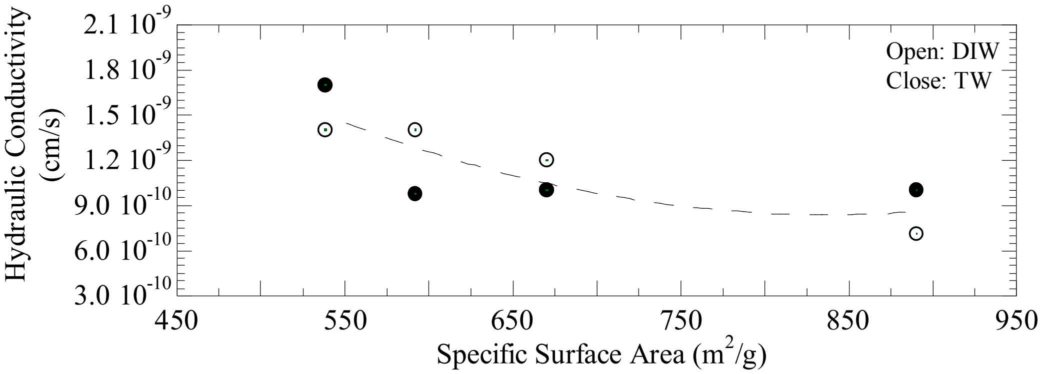

Figure 5.9 Hydraulic conductivity of GCLs versus specific surface area of bentonites.

Besides, the hydraulic conductivity of GCLs was affected by cation exchange capacity (CEC) of bentonites. Relation between the hydraulic conductivity and cation exchange capacity of bentonites is shown in Figure 5.10. According to this figure, the hydraulic conductivity decreased up to ≈79 meq/100 g of CEC, and then increased with increase of CEC.

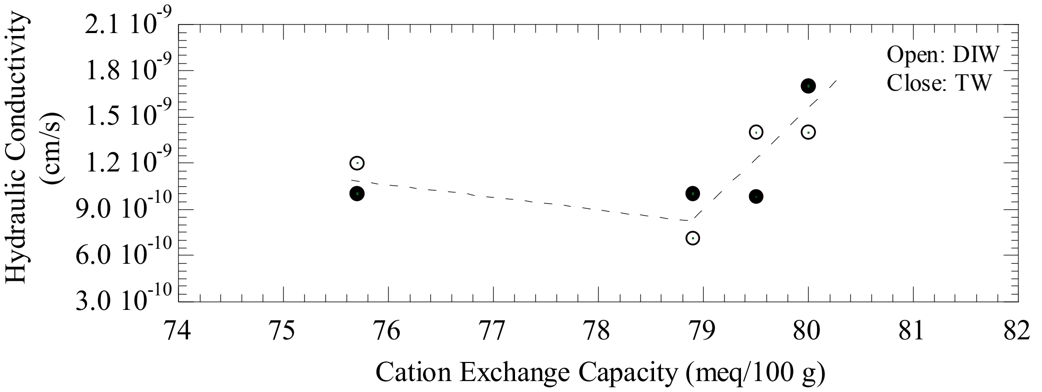

Figure 5.10 Hydraulic conductivity of GCLs vs cation exchange capacity of bentonites.

CHAPTER SIX

FREE SWELL AND THE HYDRAULIC CONDUCTIVITY OF GEOSYNTHETIC CLAY LINERS WITH LANDFILL LEACHATES

6.1 Background

Although the hydraulic conductivity of GCLs with DIW and/or TW is low, various researchers have shown that the hydraulic conductivity of GCLs can be affected by permeant solutions because of chemical interaction between permeant solutions and bentonites (Ashmawy et al., 2002; Benson et al., 2010; Jo et al., 2001; Jo et al., 2004; Jo et al., 2005; Katsumi et al., 2007; Katsumi et al., 2008; Kolstad et al., 2004; Petrov & Rowe, 1997; Ruhl & Daniel, 1997; Shackelford et al., 2000; Shan & Lai, 2002; Vasko et al., 2001). The results of these studies have demonstrated that the hydraulic conductivity and free swell of bentonite is sensitive to the concentration and ionic valence of cations.

Petrov & Rowe (1997) investigated the effect of permeant solution, static confining stress, hydrating medium and degree of bentonite hydration by using fixed ring apparatus. Tests were conducted with DIW, varying concentrations of NaCl solutions and synthetic municipal solid waste. The results of the study demonstrated that the hydraulic conductivity increased with an increase in the concentration of the permeant solution. On the other hand, if the concentration of permeant solution was less than 0.1 M, the hydraulic conductivity was negligibly changed when compared to DIW. They also revealed that prehydration had a great impact on the barrier performance of GCL when GCL was prehydrated with DIW prior to permeation. In that case, the hydraulic conductivity was obtained approximately 25 times lower than that obtained by direct permeation with NaCl solution. The results also showed that the hydraulic conductivity depends on three primary factors, which were void ratio of GCL, prehydration condition and the concentration of the permeant solution.

Ruhl & Daniel (1997) examined the influence of chemical solutions and leachates on the hydraulic conductivity of GCLs using five different types of GCLs, seven permeant solutions and three hydration conditions. Hydration conditions were prehydration, direct exposure to permeant solution and wetting with chemical solution or leachate. The results showed that the hydraulic conductivity of GCLs directly permeated with permeant solutions was 4 orders of magnitude higher than that of GCLs prehydrated with TW. In contrast, the hydraulic conductivity of prehydrated GCLs exhibited almost the same hydraulic behavior with GCLs permeated with water. One of the most significant results was that high concentrations of calcium in the permeant led to increase the hydraulic conductivity of GCLs. This is due to the replacement of calcium by sodium of bentonite. As a result of replacement, more compressed diffuse double layer occurs around the clay which increase the pore spaces available for liquid flow.

Jo et al. (2001) discussed the effect of single-species salt solutions in terms of concentration, cation valence, and pH on the swelling and hydraulic conductivity of non-prehydrated GCLs. They performed free swell and hydraulic conductivity tests by using various concentrations (0.01M-1.00M) of NaCl, KCl, LiCl, $CaCl_2$, $MgCl_2$, $ZnCl_2$, $CuCl_2$ and $LaCl_3$. They have reported that higher hydraulic conductivity and lower free swell values were obtained when concentration and cation valence of permeant solution were increased. They also claimed that the hydraulic conductivity was influenced by very low pH (<2) and high pH (>12), and thus, there is a strong relationship between free swell of bentonites and hydraulic conductivity of GCLs.

Ashmawy et al. (2002) performed the hydraulic conductivity tests using seven different GCLs, three of which is polymer treated, and three different landfill leachates. They have stated that the hydraulic conductivity of GCLs was affected by the prehydration condition, the chemical composition of permeants, etc. They have reported that although a steady-state condition was reached on prehydrated specimens, chemical equilibrium was not established on non-prehydrated specimens during the tests. They also showed that the concentration of the divalent cations such as Ca and/or Mg is one of the most important factors affecting the hydraulic conductivity of bentonite since these divalent cations increase the hydraulic conductivity due to cation exchange mechanism occurred between leachate and the bentonite.

Kolstad et al. (2004) examined the influence of multispecies inorganic solutions on swelling and hydraulic conductivity of non-prehydrated GCLs containing sodium bentonite. They also discussed the effect of prehydration condition. Moreover, the effect of ionic strength and relative abundance of monovalent and divalent cations (RMD) in the permeant solutions on the hydraulic conductivity of GCLs were investigated. They have found that the hydraulic conductivity was inversely related to free swell. Also, hydraulic conductivity was directly related to ionic strength and inversely related to RMD. In other words, hydraulic conductivity of GCL increased when ionic strength of the solution increased or RMD decreased. [RMD was defined as the following equation by Kolstad et al. (2004)].

$$RMD = \frac{M_M}{\sqrt{M_D}} \tag{6.1}$$

where M_M= total molarity of monovalent cations; M_D= total molarity of divalent cations in the solution.)

Jo et al. (2005) evaluated the impact of single species salt solutions (NaCl, KCl, $CaCl_2$) on the long term hydraulic conductivity of GCLs. Note that the hydraulic conductivity tests were lasted more than 2.5 years in their study. They reported that the hydraulic conductivity of GCLs to high concentrations of salt solutions (≥50 mM) was nearly 2 orders of magnitude greater than the hydraulic conductivity of GCLs to DIW. Although the hydraulic conductivity slightly changes with time because of cation exchange, they have stated that the hydraulic conductivities of GCLs were insensitive to concentration when concentration was less than 20 mM. On the other hand, they have found that when GCLs were permeated with strong divalent solutions ($CaCl_2 \geq 50$ mM), the hydraulic conductivity values were obtained roughly 3 order of magnitude higher (1.0×10^{-6} cm/s) than the hydraulic conductivity of GCLs permeated with DIW.

Katsumi et al. (2007) conducted free swell and long term hydraulic conductivity tests with inorganic chemical solutions (single-species and multi-species) and landfill leachates for 3 years in order to investigate the influence of electrolytic solutions on the barrier performance of GCLs. The results of this study have shown that GCL exhibited an excellent barrier performance if free swell of bentonite contained in GCL was greater than 15 mL/2 g. They have also claimed that the effect of the electrolytic solution on the hydraulic conductivity of GCL depends on the ionic strength of the solution. In addition, the sensitivity of the ionic strength to the hydraulic conductivity was determined to be independent on the type of cation. They also hold that the hydraulic conductivity for the single-species or multi-species solution which contained only monovalent cation was greater than that for multi-species solution containing the divalent cation for the same ionic strength.

Benson et al. (2010) conducted the hydraulic conductivity tests on two GCLs, one of which was treated with an additive in order to provide protection from chemical interactions, by using DIW and two salts solutions as permeant solutions. The results of this study have illustrated that the change in hydraulic conductivity is attributed to the change in osmotic swelling in the interlayer because of the chemical properties of permeant solutions.

6.2 Free Swell of Bentonite

The comparison of the free swell test results conducted using DIW, TW and landfill leachates are presented in Table 6.1. It can also be seen from Figure 6.1 that free swell values with landfill leachates were remarkably lower than those with DIW or TW. The free swell values with LL-1 and LL-2, which were independent of GCL type, clustered in 4.0-6.0 mL/2g (Figure 6.1). On the other hand, free swell values with LL-3 were obtained relatively higher than the others (6.0-8.0 mL/2g) (Table 6.1).

Table 6.1 Free swell of bentonites with DIW, TW and landfill leachates

Bentonite Type	**Free Swell (mL/2g)**				
	DIW	**TW**	**LL-1**	**LL-2**	**LL-3**
GCL-1	12	17	6	5	6
GCL-2	22	20	5	4	7
GCL-3	21	20	4	5	8
GCL-4	32	31.6	4	5	8

The low free swell values of bentonites could be attributed to chemical contents of landfill leachates. The chemical contents of the landfill leachates collapse diffuse double layer and thus, low free swell values could be obtained. It can be asserted that the chemical contents (Al^{+++}, Ca^{++}, Mg^{++}) of landfill leachates have a noticeable impact on the free swell of the bentonites.

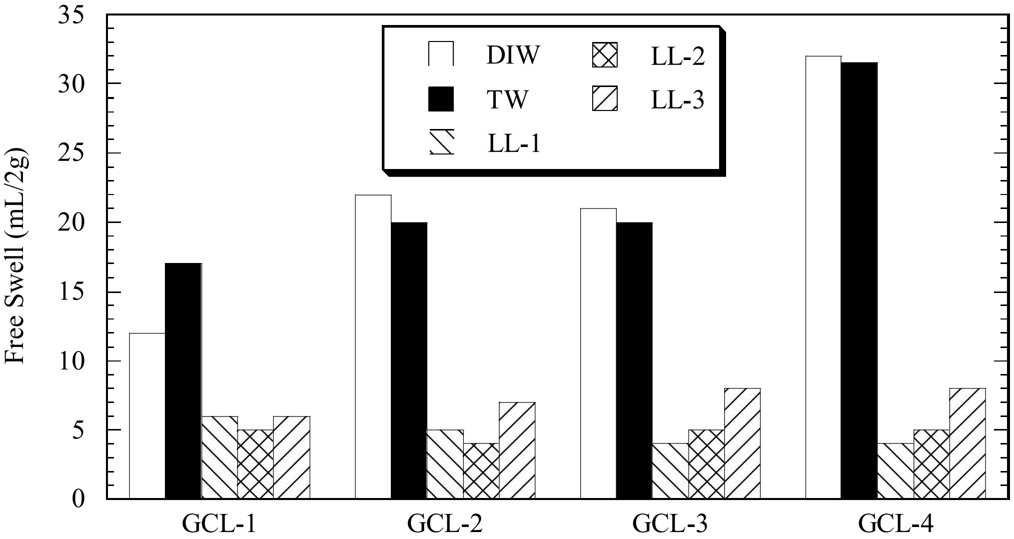

Figure 6.1 The comparison of the free swell of bentonites with DIW, TW and landfill leachates

6.3 Hydraulic Conductivity of Non-prehydrated Geosynthetic Clay Liners with Landfill Leachates

Hydraulic conductivity tests were conducted with two GCL hydration conditions. In the first set of the tests, no prehydration was applied and the GCLs were directly exposed to landfill leachates. That is, GCLs were prehydrated neither DIW nor TW before permeation (i.e. non-prehydrated condition). GCL-2 with LL-1 and GCL-4 with LL-1 were performed in this manner (two tests). In the second set of experiments, the GCLs were prehdrated for 48h and then permeated with DIW about one PVF. Then, the influent valves of permeaters were switched from DIW to landfill leachate and the permeation was continued with the landfill leachates until the end of experiments (i.e. prehydrated condition) (14 tests).

GCL-2 and GCL-4 was directly exposed to the landfill leachates and the results of the hydraulic conductivity tests are shown in Figure 6.2. As the flow was too fast, tests were lasted at 12 and 32 PVFs. In this figure, the open markers indicate the volumetric flow ratio (Q_{out}/Q_{in}) and the closed markers depict the hydraulic conductivities. The hydraulic conductivity of GCL-2 was obtained as around $\approx 10^{-6}$cm/s, the hydraulic conductivity of GCL-4 was determined as $\approx 10^{-5}$cm/s. The hydraulic conductivity behaviors of both GCLs were observed to maintain stable condition (Figure 6.2a-b).

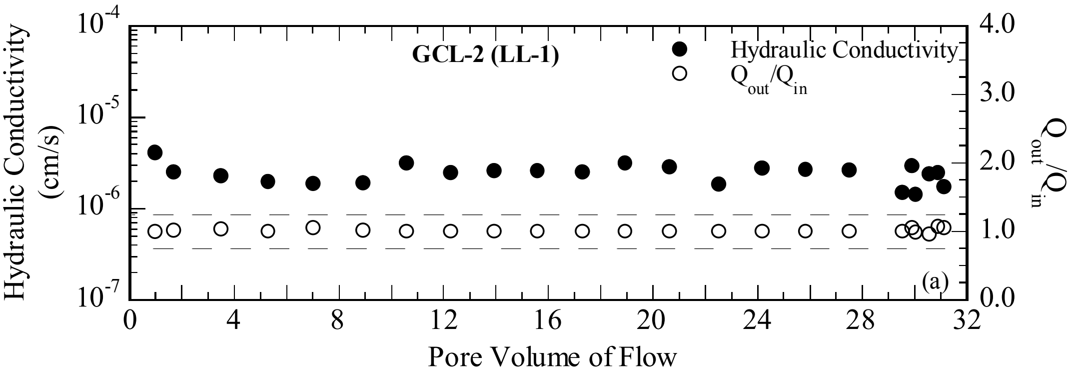

Figure 6.2 The results of hydraulic conductivity tests of non-prehydrated geosynthetic clay liners using landfill leachate-1 (LL-1) as permeant liquid a) Geosynthetic Clay Liner-2 (GCL-2)

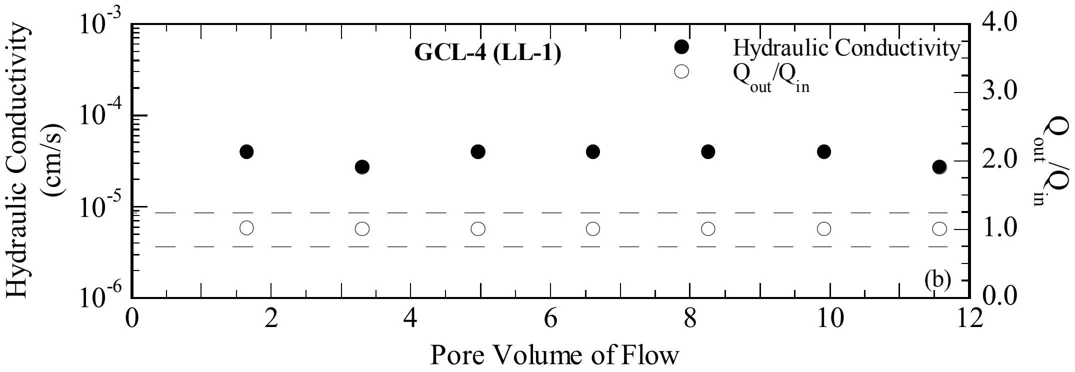

Figure 6.2 The results of hydraulic conductivity tests of non-prehydrated geosynthetic clay liners using landfill leachate-1 (LL-1) as permeant liquid. b) Geosynthetic Clay Liner-4 (GCL-4) (Continue)

The high hydraulic conductivities ($\approx 10^{-5}$cm/s) were attributed to prehydration condition. When GCLs are exposed to landfill leachates directly (non-prehydrated GCLs), cation exchange could occur and the chemical content of bentonite may change. The expansion (i.e. swelling) of bentonite, which provides GCLs low hydraulic conductivity, is also affected by this change. The swelling of bentonite has two stages: i) crystalline swelling and ii) osmotic swelling. Crystalline swelling is the initial swelling of bentonite particles when faced with water. Only four layers of water can be held between the interlayer of bentonite. Following the crystalline swelling, osmotic swelling occurs which means more layers of water can be held in the interlayer of bentonite particles. Osmotic swelling is the reason of low hydraulic conductivity for GCLs. For the solutions containing monovalent cations, crystalline swelling and osmotic swelling can be seen together. However, solutions with divalent cations, only crystalline swelling occurs which result in limited swell and thus, greater hydraulic conductivity for GCLs. Therefore, the hydraulic conductivity of non-prehydrated GCLs increased due to absence of osmotic swelling, which only appears in bentonites containing monovalent cations (Jo et al., 2001).

It can also be seen that free swell results confirm the hydraulic conductivity results of the non-prehydrated GCLs. That is, the free swell of bentonite with LL-1 is around 5 ml/2g for GCL-2 and GCL-4. These values are considerably less than the free swell values obtained with DIW or TW. In addition, hydraulic conductivity of these GCLs with LL-1 were significantly greater than the hydraulic conductivities to

DIW. In other words, the low free swell values can be thought as an indicator for the high hydraulic conductivities.

6.4 Hydraulic Conductivity of Prehydrated Geosynthetic Clay Liners with Landfill Leachates

GCLs were hydrated with DIW for 48 hours before the permeation. After prehydration, the exit valves were opened and permeation process was started with DIW. Permeation with DIW was sustained until approximately 1 PVF or more. After that, DIW was removed from all the valves and permeation with landfill leachates was started. The tests were generally lasted 5-9 months.

6.4.1 Landfill Leachate-1

The hydraulic conductivity behaviors of prehydrated GCLs with LL-1 are illustrated in Figure 6.3. Since bentonite particles in GCL-1 were granular, the hydraulic conductivity was obtained too high at the beginning of the test (Figure 6.3a). However, after 11 PVF, the hydraulic conductivity was kept to be stable to the end of the test. The final hydraulic conductivity for GCL-1 was obtained as 6.3×10^{-10}cm/s. In addition, after 1.5 PVF, the hydraulic conductivity of GCL-2 achieved almost stable condition. Although some discontinuities were observed in the hydraulic conductivity behavior, the hydraulic conductivity was determined roughly 10^{-10}cm/s (Figure 6.3b). Similarly, GCL-3 was permeated with DIW up to $\approx$2 PVF, and then test was permeated with landfill leachate. In this test GCL-3 also maintained to be stable from the beginning to the end of the test (Figure 6.3c). The final hydraulic conductivity value of GCL-3 was obtained as 5.9×10^{-10}cm/s.

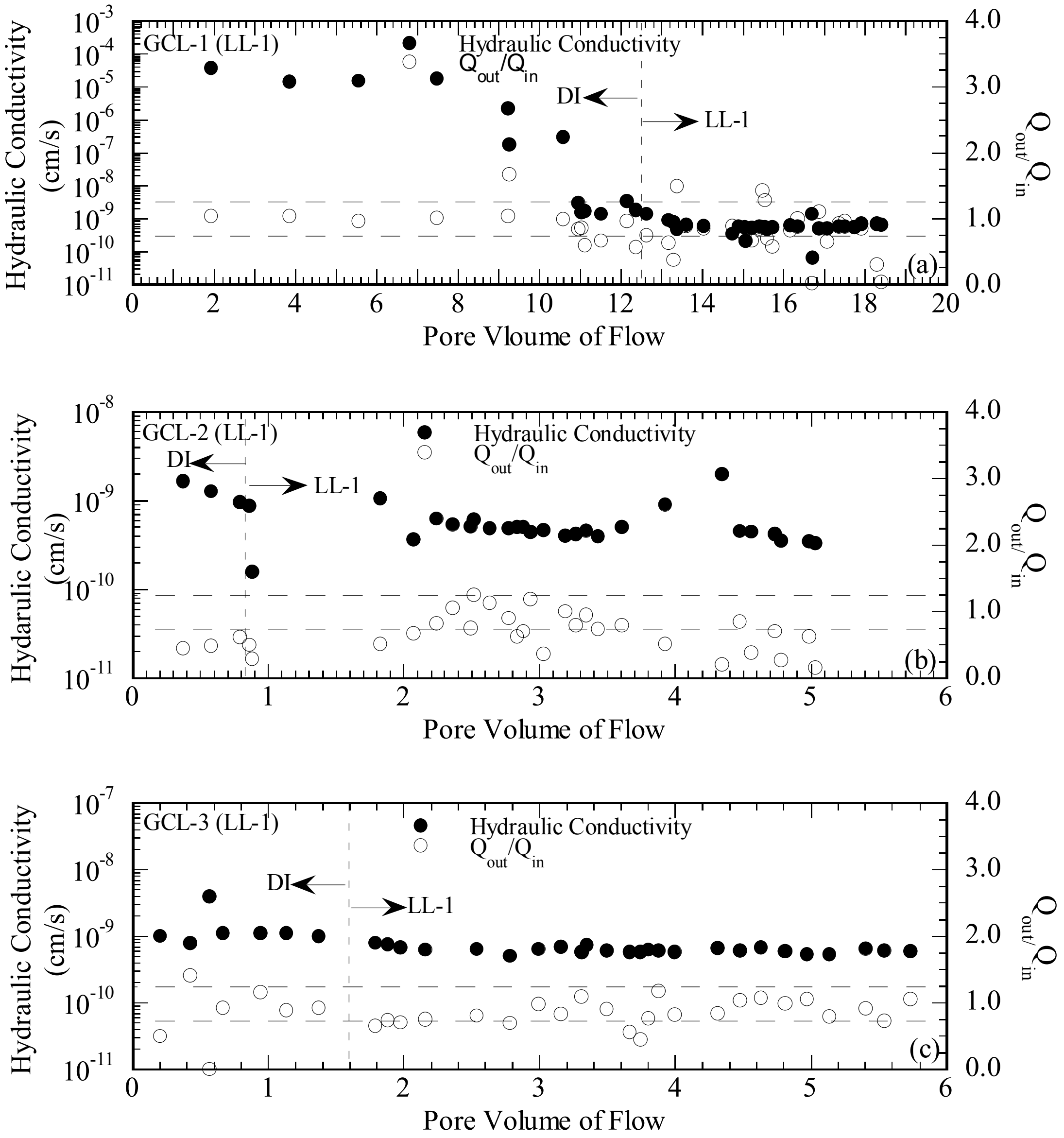

Figure 6.3 The results of hydraulic conductivity tests of prehydrated geosynthetic clay liners using landfill leachate-1 (LL-1) as permeant liquid: a) Geosynthetic Clay Liner-1 (GCL-1), b) Geosynthetic Clay Liner-2 (GCL-2), c) Geosynthetic Clay Liner-3 (GCL-3).

6.4.2 Landfill Leachate-2

The results of the hydraulic conductivity tests for non-prehydrated GCLs permeated with LL-2 are depicted in Figure 6.4.

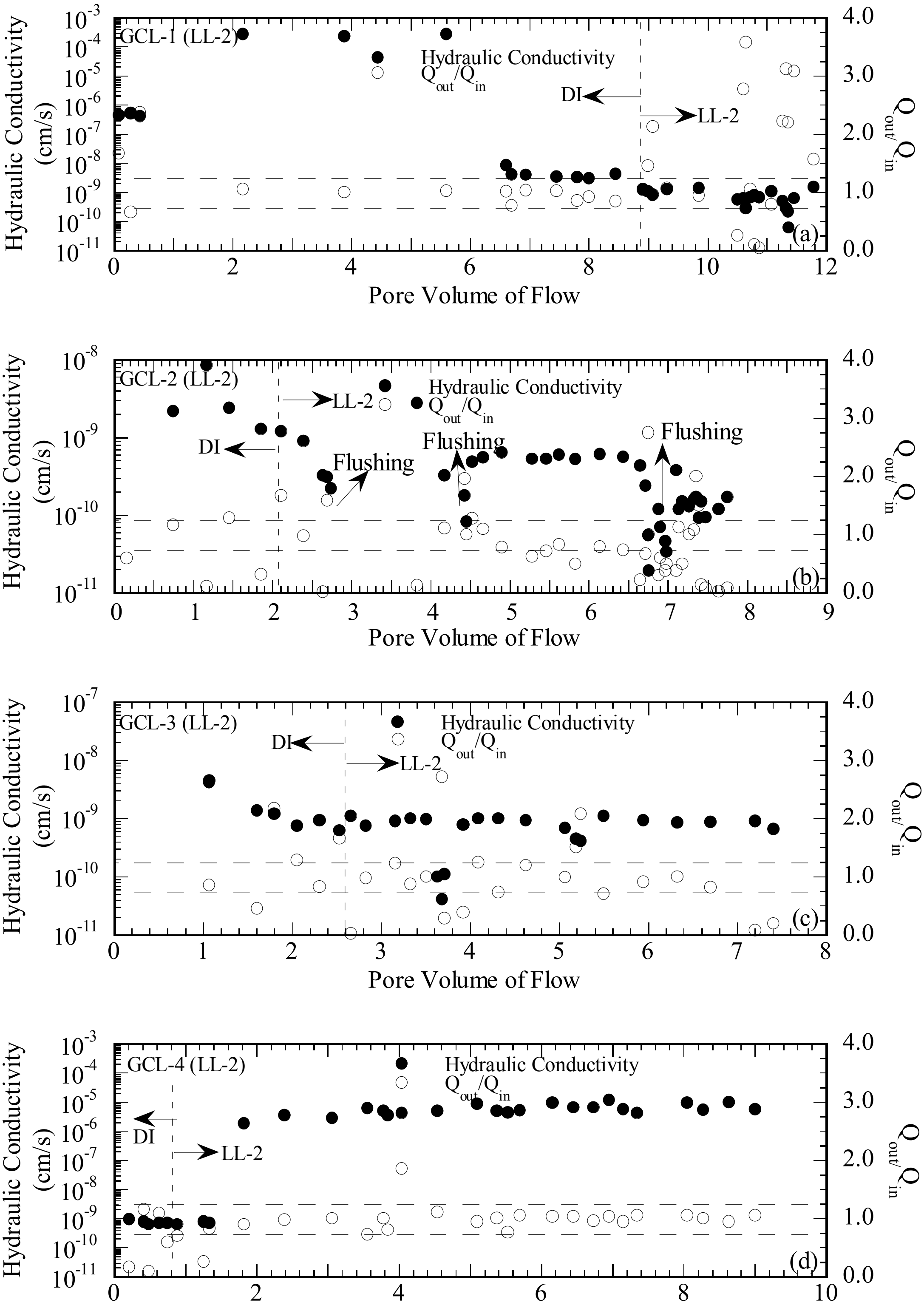

Figure 6.4 The results of hydraulic conductivity tests of prehydrated geosynthetic clayliners using landfill leachate-2 (LL-2) as permeant liquid: a) Geosynthetic Clay Liner-1 (GCL-1), b) Geosynthetic Clay Liner-2 (GCL-2), c) Geosynthetic Clay Liner-3 (GCL-3), d) Geosynthetic Clay Liner-4 (GCL-4).

As it can be seen from Figure 6.4 that although the hydraulic conductivity values were high until 6.5 PVF, the hydraulic conductivity decreased nearly 4 orders of magnitude during DIW permeation. Then, the permeant solution was switched to LL-2 at 9 PVF. The LL-2 permeation had no significant effect on the hydraulic conductivity of prehydrated GCL-1 and it was obtained as 5.9×10^{-10}cm/s at the end of the test. GCL-2 was permeated with DIW up to 2 PVF. GCL-2 had some discontinuity due to gases occurred in the hoses. This led to reduce the hydraulic conductivity rapidly. In order to maintain the flow, the hoses were flushed (Figure 6.4 b). GCL-3 kept steady state from the beginning to the end of the test. It is interesting to note that although GCL-4 exhibited low hydraulic conductivity at the beginning of the test, the hydraulic conductivity increased about 3 orders of magnitude and maintained this value to the end of the test. The final hydraulic conductivities for GCL-3 and GCL-4 were obtained as 6.7×10^{-10}cm/s and 5.6×10^{-6}cm/s, respectively.

6.4.3 Landfill Leachate-3

The results of the hydraulic conductivity tests for non-prehydrated GCLs permeated with LL-3 are shown in Figure 6.5. If the general behavior was considered for GCL-1 and GCL-2, the hydraulic conductivity was obtained as around 1×10^{-9}-1×10^{-10}cm/s (Figure 6.5a-b). No considerable change in the hydraulic conductivity occurred for GCL-3 during the test and the final hydraulic conductivity was determined as 4.6×10^{-10}cm/s (Figure 6.5c). For GCL-4 the hydraulic conductivity increased 1 order of magnitude when DIW was switched to permeant solution (LL-3) at 1.7 PVF and then, the hydraulic conductivity decreased gradually to 1×10^{-9}cm/s (Figure 6.5d).

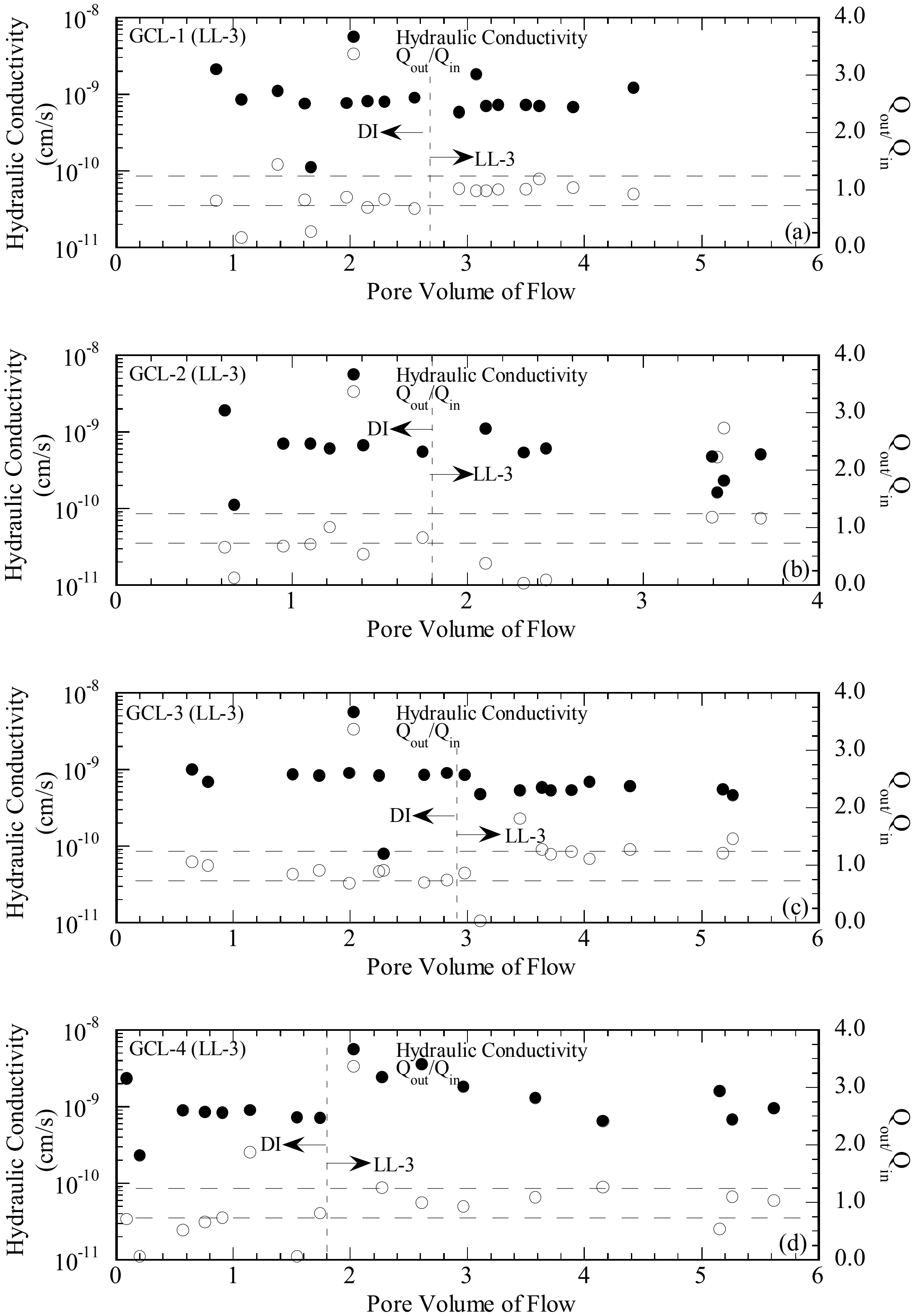

Figure 6.5 The results of hydraulic conductivity tests of prehydrated geosynthetic clayliners using landfill leachate-3 (LL-3) as permeant liquid: a) Geosynthetic Clay Liner-1 (GCL-1), b) Geosynthetic Clay Liner-2 (GCL-2), c) Geosynthetic Clay Liner-3 (GCL-3), d) Geosynthetic Clay Liner-4 (GCL-4).

In this study, however, the negative influence of landfill leachate on the prehydrated GCLs was not seen. That is, GCLs preserved their low hydraulic conductivities even at landfill leachate permeation. If the general hydraulic behavior of prehydrated GCLs was considered, it can be realized that decrease of the hydraulic conductivity can be attributed prehydration condition. In the case of prehydration of GCLs with DIW prior to landfill leachates, both expansion (i.e., osmotic and crystalline swelling) occur. Expansion, especially osmotic swelling, causes to lower the pore sizes for mobile water flow and postpone the collapse of diffuse double layer surrounding the bentonite. This leads to decrease in the hydraulic conductivity of GCLs.

On the other hand, since only crystalline swelling appears in non-prehydrated GCLs, the hydraulic conductivity of non-prehydrated GCLs is generally high due to lack of osmotic swelling.

6.5 Long Term Hydraulic Conductivity of non-prehydrated Geosynthetic Clay Liner-4

The hydraulic conductivity tests for GCL-4 were maintained for 1-1.5 year in order to investigate long term hydraulic behavior of GCL. GCL-4 was preferred to conduct the long term hydraulic conductivity tests as it exhibited the best barrier performance when permeated with DIW and TW. No change in the hydraulic conductivity for GCL-4 with LL-1 occurred and the hydraulic conductivity was obtained as $\approx 10^{-10}$cm/s (Figure 6.6a). Although the hydraulic conductivity with LL-2 was high at the beginning of the test, it decreased 4 orders of magnitude at 2 PVF and this value was maintained until the end of the test (Figure 6.6b). Hydraulic conductivity test for GCL-4 with LL-3 kept the steady state if discontinuities at some points were ignored. At these points the hoses were flushed and the tests were continued (Figure 6.6c). The final hydraulic conductivity for GCL-4 with LL-3 was determined as 2.7×10^{-10}cm/s.

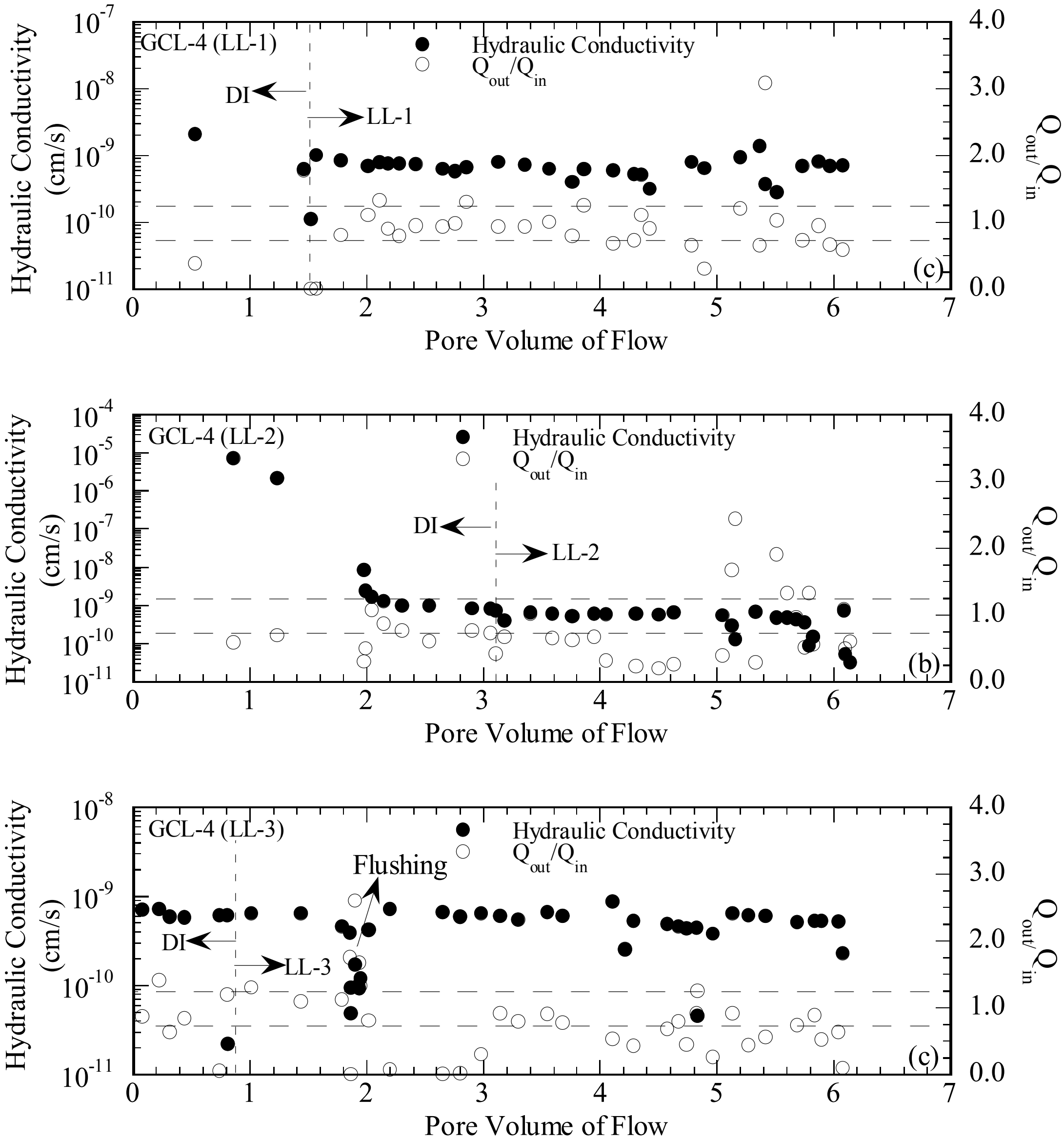

Figure 6.6 The results of long term hydraulic conductivity tests of prehydrated geosynthetic clay liner-4 (GCL-4) using landfill leachates (LLs) as permeant liquid: a) Landfill Leachate-1 (LL-1), b) Landfill Leachate -2 (LL-2), c) Landfill Leachate -3 (LL-3).

The comparison of the long term and the short term hydraulic conductivity results are shown in Figure 6.7. It is interesting to report that the results of the short term and the long term hydraulic conductivity tests with LL-2 were obtained adversely. The long term hydraulic conductivity was higher than expected at the beginning of the test and it decreased around 5 orders of magnitude at 2 PVF, and then was remained approximately 10^{-10}cm/s to the end of the test. Conversely, the short term hydraulic conductivity was obtained as $\approx 10^{-10}$cm/s at the beginning of the test and then, increased to $\approx 5.5 \times 10^{-10}$cm/s at 2 PVF, and was remained approximately 10^{-6}cm/s to the end of the test (Figure 6.6a). The reason that enables this difference between the short term and the long term hydraulic conductivities is not known.

The results of the short term and the long term hydraulic conductivity tests with LL-2 were just as the same within each other. This was an expected behavior. The both hydraulic conductivities decreased roughly 1 order of magnitude at ≈2 PVF and then increased to $\approx 7.5 \times 10^{-10}$cm/s and were remained this value to the end of the tests (Figure 6.6b).

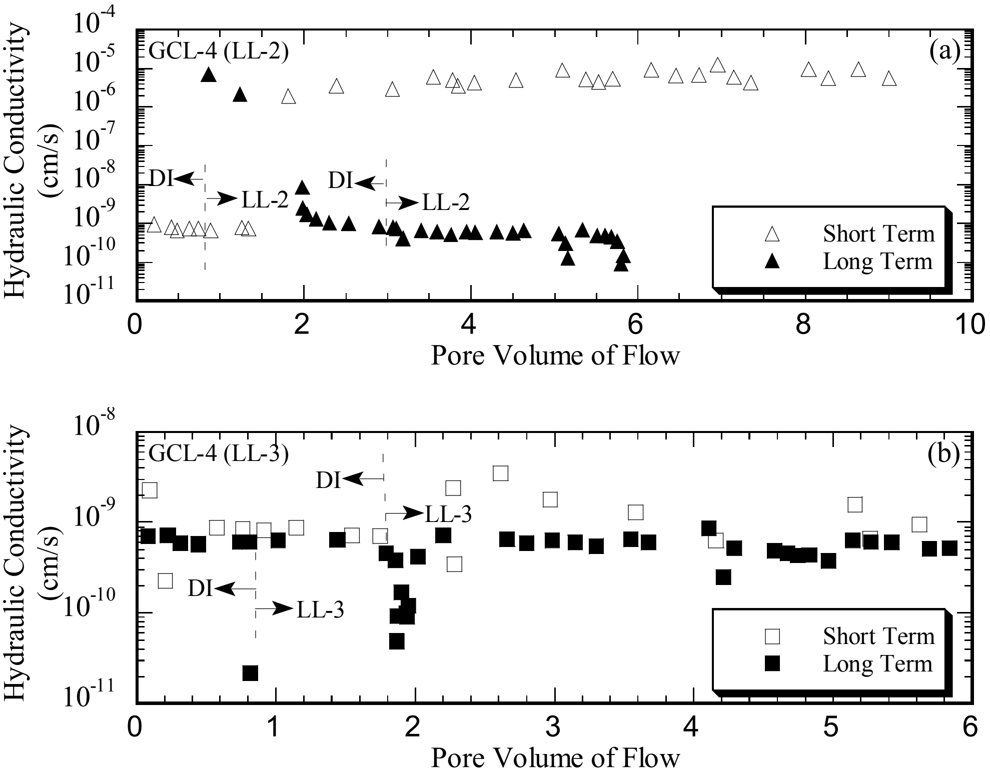

Figure 6.7 The comparison of the short term and the long term hydraulic conductivity

The hydraulic conductivity tests should be maintained long durations in order to evaluate the influence of cation exchange and osmotic swelling. Over time, osmotic swelling can decrease and diffuse double layer may be affected by landfill leachates. As aforementioned, this process can take long time (or years). Since this study was terminated in 1-1.5 year, the increase in the hydraulic conductivity of non-prehydrated GCLs was not seen along the test duration.

CHAPTER SEVEN

POST-TEST EVALUATION ON GEOSYNTHETIC CLAY LINERS WHEN PERMEATED WITH LANDFILL LEACHATES

7.1 Background

To understand the impact of leachates on the hydraulic conductivity of prehydrated GCLs, the physico-chemical properties of bentonite were investigated in terms of free swell and final water content of GCL. The previous studies reported only limited posttest properties of bentonite of which were permeated with synthetic or real leachates (Jo et al., 2001; Kolstad et al., 2004; Benson et al., 2010). In these studies, the post changes in the free swell behavior of bentonite has been well documented (Jo et al, 2001; Kolstad et al., 2004). Moreover, various researchers have examined the chemical interaction between leachates and the bentonites in terms of exchangeable cations (Jo et al., 2005; Kolstad et al., 2004; Shackelford et al., 2000). Now, it is well known that the sodium cations in GCLs replace with the divalent cations in the leachate (Mg^{++}, Ca^{++}). The exchange process generally changes the swelling of bentonites and the hydraulic conductivity of GCLs (Jo et al., 2001, 2004, 2005; Guyonnet et al., 2005, 2009; Kolstad et al., 2004; Petrov & Rowe, 1997; Shackelford et al, 2000).

Gleason et al. (1997) performed hydraulic conductivity tests on Na-bentonite and Ca-bentonite. They used the city of Austin, Texas tap water and 0.25 M $CaCl_2$ as the permeant solutions. They indicated that the hydraulic conductivity of Ca-bentonite was higher than the hydraulic conductivity of Na-bentonite. They concluded that the calcium ions in the permeant solution gradually replace with the sodium of bentonite.

Jo et al. (2005) reported that the time needs for the full replacement of monovalent to divalent cations are dependent on the concentrations of salt solution. That is, if the concentration of salt solution is greater than 50 mM, then the replacement will be fast; whereas if the concentration of salt solution is low (i.e. < 20 mM) it will take long time for whole replacement of monovalent cations to divalent cations. They conducted hydraulic conductivity tests on non-prehydrated GCLs using single species salt solutions (i.e., NaCl, KCl, $CaCl_2$, and deionized water) and also showed that Na^+ cations in the bentonite were totally replaced by the cations in the permeant solution. They concluded that the full replacement of K^+ to Ca^{++} was three years; whereas Na^+ to Ca^{++} was two years.

Eggloffstein (2001) performed hydraulic conductivity tests on two prehydrated GCLs. Eggloffstein (2001) claimed that no change in hydraulic conductivity was observed during one year of the tests. After one year, the hydraulic conductivities of both GCLs increased by one order of magnitude and were maintained at steady conditions to the end of the test. Eggloffstein concluded that the increase in the hydraulic conductivity could be attributed to ion exchange.

Kolstad et al. (2004) investigated the influence of multispecies inorganic solutions on hydraulic conductivity of non-prehydrated GCLs containing sodium bentonite. The results of that study revealed that the hydraulic conductivity of GCLs are directly related to the ionic strength and inversely related to relative abundance of monovalent and divalent cations (RMD) depending on the cation valence in the permeant solutions.

Bradshaw & Benson (2014) performed hydraulic conductivity tests of GCL using DIW, synthetic municipal solid waste (MSW), and real MSW leachate. They stated that the cation exchange has a vital impact on the hydraulic conductivity of GCLs. They also claimed that at least 80% of Na^+ cations in bentonite replaced by Ca^{++} and Mg^{++} in leachates which required long time (at $\approx$30-50 PVF).

7.3 Physical Changes Observed on Geosynthetic Clay Liners

As physical changes such as GCL height and water content affect the hydraulic conductivity of GCLs, determining these changes is curious for evaluating the hydraulic behavior of GCLs. For this reason, GCL heights and water contents were measured before and after the tests and are presented in Table 7.2. Although the final water contents of the specimens permeated with DIW and TW were ranged from 90% to 268%, the final water contents of the specimens permeated with landfill leachates were ranged from 58% to 131% (Figure 7.1). For both permeant solution types the highest final water contents were obtained on GCL-4 because of polymer treatment of bentonite and the lowest final water contents were obtained on GCL-1 or GCL-2. On the other hand, the final water content of non-prehydrated GCLs were obtained lower than prehydrated GCLs. This result also showed that the swell amount of GCLs depend upon permeation. Figure 7.2 shows that the hydraulic conductivity values of non-prehydrated GCLs were lower than values of prehydrated GCLs because of prehydration condition. Besides, the final non-prehydrated GCL heights were found a little bit lower than prehydrated GCLs, as well. This may be attributed to the chemical interaction between bentonite and leachate. Since diffuse double layer surrounding the bentonite particle tend to decrease when exposed to leachate, the thickness of GCL tend to decrease as well.

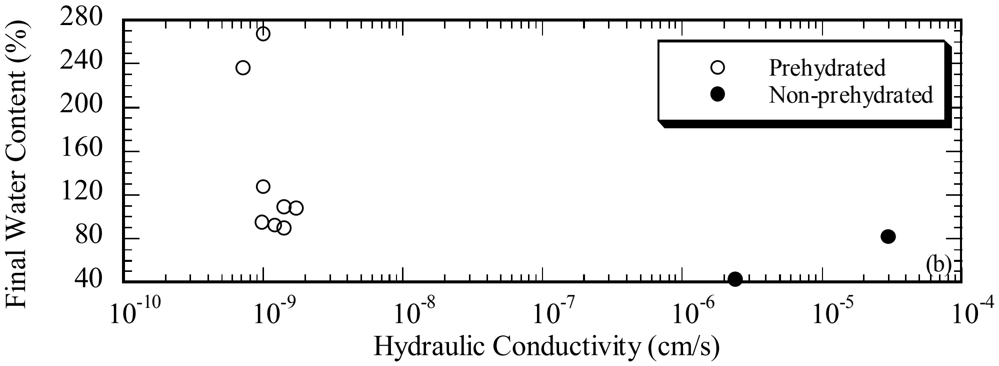

Figure 7.1 The final water content of GCLs vs the final hydraulic conductivity

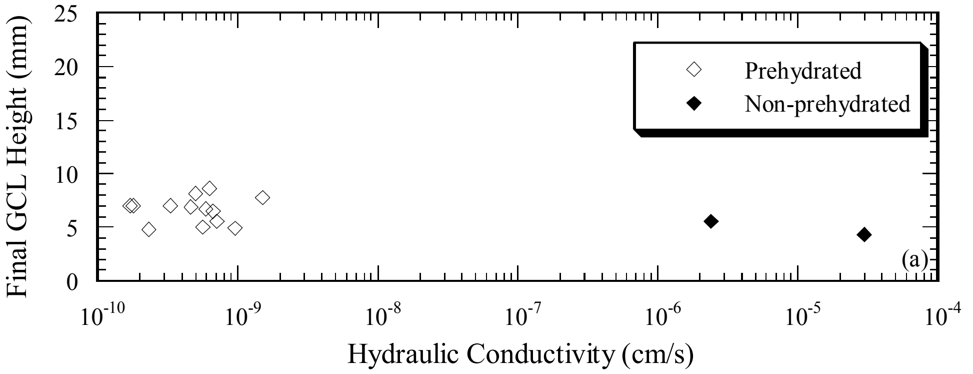

Figure 7.2 The final GCLs heights vs the final hydraulic conductivity

Table 7.1 Post-test changes of GCL height and water content

Test No	**GCL Type**	**Permeant Solution**	**GCL Height (cm)**		**Water Content (%)**	
			H_i	**H_f**	**w_i**	**w_f**
1	GCL-1	DIW	0.58	0.82	11	92
2	GCL-2	DIW	0.52	0.63	22	90
3	GCL-3	DIW	0.5	0.69	18	109
4	GCL-4	DIW	0.41	0.76	11	236
5	GCL-1	TW	0.6	0.79	11	128
6	GCL-2	TW	0.58	0.77	22	95
7	GCL-3	TW	0.51	0.65	18	108
8	GCL-4	TW	0.42	0.75	11	268
9	GCL-1	DIW/LL-1	0.8	0.86	11	77
10	GCL-2	DIW/LL-1	0.65	0.7	22	62
11	GCL-3	DIW/LL-1	0.62	0.67	18	83
12	GCL-1	DIW/LL-2	0.76	0.78	11	71
13	GCL-2	DIW/LL-2	0.67	0.7	22	58
14	GCL-3	DIW/LL-2	0.64	0.65	18	70
15	GCL-4	DIW/LL-2	0.49	0.5	11	72
16	GCL-1	DIW/LL-3	0.68	0.7	11	80
17	GCL-2	DIW/LL-3	0.77	0.81	22	62
18	GCL-3	DIW/LL-3	0.68	0.69	18	82
19	GCL-4	DIW/LL-3	0.46	0.49	11	113
20	GCL-4_LT	DIW/LL-1	0.48	0.55	11	131
21	GCL-4_LT	DIW/LL-2	0.5	0.55	11	118
22	GCL-4_LT	DIW/LL-3	0.43	0.48	11	113
23	GCL-2	LL-1	0.65	0.55	12	43
24	GCL-4	LL-1	0.45	0.43	11	82

The general views of some GCLs after the hydraulic conductivity test with landfill leachates are shown in Figure 7.3.

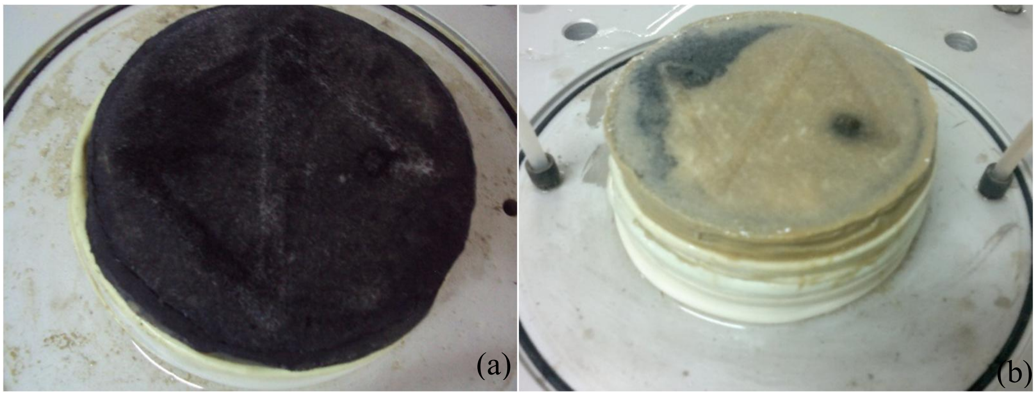

Figure 7.3 Post test changes on GCLs. a) GCL-3 with LL-2, b) GCL-2 with LL-2 LL-3.

In some specimens some bacterial formations occurred (Figure 7.4). In this specimens, microorganisms could have tended to plug the pores of bentonite, and therefore the hydraulic conductivity could be lower.

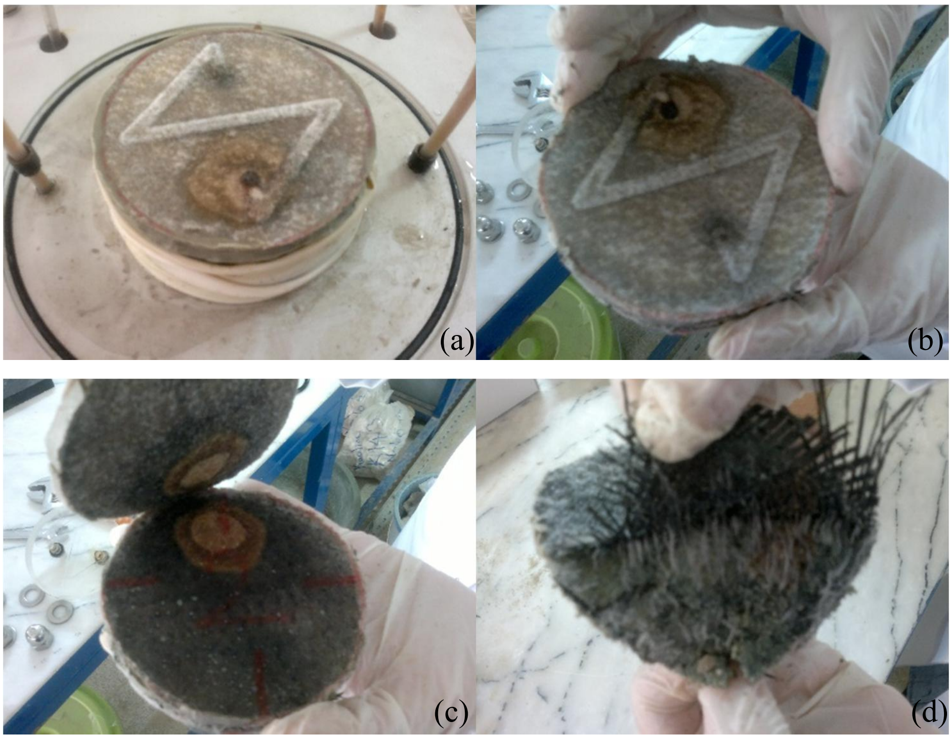

Figure 7.4 Post test changes on GCL-4 permeated with LL-3, a), b) General view of post test, c) Removing nonwoven geotextiles from GCL, d) Post test changes on bentonite

7.4 Changes in Free Swell of Bentonite with Landfill Leachate

Several researchers have shown that if the free swell of bentonite is high enough (≥ 15 mL/2g), GCL has a great barrier performance (Jo et al., 2001; Katsumi et al. 2007). Figure 7.5 demonstrates the changes in free swell of bentonites for different hydration conditions. If the free swell of bentonites with DIW were compared with those with landfill leachates, a considerable decrease can be seen easily. Landfill leachates were not allowed bentonites to swell thanks to chemical content of permeant solutions, thus the free swell values were obtained quite low. On the other hand, when GCLs were hydrated with DIW prior to the permeation with landfill leachates, the free swell values of bentonite was similar to free swell values with DIW even at the end of one year of landfill leachate permeation.

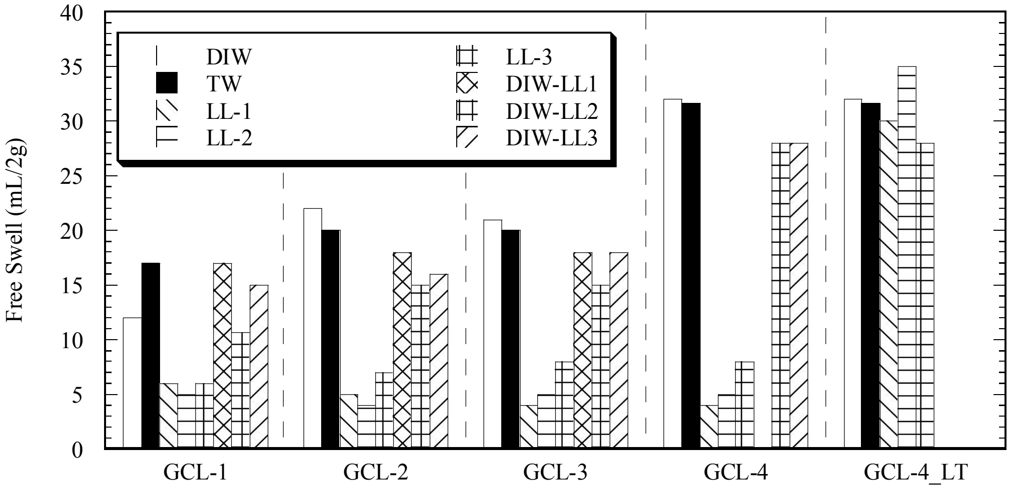

Figure 7.5 Free swell and hydraulic conductivity values of GCLs with landfill leachates

CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

This study presents the hydraulic conductivity results of GCLs. Four different GCLs- one of which were polymer treated- and three landfill leachates were used in the tests. DIW and/or TW were the reference permeant solutions. The short term and the long term tests were lasted in 4-6 months and 1-1.5 years, respectively. In addition, the effect of polymer treated GCL and prehydration condition, and the correlation of the hydraulic conductivity of GCLs with physico-chemical properties of bentonites are discussed.

The conclusions based on the results obtained in this study can be given as follows:

- Although the free swell values of bentonite were ranged from 12 to 32 mL/2 g with DIW and TW, the hydraulic conductivities with these reference liquids were approximately $\approx 10^{-9}$ cm/s which is compatible for the results of previous studies reported in the literature.

- The lowest hydraulic conductivities to DIW and TW was achieved for GCL-4 which was polymer treated ($\approx 10^{-11}$ cm/s).

- The interrelationships between the hydraulic conductivity of GCLs to DIW and TW and some phsico-chemical properties of bentonites were investigated. The physical relationships are listed below:

  - ✓ The hydraulic conductivities of GCLs increased with increase of the final void ratios of bentonites.

  - ✓ The hydraulic conductivity of the GCLs increased up to liquid limit of 400, thereafter the hydraulic conductivity decreased with the liquid limit.

- ✓ In contrast, the effect of smectite content on the hydraulic conductivity was found negligibly.

The chemical relationships obtained herein are as in the following:

- ✓ The hydraulic conductivity decreased with increase of specific surface area and decrease of cation exchange capacity.

- The free swell of bentonites in landfill leachates were remarkably lower than those in DIW or TW. The reason of this behavior was considered to proceed from chemical interactions between bentonites and landfill leachates. In other words, landfill leachates did not allow bentonites to swell. In contrast, the free swell tests were conducted on the bentonites of prehydrated GCLs that were permeated with DIW/LL. Then, the free swells of these bentonites were determined in DIW. The results showed that the free swell of bentonites prehydrated but permeated with landfill leachates are compatible with the free swell of bentonites in DIW and TW.

- The prehydration condition has a deep impact on the hydraulic conductivity of GCLs. The hydraulic conductivity of non-prehydrated GCLs permeated with landfill leachates were 3 orders of magnitude greater than those permeated with DIW or TW due to chemical interaction. This conclusion is consistent with the free swell test results. On the other hand, the hydraulic conductivity of prehydrated GCLs were low ($\approx 10^{-9}$ cm/s) even they were permeated with landfill leachates.When the specimens exposed to DIW prior to landfill leachates, bentonites swelled and less pores were available for the movement of mobile water. Hence, the hydraulic conductivity decreased, even if GCLs subsequently exposed to landfill leachates.

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APPENDIX A

THE STEPS OF SAMPLE PREPARATION FOR HYDRAULIC CONDUCTIVITY TEST

1) Cut square geosynthetic clay liner sample from the role with a dimension of 20x20 cm (Figure 1).

Figure 1. Cutting square GCL

2) Using the top pedestal to trace circle of pedestal diameter on geosynthetic clay liner, carefully cut out geosynthetic lay liner circle. Use deionized water to prevent loss of bentonite when cutting (Figure 2).

Figure 2. Cutting circle GCL

3) Using the top pedestal to trace two circles of pedestal diameter on nonwoven geotextiles, cut out both geotextiles circles. Then place the geosynthetic clay liner

circle into the flexible wall permeameter by sandwiching between two nonwoven geotextile circles (Figure 3 a-b-c).

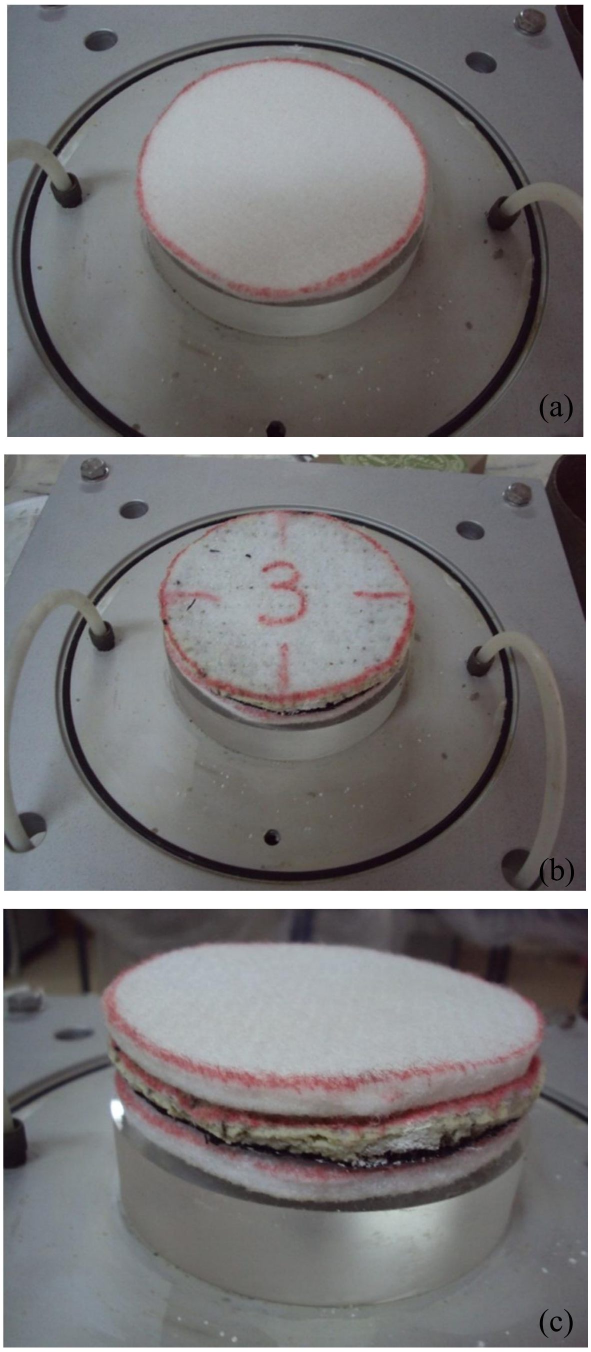


Figure 3. a) Cutting non-vowen geotextile, b) Placing GCL into permeameter, c) Sandwiching GCL between two geotextile.

4) Place top pedestal to the permeameter, and then apply bentonite paste water to the perimeter of the specimens to prevent the side-wall leakage (Figure 4 a-b).

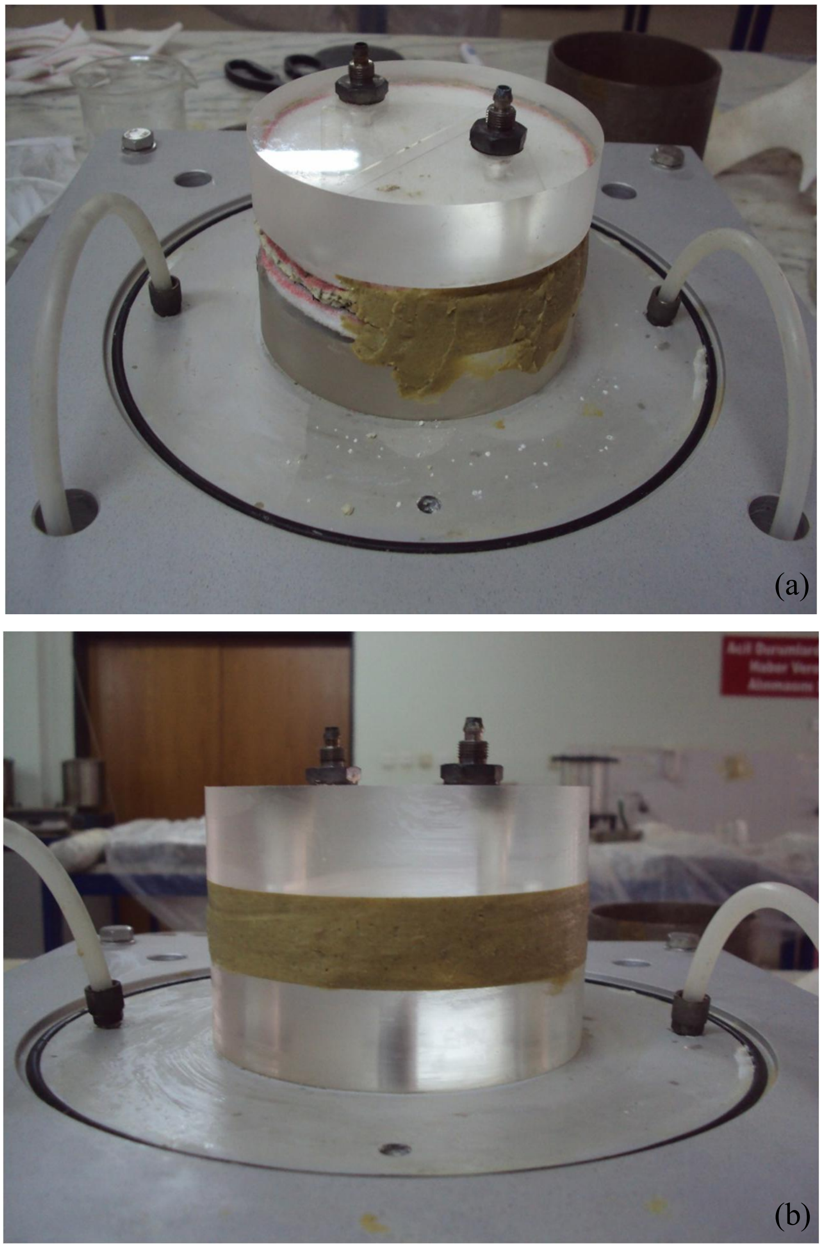


Figure 4. a), b) Applying bentonite paste to specimen.

5) Fit latex membrane to the sample (Figure 5a). Stretch two O-rings over a rigid ring with an inside diameter slightly larger than the base pedestal and membrane. Slide two O-rings over top and base pedestals (Figure 5 b-c-d).

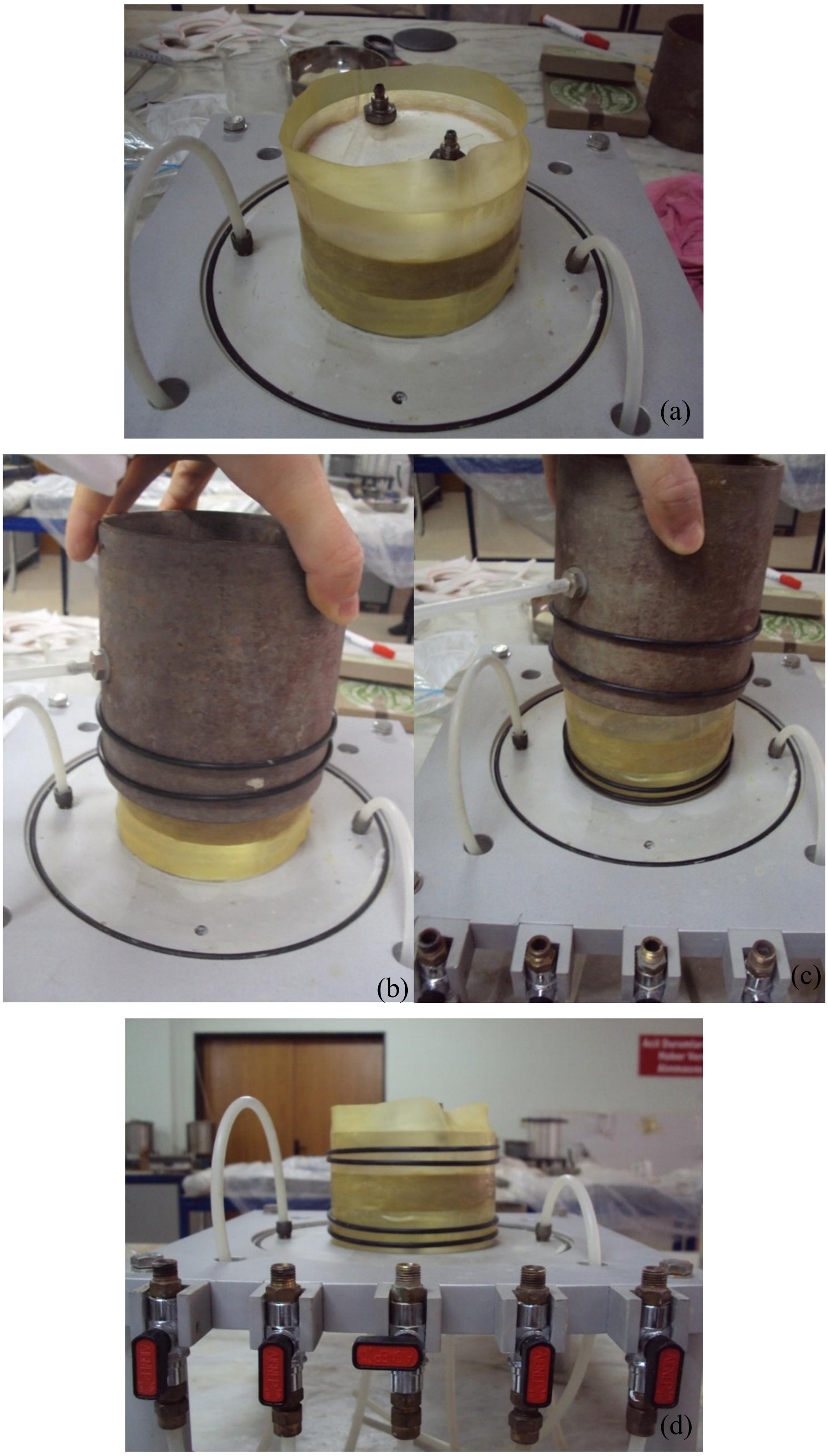


Figure 5. a) Fitting latex membrane, b), c), d) Sliding O-rings

6) Attach the tubing to top pedestal (Figure 6 a-b).

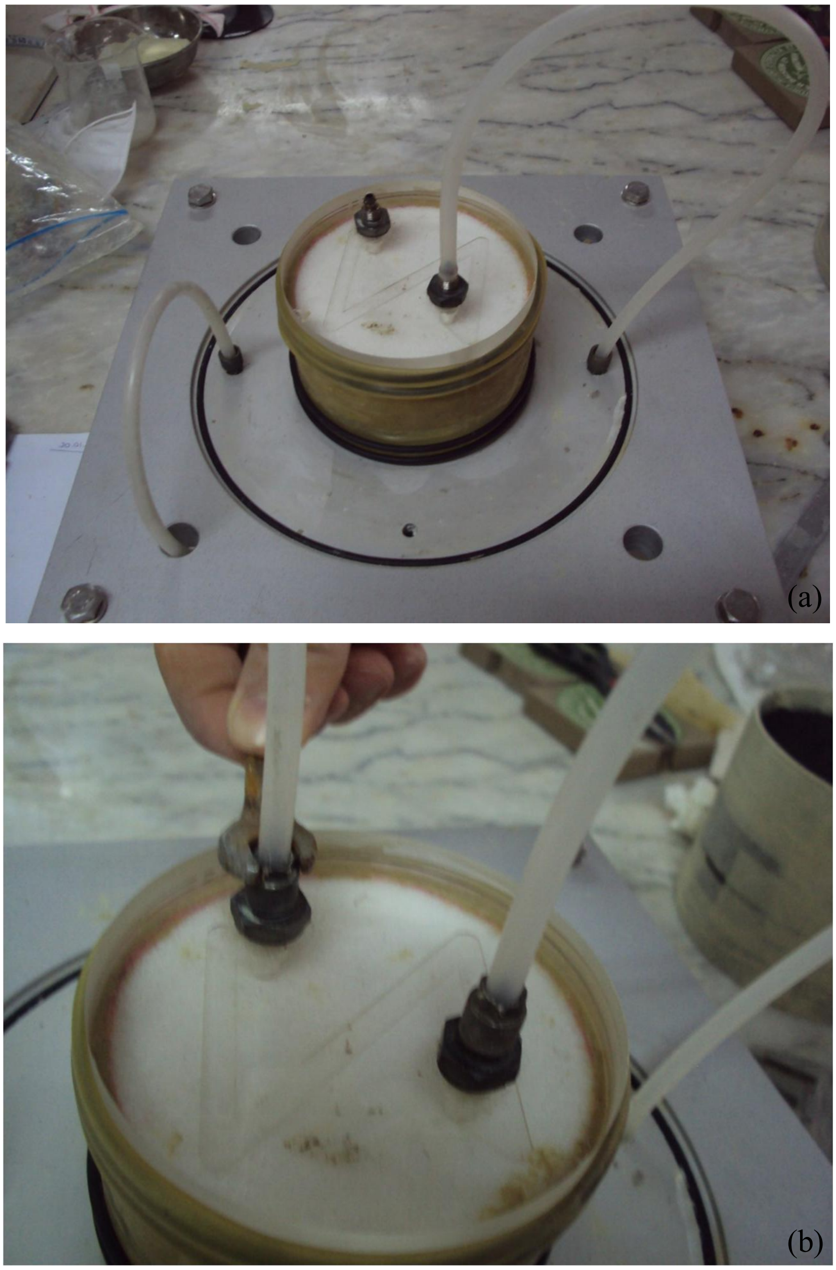


Figure 6. a), b) Attaching the tubing to top pedestal

7) Place acrylic cell on base plate by ensuring acrylic cell was fitted against the cell O-ring. Place the top plate on the acrylic cell. Ensure the acrylic cell is in contact with the top plate O-rings (Figure 7).

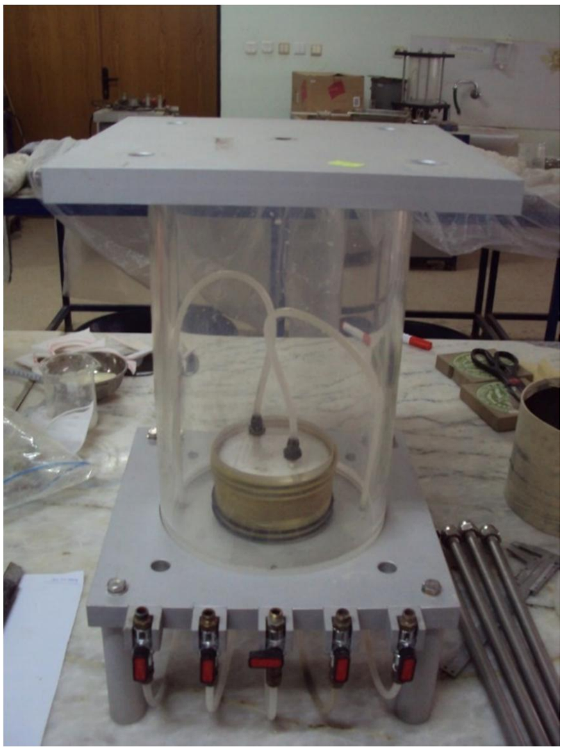


Figure 7. Placing acrylic cell

8) Install threaded rods between top and bottom plate and tighten rods in a crosswise pattern (Figure 8).

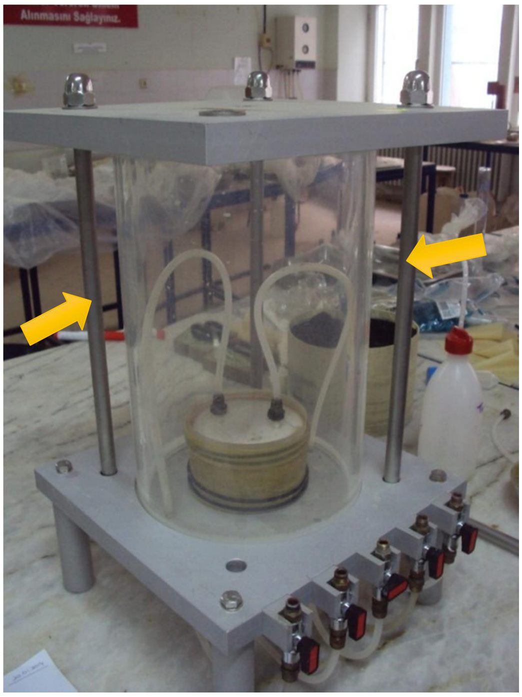


Figure 8. Installing threaded rods

9) Fill the permeameter with tap water slowly (Figure 9).

Figure 9. Filling the permeameter with water

10) Move permeameter where you will perform the hydraulic conductivity test. Apply cell pressure via cell pressure line. Attach inflow line to burette. Fill inflow line with permeant and allow permeant to flow in order to prevent to exist air bubbles in the hose. Then, fill inflow line with permeant up to zero line and allow specimen in permeameter to hydrate for 48 hours by closing the outflow line (Figure 10 a-b).

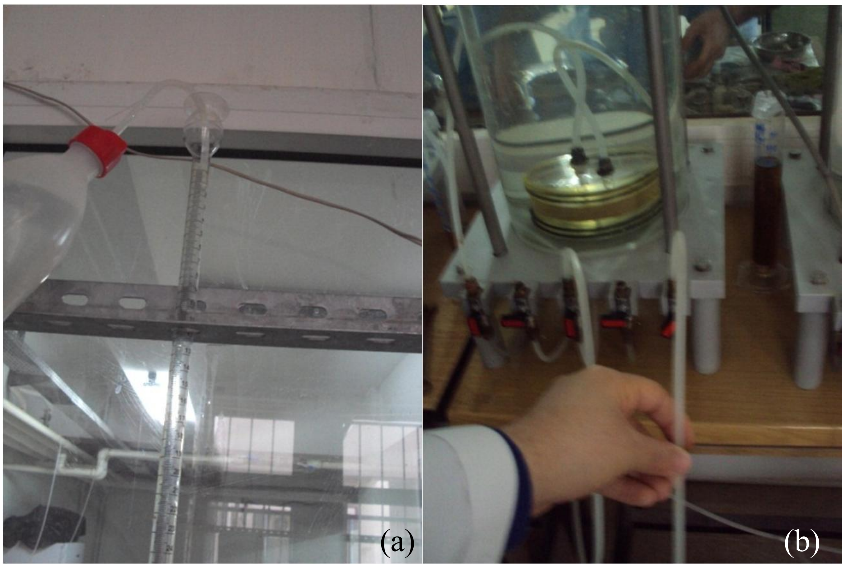


Figure 10. a), b) Allowing the flow

APPENDIX B

THE STEPS OF THE METHYLENE BLUE SPOT TEST PROCEDURE

1) Prepare 1 g dry powder methylene blue and 200 ml deionized water, and mix them in order to obtain methylene blue solution (Figure 1 a-b-c).

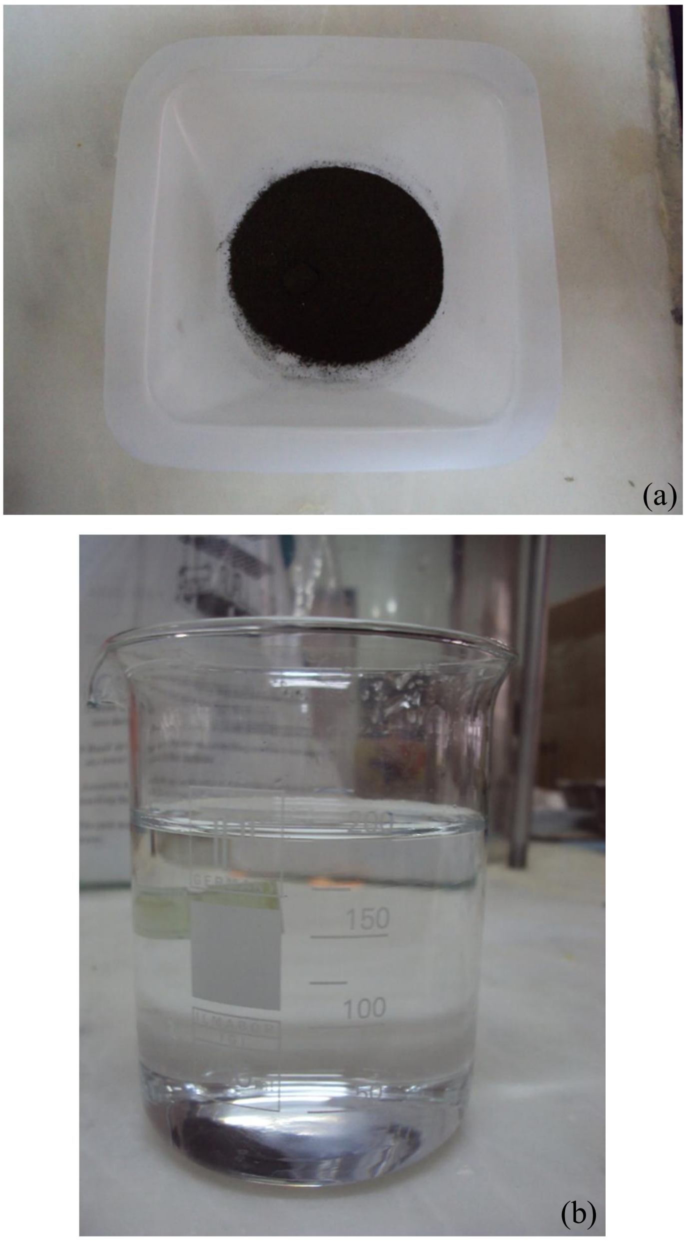


Figure 1. a), b) Preparing the methylene blue solution

Figure 1. c) Preparing the methylene blue solution (Continue)

2) Prepare 2.5 g bentonite and 7.5 g deionized water and place them into a beaker (Figure 2 a-b-c-d).

Figure 2. a) Preparing bentonite suspension

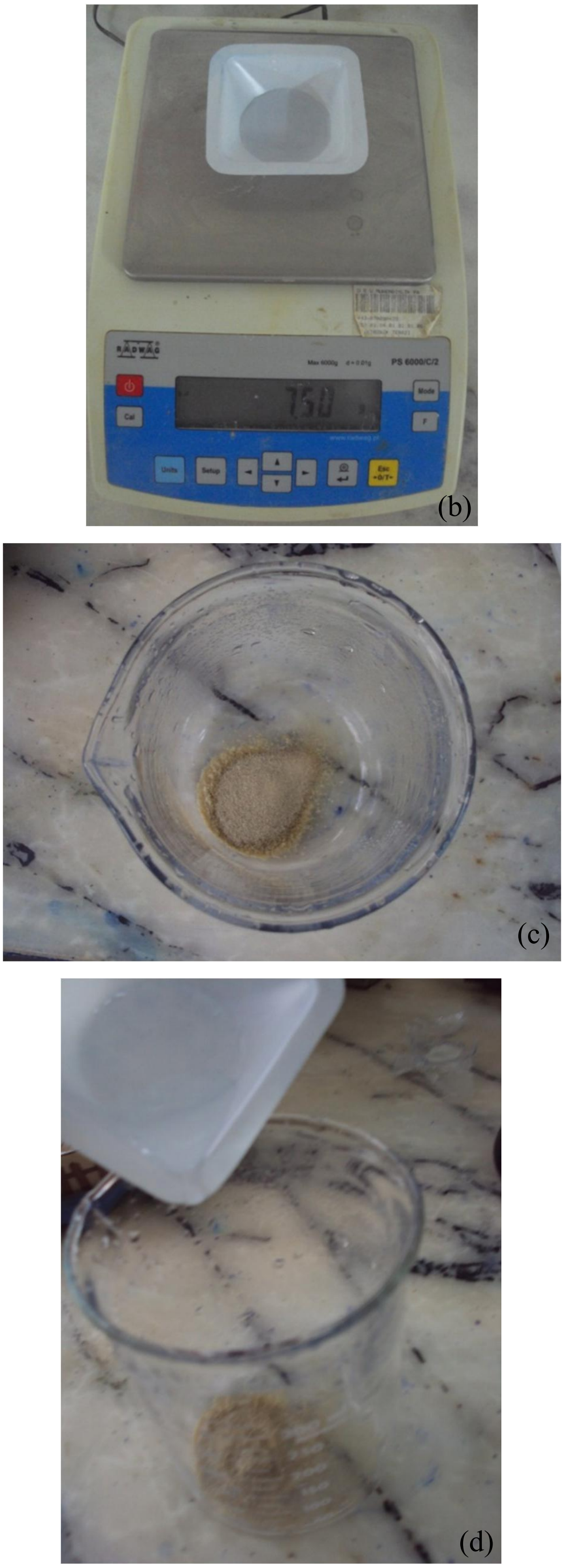


Figure 2. b), c), d) Preparing bentonite suspension (Continue)

3) Add 0.5 ml methylene blue solution into bentonite suspension carefully (Figure 3 a-b).

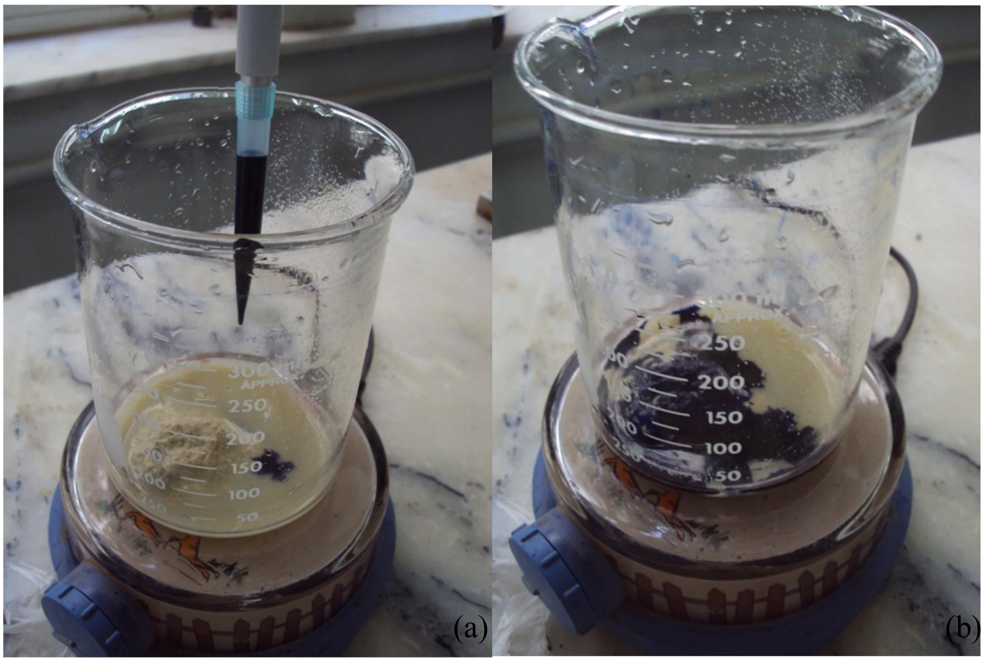


Figure 3. a), b) Adding 0.5 ml methylene blue solution into bentonite suspension

4) Mix the bentonite suspension by using magnetic stirrer for 1 minute (Figure 4 a-b-c).

Figure 4. a)Mix the bentonite suspension

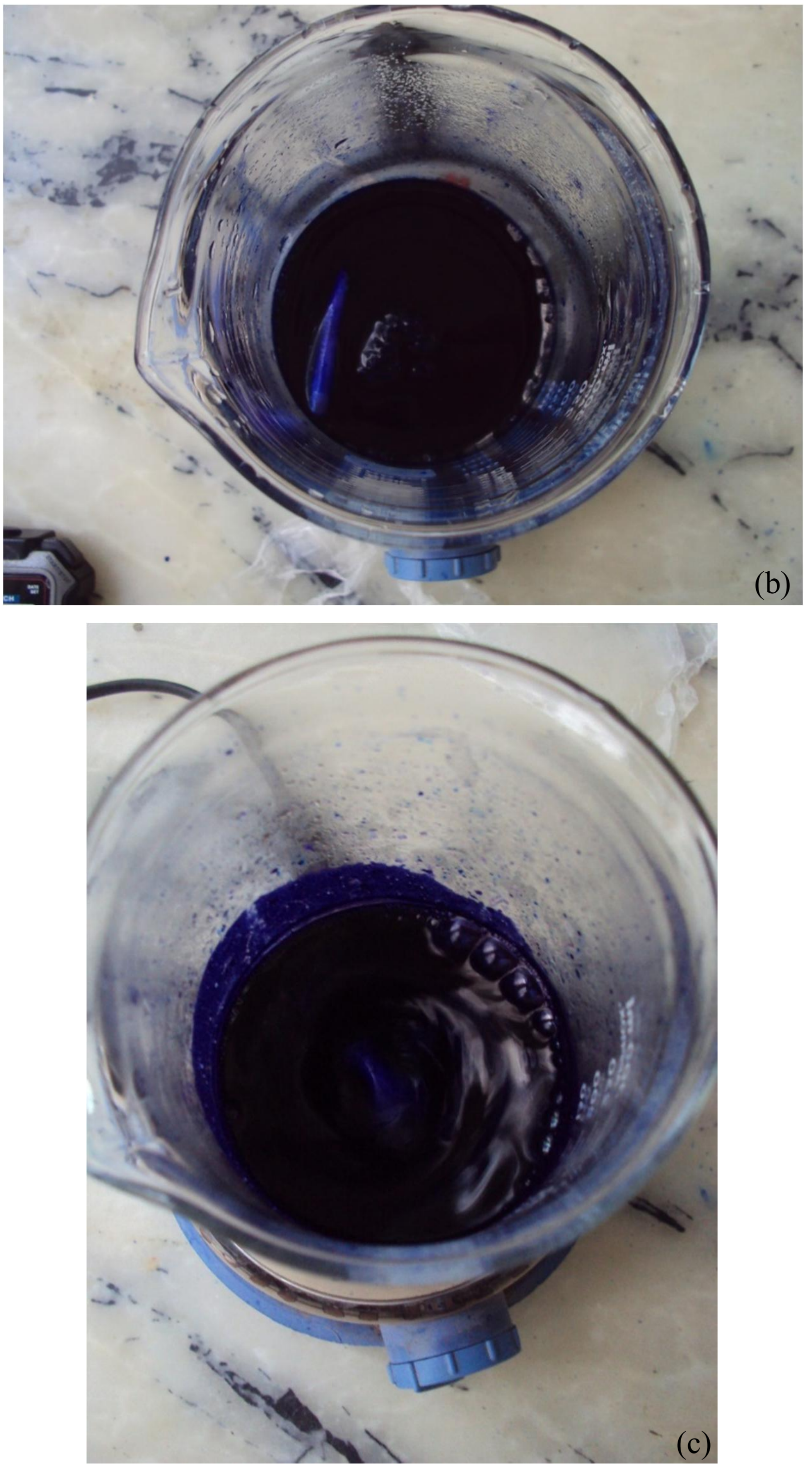
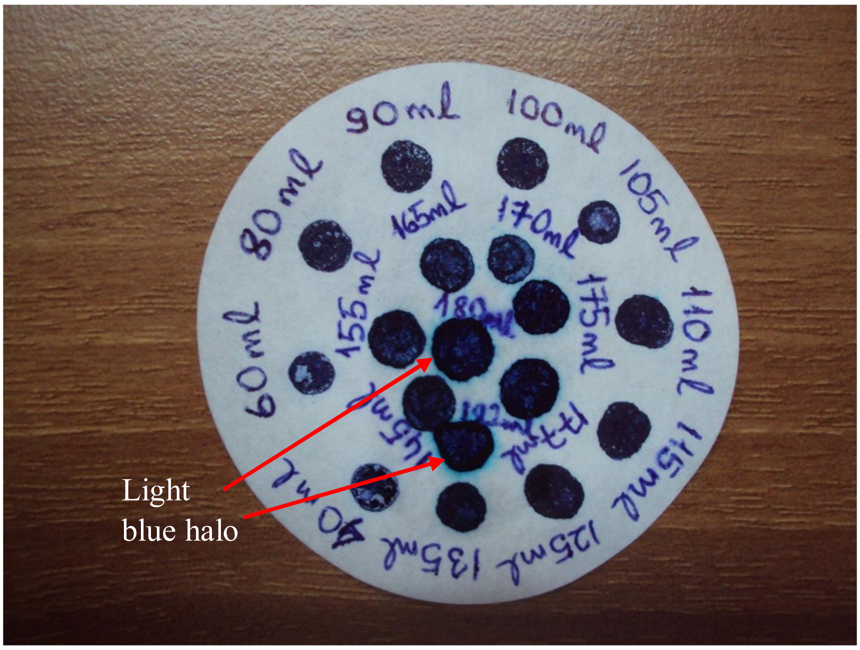


Figure 4. b), c) Mix the bentonite suspension (Continue)

5) Remove a drop from the suspension and place it onto Fisher brand P5, filter paper.

6) Continue this process to get a permanent blue halo around the soil aggregate spot onto the filter paper (Figure 5).



Light blue halo

Figure 5. The light blue halo