

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**EVALUATING THE WATER RETENTION AND
LONG-TERM HYDRAULIC CONDUCTIVITY
BEHAVIOR OF GEOSYNTHETIC CLAY LINERS**



by
Tuğçe ÖZDAMAR KUL

February, 2019
İZMİR

EVALUATING THE WATER RETENTION AND LONG-TERM HYDRAULIC CONDUCTIVITY BEHAVIOR OF GEOSYNTHETIC CLAY LINERS

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
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**by
Tuğçe ÖZDAMAR KUL**

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İZMİR

Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “EVALUATING THE WATER RETENTION AND LONG-TERM HYDRAULIC CONDUCTIVITY BEHAVIOR OF GEOSYNTHETIC CLAY LINERS” completed by TUĞÇE ÖZDAMAR KUL under supervision of ASSOC. PROF. A. 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 Doctor of Philosophy.



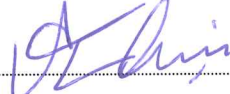
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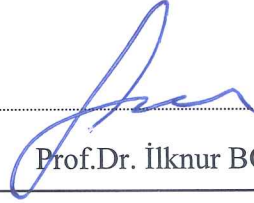
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Tuğçe ÖZDAMAR KUL

EVALUATING THE WATER RETENTION AND LONG-TERM HYDRAULIC CONDUCTIVITY BEHAVIOR OF GEOSYNTHETIC CLAY LINERS

ABSTRACT

The experimental study was conducted to determine the water uptake and hydraulic conductivity behaviors of eight needle-punched GCLs. The GCLs were denoted as low performance (LP), medium performance (MP) and high performance (HP) depending on the bentonite liquid limits. Hydration performance of GCLs and its effects on the water uptake and the hydraulic conductivity were investigated by simulating cover applications in the laboratory. For this purpose, GCLs were hydrated over compacted sand and zeolite subsoils which were placed in flexible wall permeameters with two different methods (i.e. control sample method, CSM, and single large sample method, SLSM).

The effects of hydration method, hydration duration, water contents of the subsoil, type of GCL and bentonite mass per unit area (MPUA) of GCL were the parameters investigated in this study. The suction characteristics of the subsoils and GCLs were determined as well. Hydraulic conductivity tests were conducted on the hydrated GCLs to determine the influence of hydration on the hydraulic conductivity. Since the swelling ability of bentonite influences the hydraulic performance of GCLs, the changes in the swell indices of bentonites after hydration were also investigated. Finally, the swelling performance of GCLs was linked to the cation exchange that took place between subsoil and GCL. This was quantified with cation analysis conducted on either subsoils or GCLs. Significant findings were obtained throughout the study some of which have been published in outstanding journals so far.

Keywords: Hydration, compacted subsoils, water retention, cation exchange, hydraulic conductivity, zeolite

GEOSENTETİK KİL ÖRTÜLERİN SU TUTMA VE UZUN DÖNEM HİDROLİK İLETKENLİK DAVRANIŞININ DEĞERLENDİRİLMESİ

ÖZ

İğnelenmek sureti ile imal edilen sekiz adet Geosentetik Kil Örtünün (GKÖ) su emme ve hidrolik iletkenlik davranışlarının belirlenebilmesi için deneysel bir çalışma gerçekleştirilmiştir. Çalışma kapsamında, GKÖ'ler likit limit değerlerine bağlı olarak düşük performanslı (LP), orta performanslı (MP) ve yüksek performanslı (HP) olarak adlandırılmıştır. GKÖ'lerin hidrasyon performansları ve bunun su emme ve hidrolik iletkenlikleri üzerindeki etkileri laboratuvar ortamında üst örtü teşkili simule edilerek incelenmiştir. Bu amaçla, GKÖ'ler esnek duvarlı permametre hücrelerinde sıkıştırılmış kum ve zeolit alt zeminler üzerinde iki farklı yöntem (kontrol örneklili yöntem, KÖY, ve tek büyük örneklili yöntem, TBÖY) kullanılarak hidrate edilmiştir.

Bu çalışmada, hidrasyon yönteminin, hidrasyon süresinin, alt zemin tip ve su içeriğinin, GCL tipinin ve birim alan başına bentonit kütlesinin (BABBK) etkisi irdelenmiştir. Ayrıca, alt zeminlerin ve GKÖ'lerin emme özellikleri de çalışma kapsamında incelenmiştir. Hidrasyonun GKÖ hidrolik iletkenliği üzerindeki etkisini belirlemek amacıyla hidrasyon sonrasında GKÖ'ler hidrolik iletkenlik deneylerine tabi tutulmuştur. GKÖ'lerin hidrolik performansları üzerinde şişme davranışlarının önemli etkisi bulunduğundan hidrasyondan sonra bentonitlerin şişme indeksleri de incelenmiştir. Elde edilen şişme indeksleri alt zemin ve GKÖ arasında gerçekleşen katyon değişim mekanizması ile ilişkilendirilmiştir. Bu mekanizma alt zemindeki ya da GKÖ'deki yer değiştirebilir katyon miktarlarının belirlenmesi sureti ile sayısallaştırılmıştır. Çalışma boyunca, bazıları bugüne kadar seçkin dergilerde yayımlanan önemli bulgulara ulaşılmıştır.

Anahtar sözcükler: Hidrasyon, sıkıştırılmış alt zemin, su emme, katyon değişimi, hidrolik iletkenlik, zeolit

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Engineering barriers have been used for many years in order to isolate waste from humans and environment. Traditionally, compacted clay liners (CCLs) from 0.3 to 1.5 m thicknesses were used as hydraulic barriers (Giround, Badu-Tweneboah & Soderman, 1997). However, with the recent innovation of thin prefabricated geosynthetic clay liners (GCLs), the use as liner materials instead of CCLs started.

GCLs are factory-manufactured hydraulic barriers that consist of a thin bentonite layer, between a woven and a non-woven geotextiles or bonded to a geomembrane (Koerner, 2005). The thickness of GCL is ~5-10 mm and bentonite mass per unit area (MPUA) is ~5.0 kg/m². Generally, GCLs are attached by needle punching, stitch bonding, or heat welding. These methods hold geotextiles together within the entire structure. The components of the GCLs are shown in Figure 1.1.

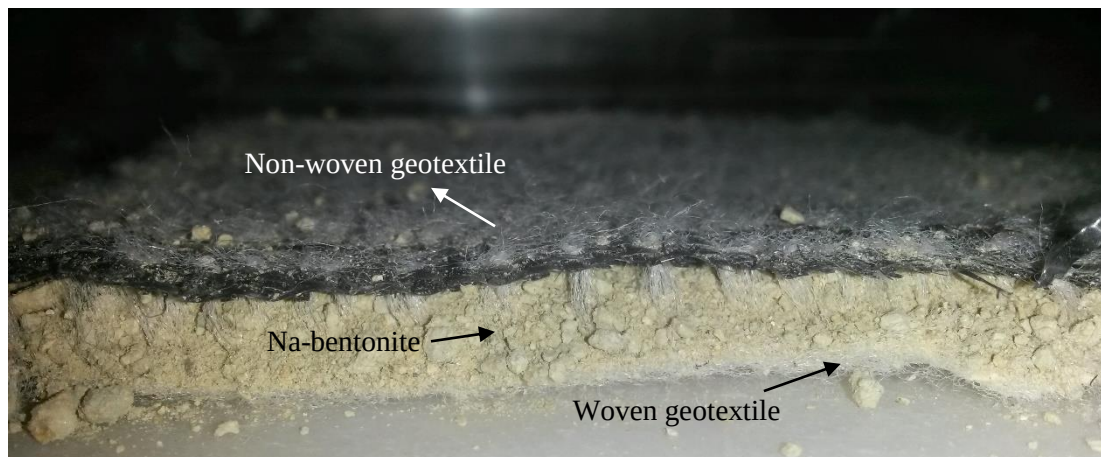


Figure 1.1 General view of GCL and GCL components (Personal archive, 2018)

GCLs are delivered in approximately 4.5 m wide rolls at around 15-20% initial water contents and installed in panel forms to the site. After installation, geomembrane is placed over the top and then the liner is covered with soil. The schematic representation of landfill liner and cover systems are shown in Figure 1.2.

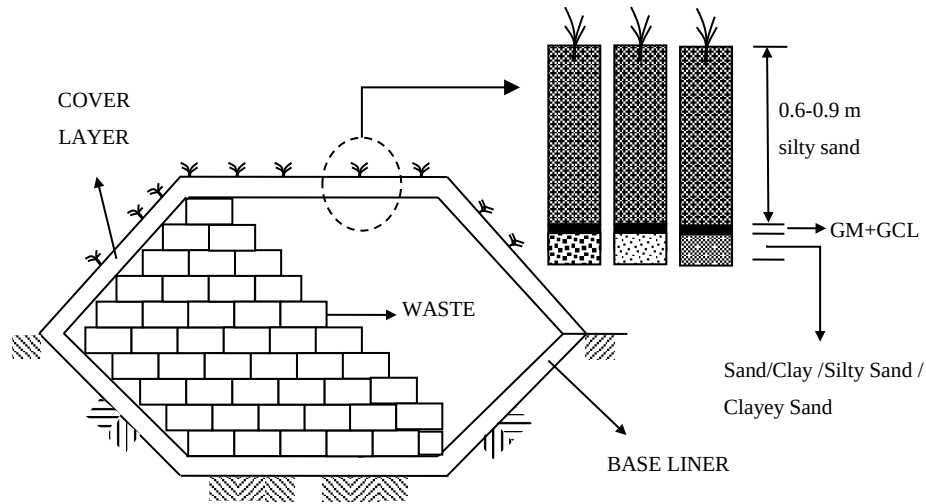


Figure 1.2 Schematic representation of landfill liner components

Bentonite, which is composed primarily of montmorillonite mineral, is the most important component in GCLs. The primary function of the bentonite layer is to obstruct the flow of liquids, dissolved chemicals and gases or vapors (Abuel-Naga, Bouazza & Lalot, 2012). GCLs are commonly used as: i) environmental protection barriers in roads and railways, ii) canal liners, iii) oil or fuel liners, iv) lagoon liners, v) base liners in mining waste ponds and vi) especially landfill liners (Bouazza, 2002; Katsumi et al., 2008a). The physicochemical properties and the mineralogy of bentonite in GCLs control the hydraulic performance of GCLs. It is reported in the literature that the hydraulic conductivity of Na^+ rich GCLs are about 2.0×10^{-11} m/s to water (Jo et al., 2001, 2005; Lee & Shackelford, 2005; Shan & Lai, 2002).

In addition to mineralogical and physicochemical properties of bentonite, hydraulic performance of GCLs depends on the degree of hydration that occurs after installation (Katsumi et al., 2008a; Rayhani et al., 2011; Rowe, 2005; Sarabian & Rayhani, 2013). To sufficiently hydrate and swell bentonite, some researchers have suggested that the water content of GCLs should be at least 100% in the field which result in lower hydraulic conductivity (Chevrier et al., 2012; Fascicule n 12, 1998; Meer & Benson, 2007).

The hydration of GCLs in the field simply simulated in the laboratory in conjunction with the hydraulic conductivity tests by allowing water to contact with

GCL for a while. In that case, the flow of water is not initiated and therefore, the outflow valve must be closed during the hydration phase. Early studies showed that the prehydration time for this simulation varied from several hours to several days (Lee & Shackelford, 2005; Petrov & Rowe, 1997; Ruhl & Daniel, 1997). However, this procedure does not reflect the real conditions of GCL hydration when installed at the field. Thus, recent studies have focused on to find out another procedure. Instead of prehydration before hydraulic conductivity, GCLs are placed over the compacted subgrade soils and left for hydration under small effective stresses (Anderson, Rayhani & Rowe, 2012, Chevrier et al., 2012). Hence, bentonite starts to take up some water from the subgrade via suction.

Hydration from the subsoil improves the hydraulic performance of GCLs. Especially, it was reported in the previous studies that increase in the water content of bentonite led to decrease the hydraulic conductivity of GCL (Meer & Benson, 2007; Scalia & Benson, 2011). Hydration duration, subgrade soil (or subsoil) type and minerology, the water content of subsoil, GCL type, the effective stress acting on the GCLs and environmental conditions such as site temperature are some of the factors that influence the hydration of GCLs (Anderson, Rayhani & Rowe, 2012; Benson & Meer, 2009; Bouazza et al., 2017; Meer & Benson, 2007; Rayhani et al., 2011; Rowe, 2012; Rowe & Abdellaty, 2012; Sarabian & Rayhani 2013; Scalia & Benson, 2010, 2011).

Although there are valuable studies on the hydration of GCLs, there are still some gaps that need to be filled. For example, the liquid limits of bentonites in GCLs were within the range of 216-620% in the literature. In this study, however, this range is further increased by considering many GCLs. Similarly, the compaction water contents of sandy subsoils used during hydration studies were between 10 and 20% at most. This study offers zeolite which has optimum water content of 42% (far above sand). Therefore, it seeks an answer to the question: What if zeolite is used instead of sand during hydration. Moreover, most studies reported in the literature generally deal with the hydration water content of GCLs after subjected to thermal cycles. This study not only deals with hydration, but also widely investigates the hydraulic conductivity

behavior of GCLs after hydration. The many other things are considered in this study as well. These are explained under the following section, “Objectives and Scopes”, in detail.

1.2 Objectives and Scopes

The principal objective of this study is to investigate the hydration of GCLs from compacted subsoils and its effects on the hydraulic conductivity. The detailed scopes of the investigation are as follows:

- Determination of most suitable hydration method for the GCL. The study compares the GCL hydration methods (i.e. Control Sample Method, CSM, and Single Large Sample Method, SLSM) using flexible-wall permeameters in terms of bentonite water contents. The study investigates the influence of hydration duration, subsoil diameter and height on the hydration of GCL. In addition, the influence of hydration on the subsoil water content profiles and the hydraulic conductivity of GCLs were also investigated. The visual conditions of bentonite layers were also compared within each other after hydration and hydraulic conductivity testings.
- Determination of hydration behaviors of GCLs in terms of their performance (i.e. liquid limits). The hydration studies were conducted first on three different GCLs which had distinct liquid limits within each other (i.e. 108%, 320% and 1163%). To investigate the influence of GCL performance depending on the quality of the GCLs, hydration and hydraulic conductivity tests were conducted. The influence of subsoil hydration on the GCL thicknesses and hydraulic behaviors were also investigated.
- Since the subsoil water content has an important effect on the hydration water content of GCL, zeolite that had greater compaction water contents (i.e. 41% and 46%) were proposed as an alternate subsoil in this study. The influence of compacted zeolite on the hydration of GCLs were investigated as well.

- The cation exchange during subsoil hydration and its effect on the swell indices of GCLs were also taken into consideration. The cation exchange mechanism was evaluated in terms of major bound cations in the exchange complex of GCLs.
- To understand the basic water transfer mechanism between the subsoil and GCL, the total and matric suction behaviors of both subsoils and GCLs were investigated with the filter paper method. The water retention curves (WRC) of the subsoils and GCLs were drawn by curve fitting technique.
- The influence of bentonite mass per unit area (MPUA) on the hydration and hydraulic conductivity of GCLs were investigated using sand and zeolite.

1.3 Outline of the Dissertation

This thesis consists of eight chapters. Chapter One outlines the general overview and the scope of this study and organization of the thesis.

Chapter Two describes the material characterization and experimental procedures which were followed in this study.

Chapter Three compares the performance of two test methods that were used during the hydration of GCLs over compacted subsoils.

Chapter Four describes the liquid limit-based evaluation of hydration and hydraulic conductivity behaviors of GCLs when placed over compacted sand.

Chapter Five examines the influence of zeolite subsoil on the hydration of GCLs. The cation exchange process during the subsoil hydration and its effect on the swell indices and hydraulic conductivity are also presented.

Chapter Six presents the suction characteristics of subsoils and GCLs by an indirect measurement method, i.e. filter paper method.

The effects of mass per unit area and the subsoil water contents on the hydration and hydraulic conductivity of GCLs are discussed in Chapter Seven.

Chapter Eight presents the conclusions and recommendations for future studies based on the results obtained in this study.



CHAPTER TWO

MATERIALS AND METHODS

2.1 Materials

2.1.1 Geosynthetic Clay Liners (GCLs)

Eight needle-punched geosynthetic clay liners (GCLs) were used in this study. In the first set of tests, two Na-GCLs (GCL-1 and GCL-2) and one polymer treated GCL (GCL-8) which were provided by local manufacturers in Turkey were used. In the second set of experiments one Na-GCL (GCL-3) and four polymer treated GCLs (GCL-4, GCL-5, GCL-6 and GCL-7) were gathered from the same local company. All GCLs contained granular sodium bentonite. However, GCL-3 also contains considerable amount of Ca^{++} cations in the exchange complex (i.e. Ca^{++} mole fractions were between 0.19 and 0.27). Based on the given information from the manufacturers polymer treated GCLs include additionally sodium polyacrylate and polyacrylamide (SAP) anionic polymers.

The mass of bentonite per unit areas (MPUA) of GCLs were determined in accordance with ASTM: D5993-99 (2010) and were between 2.68 and 11.23 kg/m². The initial air-dry heights of GCLs ranged from 3.3 mm to 11.2 mm. The general views of GCL rolls that were delivered by the manufacturer to Dokuz Eylül University, Department of Civil Engineering, Soil Mechanics and Geotechnical Modeling Laboratory are shown in Figure 2.1. It should be noted that the denotations of the GCLs were selected based on the liquid limits of bentonites in GCLs. That is the GCLs which had 100-200% liquid limits were named as low performance (LP) whereas the GCLs whose liquid limits were greater than 500% were named as high performance (HP). The GCLs with liquid limits between 200% and 500% were denoted as medium performance (MP).

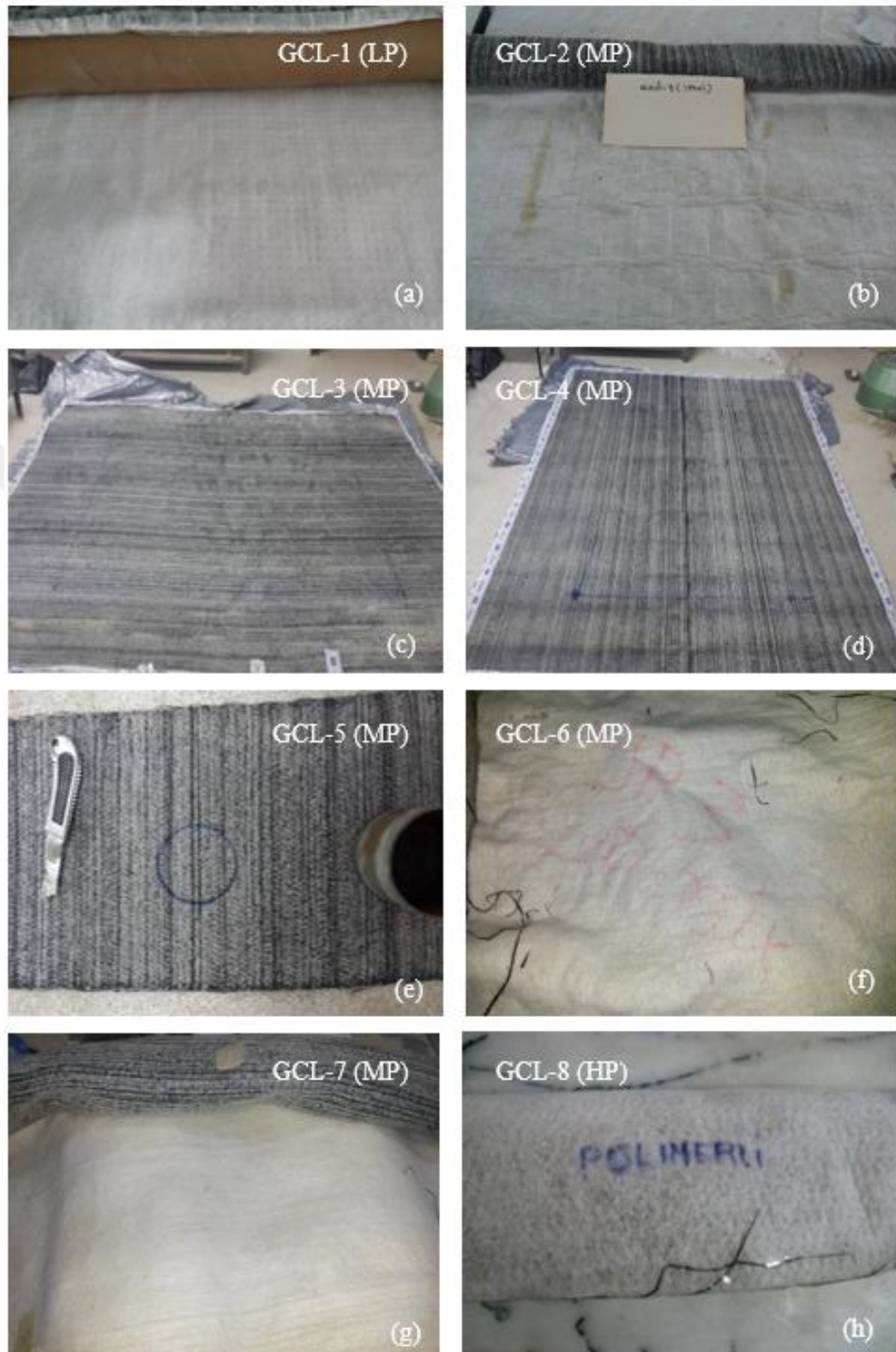


Figure 2.1 Photographs of tested GCLs: a) GCL-1 (LP), b) GCL-2 (MP), c) GCL-3 (MP), d) GCL-4 (MP), e) GCL-5 (MP), f) GCL-6 (MP), g) GCL-7 (MP), h) GCL-8 (HP) (Personal archive, 2014-2016)

2.1.2 Subsoils

The sand subsoil gathered from Aydın Municipal Solid Waste (MSW) landfill area that is located in the western part of Turkey and two commercial zeolites which were obtained from Rota Mining Co Gördes/Manisa were used as the subsoil. The photographic images of subsoils which were used throughout the study are shown in Figure 2.2.

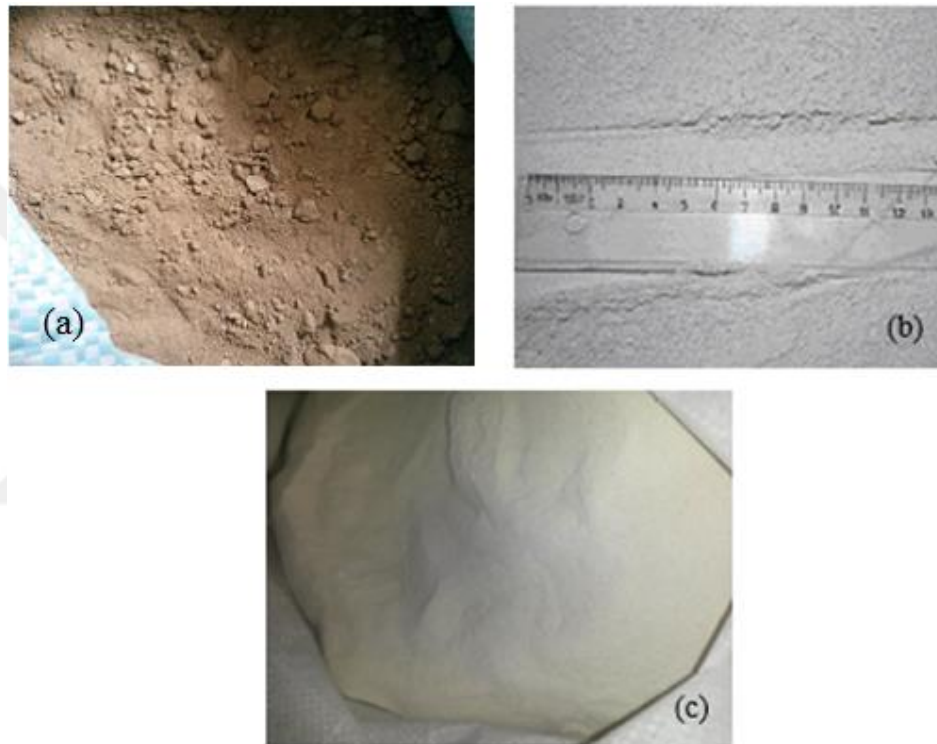


Figure 2.2 Photographs of tested subsoils: a) sand, b) zeolite-1 and c) zeolite-2 (Personal archive, 2014)

According to the Unified Soil Classification System (USCS), the sand subsoil had 42% fine content and was classified as silty sand (SM). To represent silty sand gradation which has been mostly studied in the literature and to get better compaction characteristic, from medium to fine sand-sized particles of zeolites with fines content of 48-46% was preferred for this study. Thus, the zeolites were classified as SM, as expected. However, not to allow any confusion, the commercial name “zeolite” will be used for the denotation of these subsoils (i.e. zeolite-1 and zeolite-2) while the natural subsoil will be referred as sand henceforth. The predominant mineral in both

zeolites is clinoptilolite whereas the associate mineral is mordenite (Ören, Durukan, & Kayalar, 2014).

2.2 Methods

2.2.1 Index Tests

2.2.1.1 Geosynthetic Clay Liners

To determine some index properties of bentonites, the fibers that connect the geotextile parts (i.e. nonwoven and woven geotextile) of the GCLs were detached and the bentonite portions were separated. Some physical characteristics and index properties of bentonites taken from eight different GCLs are summarized in Table 2.1.

Table 2.1 The physical characteristics and index properties of subsoils

GCL Type	Specific Gravity	Initial Water Content (%)	Fine Content (%)	Liquid limit (%)		Plasticity Index (%)	
				Casagrande	Fall Cone	Casagrande	Fall Cone
GCL-1 (LP)	3.04	12	84	108	99	48	39
GCL-2 (MP)	2.79	18	95	320	236	290	206
GCL-3 (MP)	2.64	8	86	240	215	187	162
GCL-4 (MP)	2.77	9	94	385	325	327	267
GCL-5 (MP)	2.73	10	94	356	338	292	274
GCL-6 (MP)	2.75	12	91	240	230	186	176
GCL-7 (MP)	2.70	8	90	400	282	340	222
GCL-8 (HP)	2.70	11	95	1163	800	1111	748

The specific gravities of bentonites were determined in accordance with ASTM: D854-14 (2014). The specific gravities of GCLs were between 2.7 and 3.04. It should be noted that the specific gravity test for GCL-1 was replicated for three times owing to high specific gravity values. As described in ASTM: D422-63 (2007), wet sieving and hydrometer analysis were performed to determine the grain size distributions of

GCLs. The grain size distribution curves of GCLs are shown in Figure 2.3. Except GCL-8, grain size distributions of all other GCLs (GCL-1, GCL-2, GCL-3, GCL-5, GCL-6, GCL-7 and GCL-8) are quite similar to each other. However, GCL-8 had a slightly different particle size distribution curve. The reason for this difference may be due to the amount of polymer inside of this GCL. Although the type and percentage of polymer additives are not known, the most gelatinous form was observed for GCL-8 during the sieve analysis.

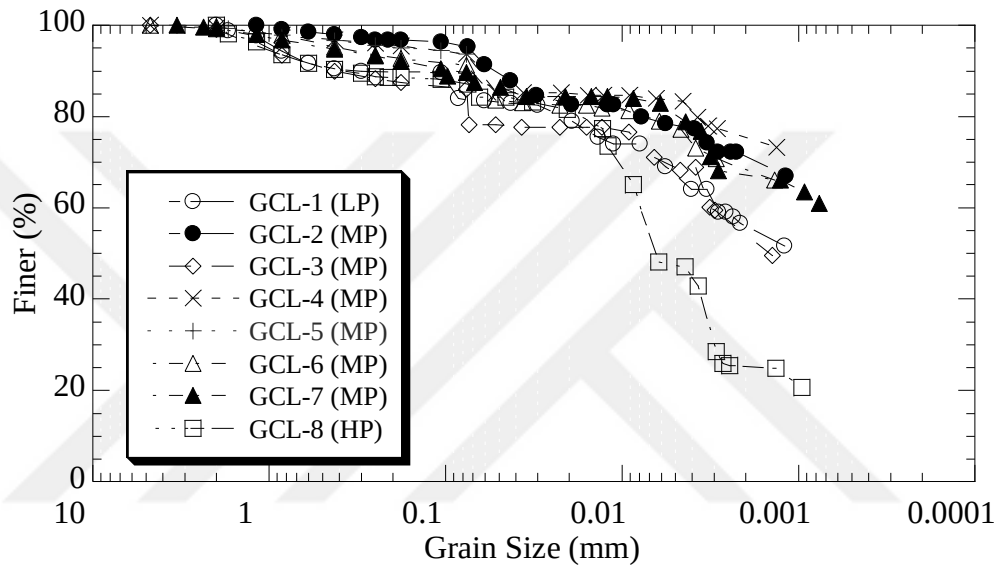


Figure 2.3 Grain size distribution of the bentonites in GCLs

The consistency limits of bentonites were determined according to the ASTM: D4318-05 (2005). Although Casagrande method is more convenient for high plastic clays (Sridharan & Prakash, 2000), the liquid limits of bentonites were determined with both Casagrande and fall cone methods. The liquid limits of GCLs were determined between 99-800% with fall cone method and between 108-1163% with Casagrande method. Liquid limit values from these two methods are compared and illustrated in Figure 2.4. It can be seen from this figure that greater liquid limit values were obtained with Casagrande method compared to the fall cone method. Results are consistent with the findings reported in the literature (Sridharan & Prakash, 2000).

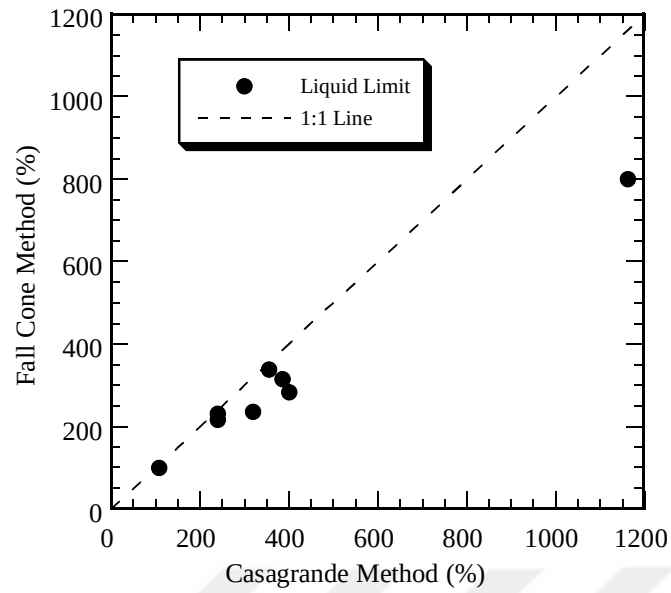


Figure 2.4 Comparison of the liquid limit values depending on the testing methods

2.2.1.2 Subsoils

Grain size distributions of the subsoils (i.e. sand, zeolite-1 and zeolite-2) were determined by following ASTM: D422-63 (2007). Like bentonites, wet sieving method and hydrometer analysis were conducted to determine the grain size distributions of the subsoils (Figure 2.5). As mentioned in materials section, all subsoils were classified as silty sand, SM, according to ASTM: D 2487-11 (2011) (USCS). However, the sand subsoil gathered from Aydın MSW landfill is denoted as “sand” whereas other subsoils are named as “zeolite-1” and “zeolite-2” for simplicity.

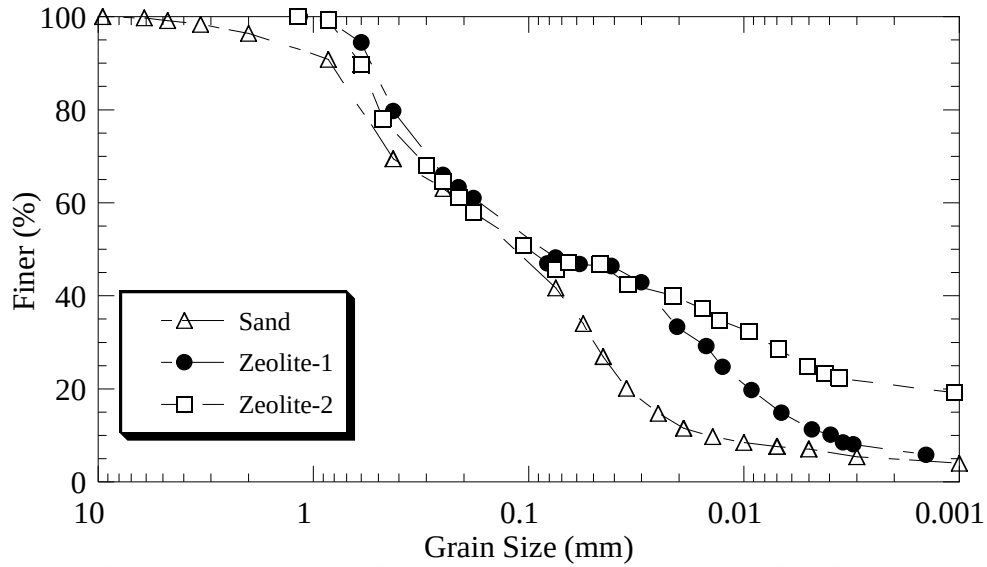


Figure 2.5 Grain size distributions of subsoils

Liquid limits of the materials were determined using fall-cone test method as described in BS 1377-2 (1990). The plastic limit tests were performed by following ASTM: D4318-05 (2005). The liquid and plastic limits of zeolites were determined as 67.5% and 43.2% for zeolite-1 and 61.5% and 34% for zeolite-2, respectively. Similarly, the liquid limit of sand was determined as 30.7%. However, it did not show any plastic characteristics (i.e. non-plastic). The specific gravities were determined in accordance with ASTM: D854-14 (2014). Some physicochemical properties of subsoils are summarized in Table 2.2.

Table 2.2 The physical characteristics and index properties of subsoils

Subsoil properties	Sand	Zeolite-1	Zeolite-2
Gravel size fraction (%)	1	-	-
Sand size fraction (%)	57	52	54
Silt size fraction (%)	37	41	26
Clay size fraction (%)	5	7	20
Specific Gravity, G_s	2.67	2.34	2.34
Liquid Limit w_L (%)	30.7	67.5	71.5
Plastic Limit w_P (%)	NP	43.2	42.7

Furthermore, compaction characteristics of the subsoils were obtained using standard Proctor compaction energy by following ASTM: D698-12 (2012). The compaction curves of the subsoils are shown in Figure 2.6. The maximum dry unit weights ($\gamma_{d,max}$) were 18.3 kN/m³, 10.7 kN/m³ and 11.2 kN/m³ and the optimum water contents (ω_{opt}) were 12%, 46% and 41% for sand, zeolite-1 and zeolite-2, respectively.

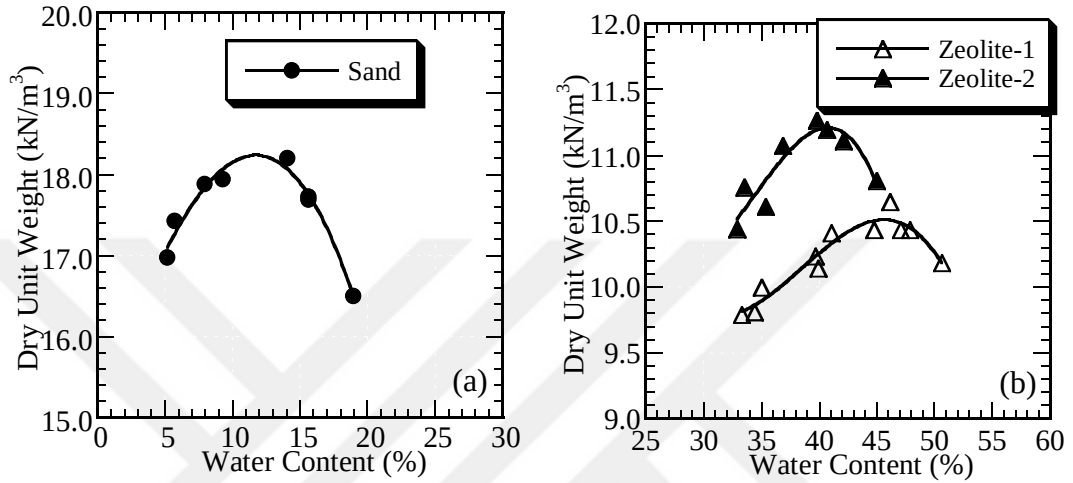


Figure 2.6 Compaction curves of the subsoils: a) sand and b) zeolite-1 and zeolite-2

2.2.2 Swell Index Test

Swell index tests were performed by following the procedures described in ASTM: D5890-11 (2011) (Figure 2.7). Bentonites were powdered in a mortar, sieved from No.200 standard sieve, and dried in an oven at 105°C. Then, 2 grams of oven dried bentonite was added in 0.1 g increment to 90 ml of deionized water (DIW) in a 100 ml graduated cylinder (Figure 2.7a). At the end of this process, remaining bentonite particles through the side of the cylinder were rinsed and the cylinder was filled with DIW up to 100 ml (Figure 2.7b). The swell index was recorded in terms of mL/2g after at least 16 hours.

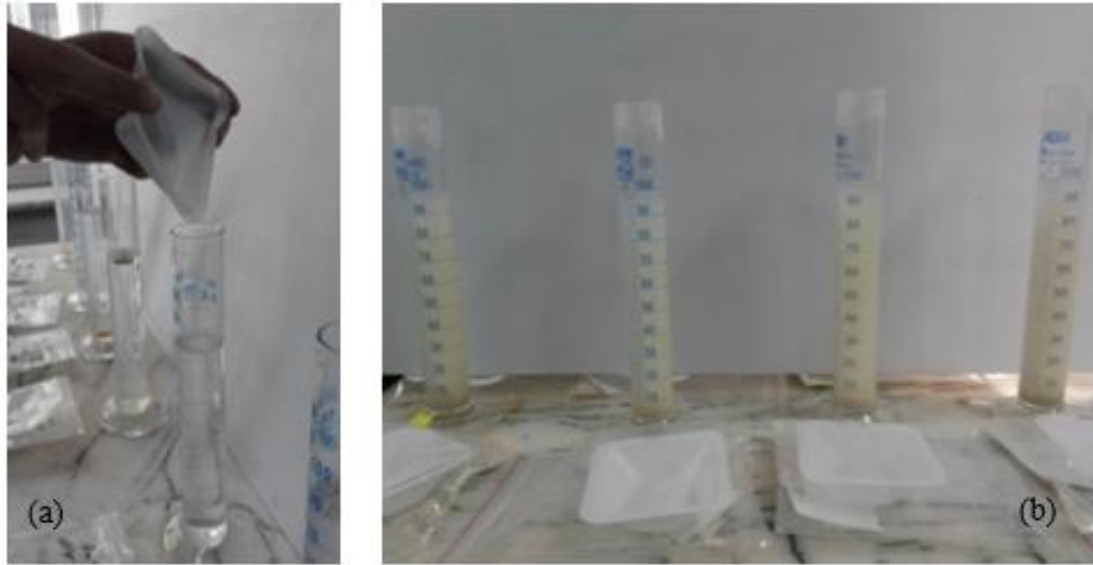


Figure 2.7 Photographs a) during bentonite addition and b) at the end of the swell index test (Personal archive, 2016)

2.2.3 Compaction of the Subsoils for Hydration Studies

Standard Proctor compaction energy was applied to compact the subsoils (ASTM: D698-12). Before compaction, subsoils were placed in plastic bags in their air-dry state. Then tap water was added to the samples with a spray bottle up to 2% wet of optimum water contents (i.e. 14% for sand, 48% for zeolite-1 and 43% for zeolite-2). To ensure a uniform water distribution throughout the samples, wet soils were allowed hydration in plastic bags for 24 hours. After hydration, soils were compacted with automatic compactor by following the procedure described in ASTM: D698-12. Depending on the applied hydration method, subsoils were compacted within molds with 100 mm or 150 mm in diameters. Photographic images of compaction test equipment are shown in Figure 2.8.

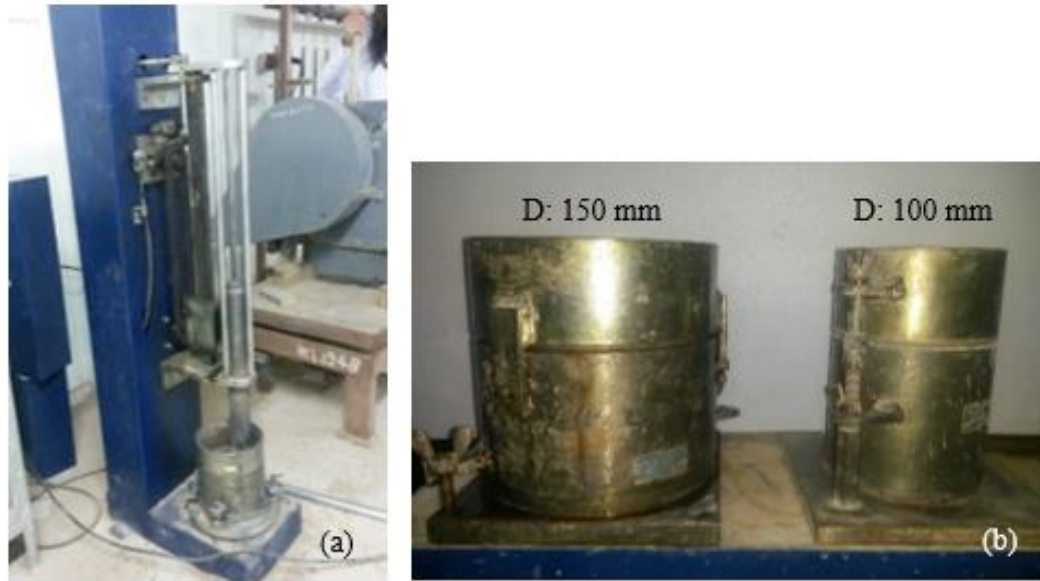


Figure 2.8 Photographs of compaction test equipment a) automatic compactor and b) compaction molds in 100 mm and 150 mm diameters (Personal archive, 2014)

2.2.4 Hydration of Geosynthetic Clay Liners

GCL hydrations were performed in flexible-wall permeameters. For this purpose, two different methods: i) Control Sample Method (CSM) and ii) Single Large Sample Method (SLSM) were used. In the first method (CSM) two GCL samples with 100 mm diameter were hydrated over compacted subsoils. In the second method (SLSM) only one sample with 150 mm diameter was prepared and left for hydration over the subsoil. The photographic images of GCL samples which were hydrated with these two methods are shown in Figure 2.9.

To prepare GCL samples for the first method (CSM), square samples (200 mm × 200 mm) were cut from the GCL roll. Then, circular GCL samples that had 100 mm diameter were cut from the center of these squares. Prior to cutting of these circular samples, the circumference of 100 mm diameter GCLs was hydrated with DI water to prevent the bentonite loss. The thicknesses were measured at four random locations on the GCLs by using a Vernier. Then, the initial weight of the GCL sample was determined. In this method, two GCL samples were prepared for each period of hydration one of which was used for water content determination and the other was used for the hydraulic conductivity test.

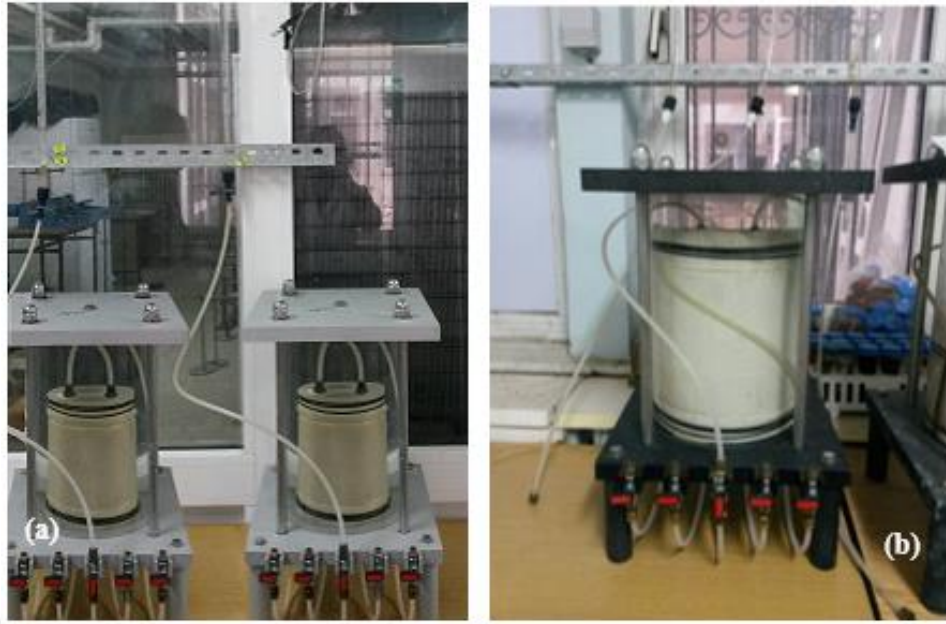


Figure 2.9 General view of permeameters used for GCL hydration with: a) Control Sample Method (CSM) and b) Single Large Sample Method (SLSM) (Personal archive, 2015)

In the second hydration method (SLSM), 150 mm in diameter circular samples were cut from $300 \text{ mm} \times 300 \text{ mm}$ square GCL samples. The remaining procedure was the same as the procedure adapted for CSM. At the end of the hydration period, a sample in 100 mm diameter was cut from the hydrated GCL sample for the hydraulic conductivity test (Figure 2.10 a). The remaining part of GCL was used to determine the water content of hydrated GCL (Figure 2.10 b).

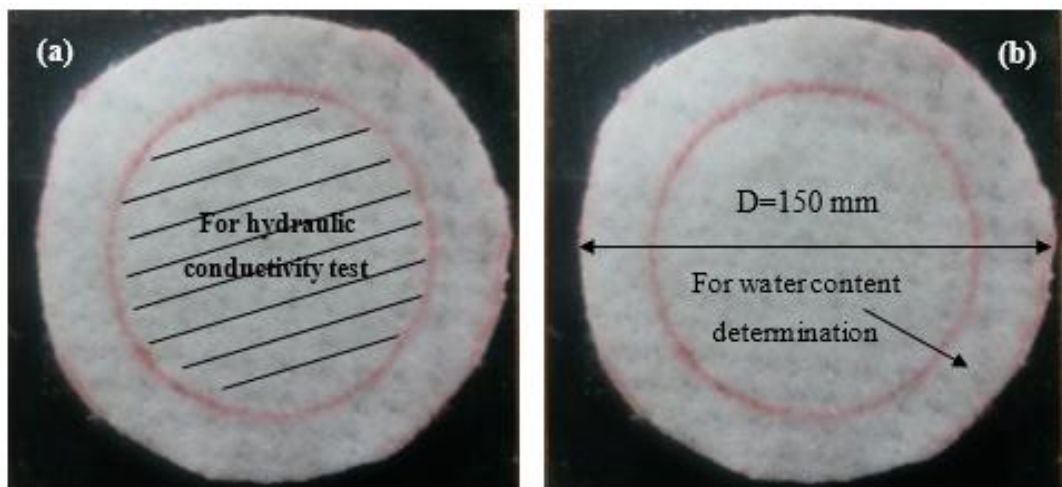


Figure 2.10 GCL samples used in SLSM parts of which were for: a) hydraulic conductivity test and b) water content determination (Personal archive, 2015)

GCL samples prepared from both methods were placed into the flexible-wall permeameters in a similar manner with landfill liner covers. The placement order of the components from bottom to top was: a nonwoven geotextile disk, compacted subsoil, GCL specimen, geomembrane, nonwoven geotextiles disk and top (Figure 2.11 a). Note that the nonwoven side of the GCL was in contact with the subsoil. System was covered with latex membrane and three O-rings were placed on each top and bottom plates (Figure 2.11 b). The cell was filled with water and 10 kPa cell pressure was applied to the permeameter. Inflow and outflow valves were closed throughout the hydration duration.

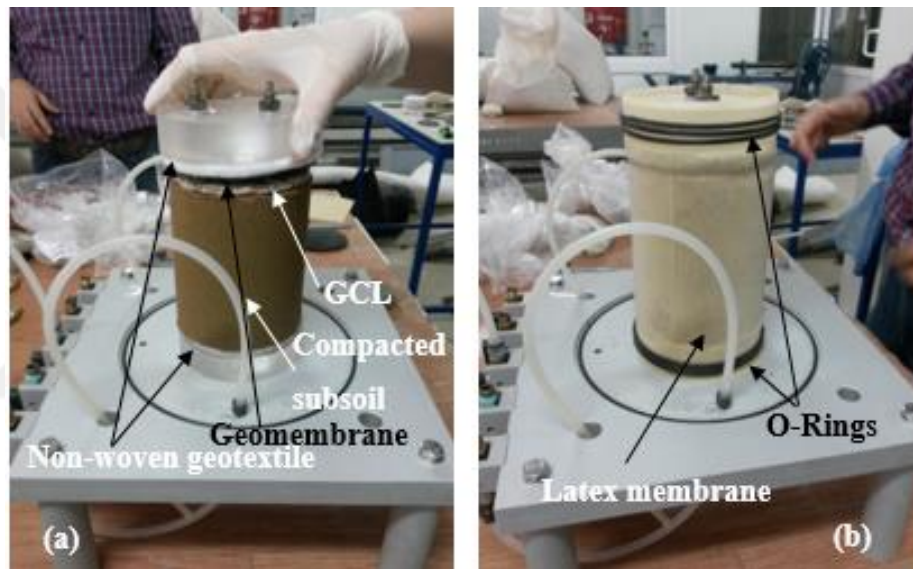


Figure 2.11 Sample preparation for GCL hydration: a) components (CSM); b) placement of latex membrane and O-rings (Personal archive, 2015)

2.2.5 Water Content Determination of Geosynthetic Clay Liners and Subsoils After Hydration

Water contents of the GCLs and subsoil layers were determined at the end of each hydration period. When CSM was used for the hydration of GCL (two GCLs were hydrated at the same time), one GCL was used for determining the water content. For this purpose, fibers that were connected the woven and nonwoven geotextiles by needle punching were detached with a sharp razor knife (Figure 2.12). Special care was taken to not disturb the swollen bentonite while cutting the fibers. The swollen

bentonite layer between geotextiles was monitored by taking photos. After that, bentonite was scratched with a spatula and dried in an oven at 105 °C to determine the water content of bentonite portion of GCL.

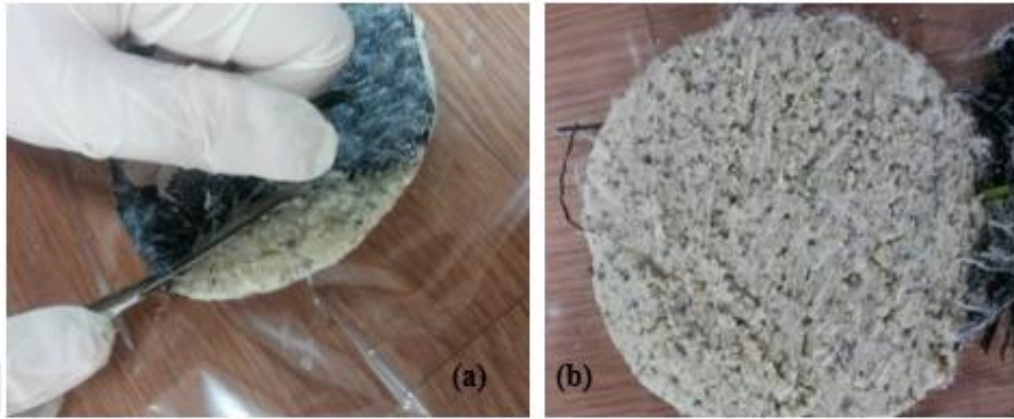


Figure 2.12 Sampling and monitoring of bentonite in CSM after GCL hydration: a) detachment of GCL, b) photographic image of swollen bentonite layer (Personal archive, 2015)

In the SLSM, however, sample with 100 mm diameter was cut from the origin of the hydrated GCL samples (D=150 mm) for hydraulic conductivity test (Figure 2.13). The remaining part of the GCL was used to determine the water content of bentonite portion of the GCL. Like CSM, bentonite layer was scratched to take sample for water content determination. Then, the sample was dried in an oven at 105 °C. The water content which was determined at the end of the hydration stage were denoted as “water content of GCL after hydration”.



Figure 2.13 Sampling and monitoring of bentonite in SLSM after GCL: a) Cutting of GCL for hydraulic conductivity test, b) photographic image of swollen bentonite layer (Personal archive, 2015)

The subsoil water contents were determined by layering the compacted soil samples. For this purpose, subsoils were divided into 4, 5 or 7 layers by spatula depending on the heights of the sample (Figure 2.14). The water contents of each layers were determined after 24 hours of drying in an oven at 105 °C.



Figure 2.14 Subsoil after hydration: a) Marking the thicknesses; b) cutting the layers with spatula (Personal archive, 2015)

2.2.6 Hydraulic Conductivity Tests

Hydraulic conductivity tests were performed immediately after the hydration phase was complete. At the end of the hydration with both methods (CSM and SLSM), GCL samples were removed from the permeameter cells and final weights and thicknesses of the GCLs were measured. The hydraulic conductivity tests were performed using flexible wall permeameters in accordance with the ASTM: D6766-14 (2014) and on GCL samples with a diameter of 100 mm. Then, GCLs were placed between two non-woven geotextiles and the perimeter of each GCL was sealed with bentonite. The latex membrane and O-rings were placed to prevent the side-wall leakage.

The falling head water and constant tail water method was employed for the hydraulic conductivity test. Depending on the GCL thickness the hydraulic gradient varied between 80-220 and the average cell pressure was 35 kPa. To simulate the in-situ conditions, back pressure was not applied during the tests. The flow was from top to bottom across the specimen and the outflow was open to the atmosphere. The

influent was given by 50 ml glass burettes and the effluent was collected in 100 ml glass graduated cylinder. Long-term hydraulic conductivity tests were conducted (> 6 months) and terminated when the last 4 consecutive hydraulic conductivity values were within the range of 1.0 ± 0.25 . Based on the principle of head difference that occurs within a specific time interval. GCL hydraulic conductivities were calculated with Equation (2.1) as follows:

$$k = \frac{aL}{A\Delta t} \ln \frac{h_0}{h_1} \quad (2.1)$$

In this equation; k is the hydraulic conductivity (m/s), A is perpendicular cross section area through the flow direction (m^2), a is cross section area of burette (m^2), L is specimen length (m), h_0 (m) and h_1 (m) are initial and final water level in the burettes, respectively and Δt (s) is the elapsed time between two readings.

Hydraulic conductivity test results were expressed in terms of pore volumes of flow (PVF). For example, if the GCL sample have 30 cm^3 voids, this amount of flow through the sample corresponds to 1 PVF. Volume of voids in the GCL was determined in accordance with Petrov et al. (1997). The tests were conducted up to 12 months.

2.2.7 Suction Tests on Geosynthetic Clay Liners and Subsoils

2.2.7.1 Geosynthetic Clay Liners

Suction or water retention of GCLs were evaluated based on ASTM: D5298-16 (2016). Although the filter paper method is an indirect method to determine the suction behavior of GCLs, this method was used for the experiments because of its simplicity and ability to measure both matric and total suction. Suction measurements were conducted on GCL samples with a 55 mm in diameter. To prevent the loss of bentonite during the hydration process, the periphery of GCL sample was covered with silicone grease as shown in Figure 2.15.



Figure 2.15 Photographic image of GCL sample during covering with silicone grease (Personal archive, 2018)

Before starting the suction measurements, GCL samples were hydrated with water at different water contents. As suggested by Barroso et al. (2006), two techniques were used for the hydration of GCLs (Figure 2.16). In the first technique, GCLs were hydrated by spraying a known mass of water onto the surfaces of GCLs to achieve bentonite water contents lower than 45% (Figure 2.16a). In the second technique, however, GCLs were submerged into a water container and each GCL was removed from the container at the end of 1 min, 5 min, 10 min, 15 min, 30 min, 1 h, 4 h, 8 h and 24 h. Hence, greater bentonite water contents ($>45\%$) were achieved (Figure 2.4b).

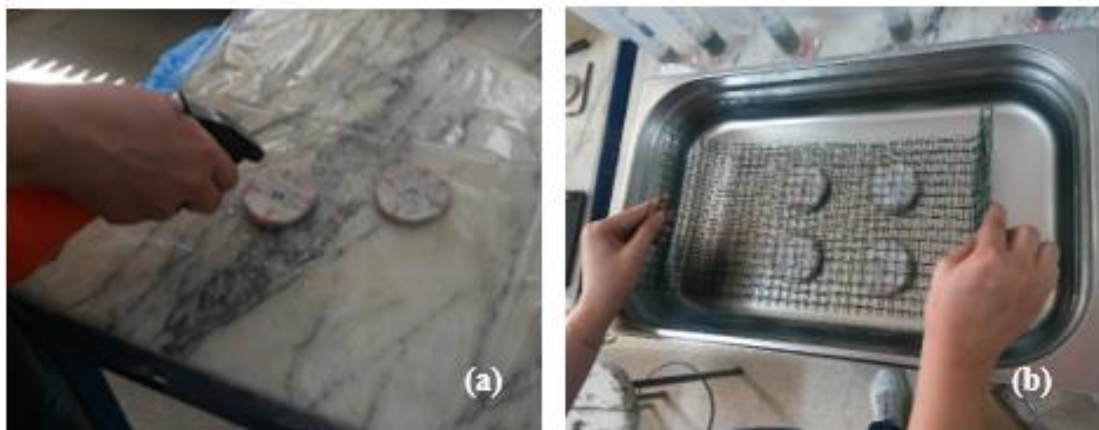


Figure 2.16 Hydration technique applied on GCLs before suction measurements: a) Spraying for low water content and b) submerging for high water content (Personal archive, 2018)

For each water content, two GCL samples were prepared. Once GCLs were moistened or wetted, a parafilm was wrapped around these two GCLs and then, they were put into separate zipper bags for three weeks to obtain homogeneous water contents. Confining stress was not applied on the specimens during the homogenization process. At the end of three weeks, it was assumed that two GCL specimens had the same water contents and identical suction behaviors. Therefore, one of the GCL sample was used for the suction measurement and the other was used for the water content determination. The photos taken during sample preparation for homogenization process are shown in Figure 2.17a and Figure 2.17b.



Figure 2.17 Storage of moistened or wetted GCLs: a) Wrapping with parafilm and b) kept into zipped bags (Personal archive, 2018)

In the content of the matric suction measurements, initially dry contact filter paper test (ID-CFPT) and initially wet contact filter paper test (IW-CFPT) procedures were applied (Acikel et al., 2015). The sensor filter paper was soaked with DIW for 1 h before using for IW-CFPT, whereas air-dried state sensor filter paper was used in ID-CFPT. Therefore, the only difference between the ID-CFPT and IW-CFPT procedures was the initial water content of the sensor filter papers which were placed between two protector filter papers. The other sample preparation steps were the same in both methods.

For the matric suction measurements, three pieces of Whatman No. 42 filter papers (55 mm protector - 47 mm sensor - 55 mm protector) were placed in contact with the

nonwoven side of the GCL (Figure 2.18a). It should be noted that the nonwoven side was selected as the contact face because the GCLs were placed in contact with the subsoils from their nonwoven faces during the hydration process in this study. Then, plastic basement was put over the filter papers and the perimeter of the whole sample was sealed with plastic tape to provide an intimate contact between the filter papers and the GCL (Figure 2.18b). After that, plastic ring type support with a height of 10 to 20 mm was placed on the GCL to provide a non-contact condition for total suction measurements. Then, two filter papers (55 mm in diameter) in initially dry conditions were placed on this support as shown in Figure 2.18c. The edge of the filter paper should be bent up 90° to simplify its later removal. Additionally, 50 mm in thickness plastic protector ring was placed on the circumferences of the GCL to prevent the contact of filter paper in any place. Finally, the whole sample was placed into a zipped bag for three weeks to reach equilibrium (Figure 2.18d).

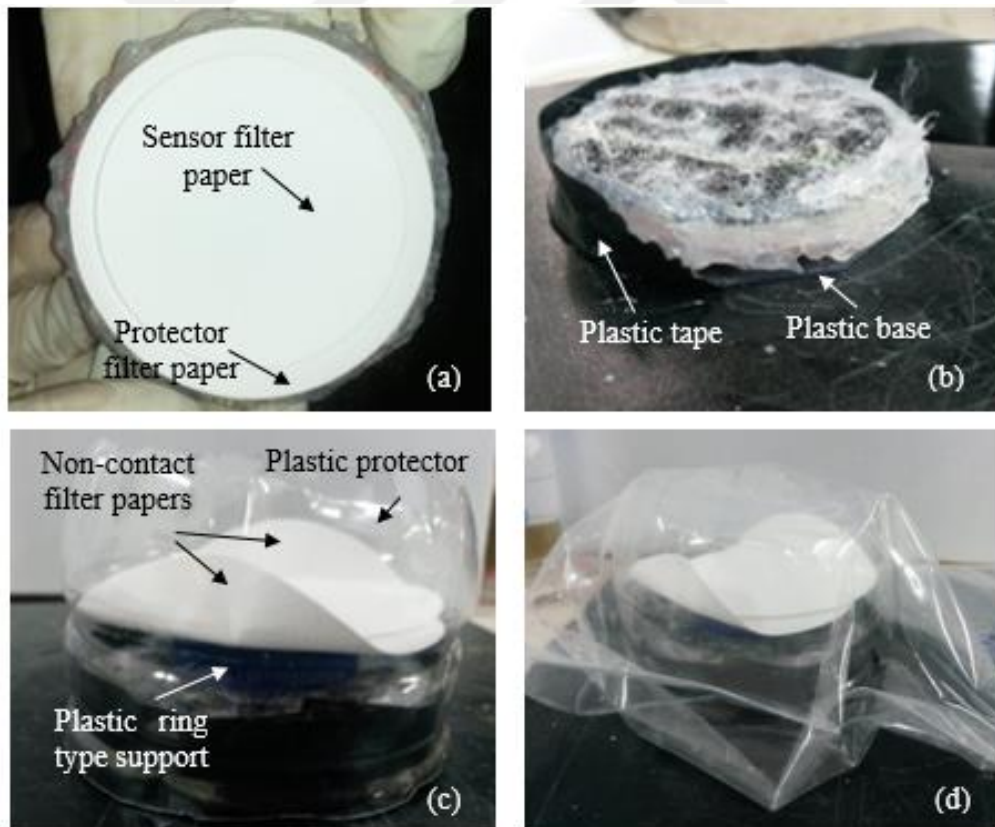


Figure 2.18 Sample preparation steps for suction tests: a) Placing the sensor filter paper in contact with protector filter paper, b) sealing the perimeter of GCL with plastic tape, c) placing the non-contact filter paper over plastic ring support and d) covering all the test setup with nylon bag (Personal archive, 2018)

At the end of the equilibration period, the whole sample was removed from the zipped bag and the water contents of non-contact and in-contact filter papers were determined. As seen in Figure 2.19a and Figure 2.19b, the non-contact filter papers were removed, and their weights were recorded in nearest 0.0001 g accuracy. After that sealed plastic tape was removed, and the in-contact sensor filter paper was removed for the weight determination (Figure 2.19c and Figure 2.19d). The weights of filter papers were recorded very quickly not to allow any evaporation. Subsequently, filter papers were dried in an oven at 105°C to determine the water contents. It should be noted that the water content of the sensor filter paper that in contact with the GCL was used for the matric suction measurement whereas the average of the water content of non-contact two filter papers was used for the total suction measurements.

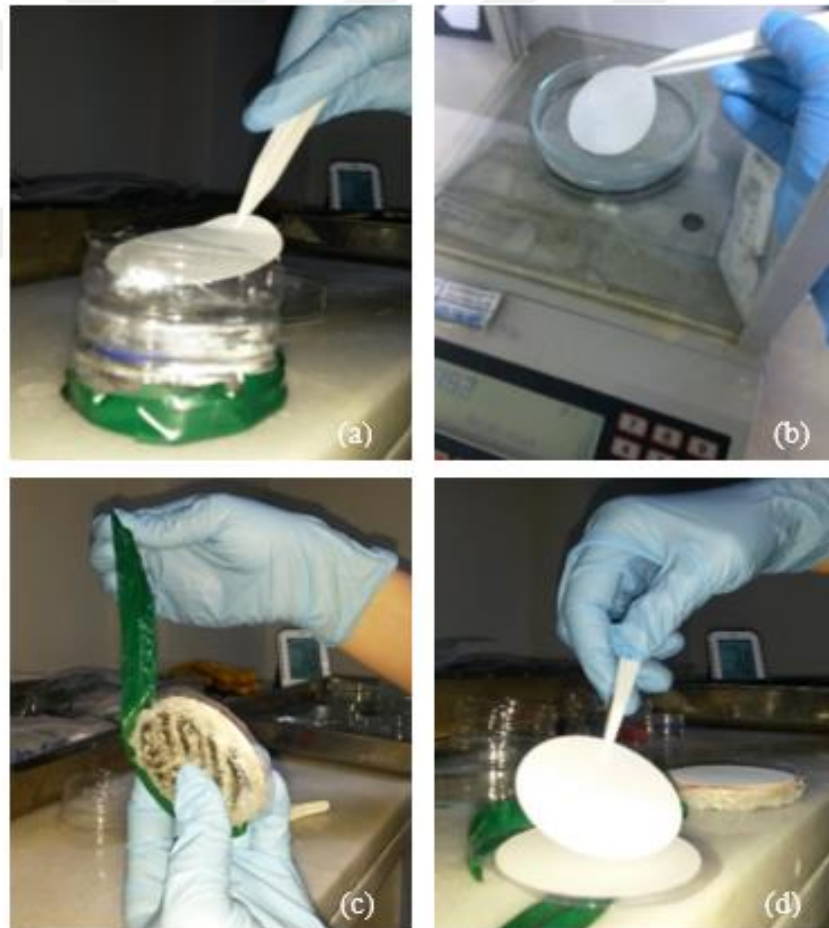


Figure 2.19 Water content determinations of filter papers: a) removing the non-contact filter paper, b) weighing the filter paper, c) removing the plastic tape and d) removing the in-contact filter paper (Personal archive, 2018)

2.2.7.2 Subsoils

Like GCLs, the suction characteristics of subsoils were determined by using the filter paper method as described in ASTM: D 5298-16. The suction measurements were conducted on compacted subsoils at different water contents. For this purpose, subsoils were prepared at different water contents first and left for hydration for one day in a plastic bag. Then, the subsoils were compacted in a mold that had 150 mm diameter and 56 mm thickness (Figure 2.20).

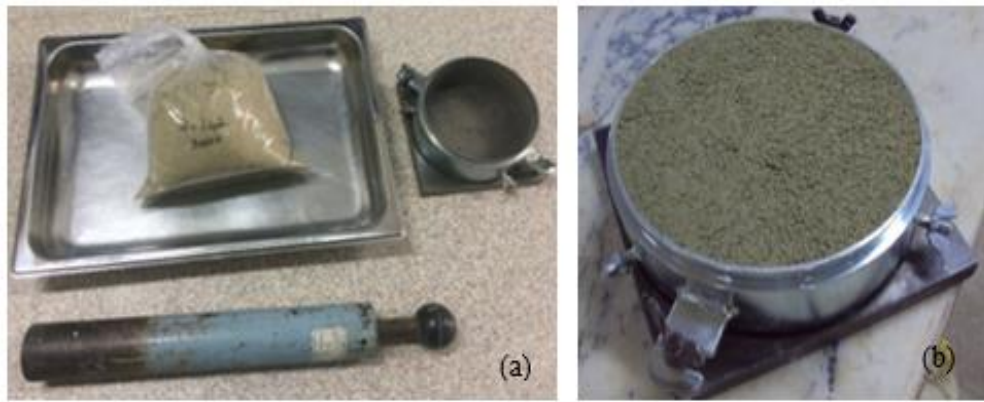


Figure 2.20 Subsoil preparation for suction tests: a) testing equipment and b) compacted subsoil (Personal archive, 2018)

Both matric suction and total suction measurements were conducted on each subsoil (i.e. sand and zeolite). The suction measurements were performed on 55 mm in diameter samples with two replicates. To do this, two samples were taken from the compacted subsoil with a sample extruder. Then, these samples were horizontally divided into two pieces with a sharp razor knife. To represent the drying conditions of the subsoils in field, initially dry contact filter paper test (ID-CFPT) method was used for the measurements. The sample preparation stages for suction tests are shown in Figure 2.21.

A sensor filter paper ($D=47$ mm) was sandwiched between two larger size protector filter papers ($D=55$ mm) and inserted into the soil sample (Figure 2.21a and Figure 2.21b) for matric suction measurements. Note that all filter papers were Whatman No. 42. To provide an intimate contact between the filter paper and the subsoil, the

circumferences of the sample was sealed with a plastic tape (Figure 2.21c). The soil sample with embedded filter papers was put into a 400 ml glass jar with 75 mm in diameter and 90 mm in height. Then, a plastic ring type support was placed on the top of the soil and two initially dry filter papers were inserted on the support for total suction measurements (Figure 2.21d and Figure 2.21e). The cap of the jar was closed at the end of this stage and sealed with plastic tape (Figure 2.21f). The system was placed in a temperature and humidity-controlled room at 20 °C (± 1 °C) temperature and 60% ($\pm 1\%$) humidity for two weeks.

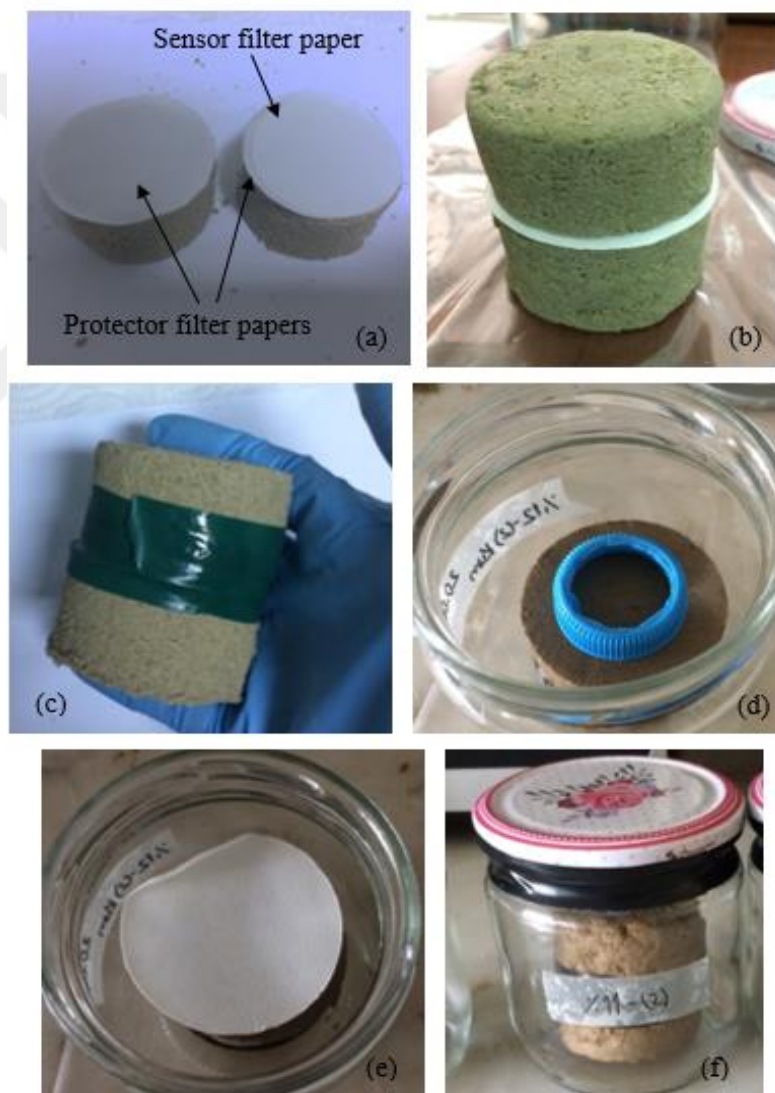


Figure 2.21 Sample preparation for subsoils for matric and total suction tests: a-b) placing the in-contact filter paper between the halves, c) sealing the filter papers with a plastic tape, d) placing the subsoil in a glass jar and mounting the plastic support over the subsoil, e) placing the non-contact filter paper over the plastic support and f) closing the glass jar and sealing it with a plastic tape (Personal archive, 2018)

At the end of two weeks, sealed plastic tape was removed from the circumferences of the jar and the weights of both non-contact and in-contact filter papers were measured. Then, these filter papers were put in to an oven at 105 °C for water content determinations. The removal of the filter papers from the system was also shown in Figure 2.22a-d.

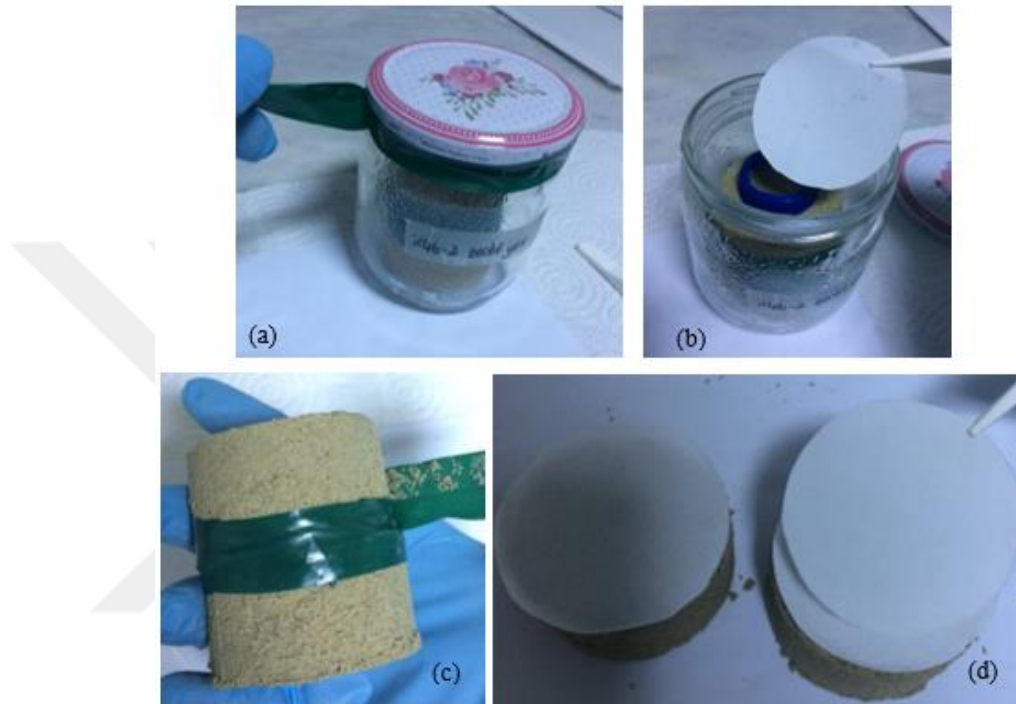


Figure 2.22 Water content determinations of the filter papers after two weeks: a) removing plastic tape from the jar, b) taking out the non-contact filter papers, c) removing plastic tape from the sample and d) handling the sensor filter paper with a tweezer (Personal archive, 2018)

2.2.7.3 Calibration

Filter paper calibration for the suction-water content curves which is suggested in ASTM D5298-16 was performed with salt solutions. For this purpose, sodium chloride (NaCl) solutions of different concentrations (from 0 M (deionized water) and 1 M) were prepared. Each jar was filled with 100 ml NaCl solution, but they were at different concentrations. Then, two Whatman No. 42 filter papers were suspended above the solutions for 15 days. Edges of the caps were also sealed with plastic tape to prevent the air entry. The image of the prepared samples for calibration test is shown in Figure 2.23.



Figure 2.23 Calibration of filter papers (Personal archive, 2018)

At the end of the 15 days of curing, the weights of filter papers were measured with a balance which had 0.0001 g accuracy and dried in an oven at 105 °C for water content determinations. Then, the corresponding suction values, which were calculated based on the concentration of the solutions, were drawn as a function of filter paper water contents. Figure 2.24 shows the calibration suction-water content curves for initially dry (wetting) filter papers obtained from ASTM D5298-16 (2016) and this study. Since as much as 32% water content was obtained from the calibration tests, the calibration curve suggested for Whatman No. 42 by ASTM D5298-16 (2016) was used for the filter papers at initially dry state. It should be noted that the calibration tests were not conducted for initially wet filter papers. The calibration curve suggested by Parcevaux (1980) was used for this purpose. The calibration curves for wet filter papers (drying of filter paper) adopted from Parcevaux (1980) is shown in Figure 2.24.

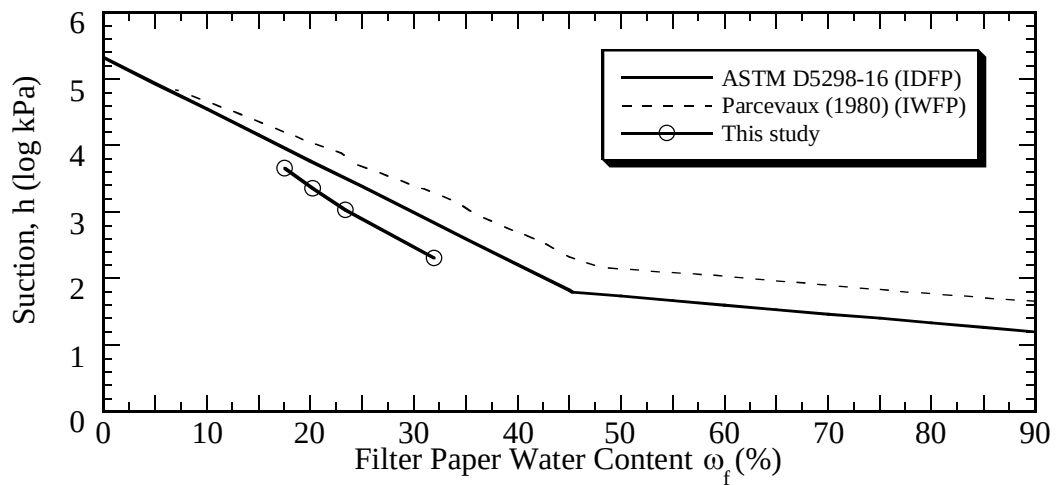


Figure 2.24 Calibration suction-water content curves for initially dry and initially wet filter papers

2.2.8 Chemical Analysis

2.2.8.1 Chemical Analysis of GCLs

Chemical analyses were performed to determine the influence of subsoil hydration on the GCLs. For this purpose, bound cations and cation exchange capacities of GCLs were investigated. The bound cations of bentonite were determined by following ASTM: D7503-10 (2010). Ten-gram bentonite and 40 ml of 1 M ammonium acetate (NH_4OAc) solution were added to 100 ml plastic covered container. This container was shaken in end-over-end shaker at 30 rpm and then the suspension was left for 24 hours at room temperature. After 24 hours, the suspension was shaken for 15 minutes again and filtered through ashless filter paper which was lined on Buchner funnel. Low suction was applied ($< 10\text{kPa}$) during filtering and the filtrate was collected in 500 ml filtering flask. Bentonite was washed four times with 30 ml of 1 M NH_4OAc solution. The filtrate was then transferred to 250 ml volumetric flask and a few drops of nitric acid was added to the solution maintain a pH of 2.

The filtrate was analyzed with Pelkin Elmer DV 2100 Optima ICP-OES to determine the concentrations of Na^+ , K^+ , Ca^{2+} , and Mg^{2+} in the exchange complex of bentonite. This device is available in the Department of Environmental Engineering Laboratories at Dokuz Eylül University (Figure 2.25).



Figure 2.25 Pelkin Elmer DV 2100 Optima ICP-OES device that was used for the determination of cation concentrations in bentonites (Personal archive, 2017)

When washing process with the NH_4OAc solution was completed, the same bentonite was used to determine the CEC. To do this, bentonite was washed three times with 40 ml of isopropanol and then four times with 50 ml of 1 M potassium chloride (KCl) solutions. Last extract (KCl extract) was transferred to the 250 ml volumetric flask and filled to volume with water (ASTM: D7503-10, 2010). Spectroquant Ammonium cell test (NH_4^+) kits were used for the CEC. Since NH_4^+ measurement range of the kits was between 4 mg/L and 80 mg/L, all filtered extracts were initially diluted. Then, 0.1 ml diluted KCl extract and one dose of $\text{NH}_4\text{-1K}$ reagent were dropped into the reaction cell. The reaction cell was shaken to dissolve the reagent. After 15 minutes, the nitrogen concentration (mg/L) in the KCl extract was determined with photolab S12 type spectrophotometer which was available in Department of Environmental Engineering Laboratories at Dokuz Eylül University (Figure 2.26). before the measurement. The nitrogen concentration was determined in terms of mg/L and calculated as following:

$$CEC (cmol^+/kg) = N \times \frac{1 (cmol^+)}{140 (mg)} \times \frac{0.25 (L)}{M_0 (g)} \times 1000 \frac{g}{kg} \quad (2.2)$$

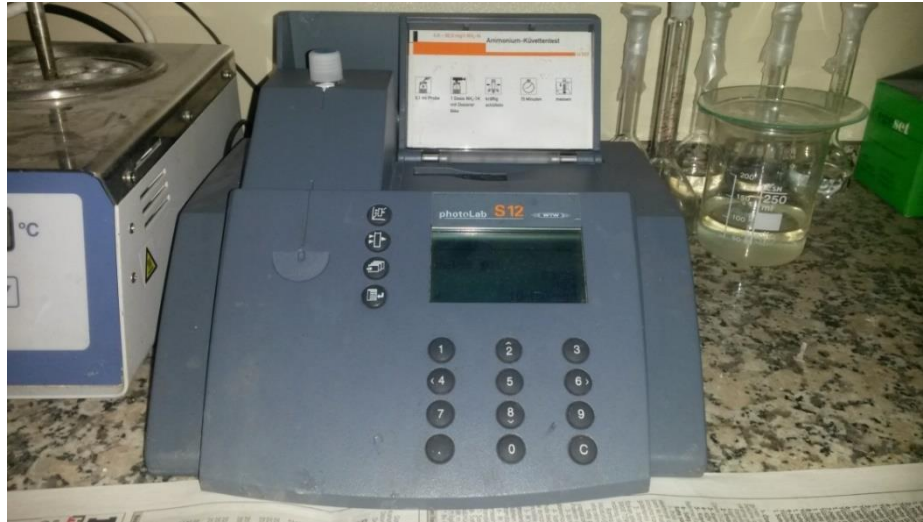


Figure 2.26 PhotoLab S12 type spectrophotometer device that was used while determining the cation exchange capacity (CEC) of bentonites (Personal archive, 2017)

2.2.8.2 Chemical Analysis on Subsoils

The major cation concentrations of the subsoils (Na^+ , K^+ , Ca^{++} and Mg^{++}) were detected with batch test. For this purpose, batch elution tests were conducted on the subsoils in accordance with ASTM: D6141(2014) and Meer and Benson (2007). The slurry samples in 1.3:1.0 liquid to dry solid ratio were prepared and tumbled at 30 rpm for 24 h and then, the slurry was centrifuged to separate the solid and liquid phases. The liquid phase (or supernatant) was used for the chemical analysis after filtration from the $0.45\mu\text{m}$ ashless filter paper. The chemical characteristics of pore waters of sand and zeolite-2 are given in Table 2.3.

Table 2.3 Chemical characteristics of pore water of subsoils

Subsoil	Pore Water Property			
	Na (mM)	K (mM)	Ca (mM)	Mg (mM)
Sand	0.872	0.265	0.402	0.363
Zeolite-2	1.075	0.206	0.494	0.271

CHAPTER THREE

DETERMINATION OF TESTING METHOD FOR THE HYDRATION OF GEOSYNTHETIC CLAY LINERS OVER COMPACTED SUBSOILS

3.1 Background

GCL water content is related to the amount of water that is taken from the subsoil by suction. Swelling of bentonite by water suction from the subsoil is referred to as “hydration”. Recently, studies on the GCL hydration increased in number and this subject became especially important for cover constructions.

In order to simulate the in-situ conditions better, GCL hydration studies have been conducted on the compacted subsoils. Experiments on GCL hydration over the compacted subsoils can be classified in two groups: i) tests that were conducted in PVC (and/or acrylic) molds and ii) tests with control samples which were performed in flexible-wall permeameters.

GCL hydration in PVC molds enable to prepare large samples. Thus, sample size can be increased, and site conditions can be simulated better. Then, samples could be cut out from the center of hydrated GCLs for the hydraulic conductivity tests. Bentonite water contents in GCLs can be determined from the remaining pieces as well. Therefore, bentonite water content and hydraulic conductivity relationship could be compared more realistically.

The tests conducted in PVC molds were used more often in the literature for GCL hydration. Rayhani et al. (2011) used PVC molds with 150 mm in diameter and 500 mm in height; Anderson, Rayhani & Rowe (2012), Barclay & Rayhani (2013) and Sarabian & Rayhani (2013) used 150 mm diameter and 300 mm height PVC molds and Chevrier et al. (2012) used little smaller PVC molds (i.e. 95 mm in diameter and 300 mm in height). However, only hydration behaviors of GCLs over different subsoils were investigated in these studies. That is, hydraulic conductivity performances of

hydrated GCLs were out of the scope of those studies. On the other hand, Katsumi et al. (2008a) hydrated two different GCLs in 100 mm diameter and 150 mm height acrylic mold. After that, they conducted hydraulic conductivity tests on 60 mm diameter samples which were cut from the hydrated GCLs. It should be noted that only Katsumi et al. (2008a) was able to explain the relationship between the GCL hydration and hydraulic conductivity.

The studies conducted in PVC molds, the vertical stress applied on the GCLs were around 1-2 kPa. However, it would be hard to apply relatively high stresses on the samples with this method. For example, in order to apply 1 kPa stress on GCL with 150 mm diameter, 1.8 kg load is required. When the sample diameter is increased to 600 mm, the required load for the same stress becomes 28 kg. On the other hand, if the applied stress increases so as to simulate the site conditions, greater loads are required (i.e. for 10 kPa stress application on 150 mm and 600 mm diameter GCL samples, 18 kg and 280 kg load should be applied, respectively). Thus, it is hard to apply such loads in the laboratory.

In the second method which is conducted in flexible-wall permeameters, two GCL samples with the same diameter (generally 100 mm in diameter) are cut from the GCL roll. Both GCLs are left for hydration. At the end of hydration, one of these GCL samples is used for the hydraulic conductivity test, whereas the other is used for water content determination. Since the system is connected to the pressure control panel, the target pressure can be easily applied on GCLs. In addition to this, impact of hydration on the swollen bentonite can be observed by separating the geotextiles components from each other. However, the studies that use control samples are very scarce in the literature. Bradshaw et al. (2013) investigated the hydraulic conductivity behavior of GCL samples which were hydrated with this method.

When test set up with control sample is preferred to be used for hydration, the comparison between the water content and hydraulic conductivity of GCLs becomes difficult. This is because of the difficulties in preparing unique samples not only for the subsoil but also for the GCL (i.e. compaction parameters of the subsoils or mass

per unit area of GCLs may be different with each other). This may be eliminated by adapting the hydration of larger GCLs in flexible-wall permeameters (Katsumi et al., 2008a). By this new method, a permeameter with testing ability of 150 mm in diameter can be manufactured and GCL sample can be hydrated even under greater stresses in such kind of flexible-wall permeameters. Hence a 100 mm in diameter sample can be cut from the center of hydrated GCL for the hydraulic conductivity test and rest of the GCL can be used to determine water content. Thus, the interpretation of test results becomes more realistic.

Some factors that affect the hydration of GCL (i.e. subsoil type, hydration duration and temperature) have been investigated so far. However, the method that should be used for GCL hydration is still questionable. This study compares the GCL hydration methods using flexible-wall permeameters. For this purpose, GCL-1 (LP) was hydrated with two different methods. In the first method, which is named as “Control Sample Method (CSM)”, GCLs were individually hydrated in two flexible wall permeameters (Bradshaw et al., 2013). The second method was adapted from Katsumi et al. (2008a). A larger permeameter was used to hydrate the GCL. Therefore, this method is called as “Single Large Sample Method (SLSM)”. The method efficiency was discussed in terms of bentonite water content henceforth.

3.2 Influence of Hydration Method on the Geosynthetic Clay Liners

The influence of hydration method on the water contents of GCL-1 were investigated by hydrating the GCL over the compacted sand which had the same aspect ratios ($AR = \text{Length/Diameter} = 1.14$). For this purpose, GCL-1 was hydrated with two different methods (CSM and SLSM). The results were compared based on the water contents of GCL-1 after hydration. Figure 3.1 shows the influence of hydration method on the GCL-1 by considering the hydration durations.

As seen in Figure 3.1a, water contents of GCL-1 increased from 12.6% to 56.9% with CSM and to 55.4% with SLSM in the first 7 days of hydration. At the end of the 62 days of hydration, water contents were determined as 66.7% and 71.7% with CSM

and SLSM, respectively. When the results were compared based on the hydration durations, it can be stated that, there are no significant differences between the bentonite water contents from both hydration methods (Figure 3.1b). It was observed that the water content of GCL-1 after 62 days of hydration with SLSM was 5% greater than that of obtained with CSM.

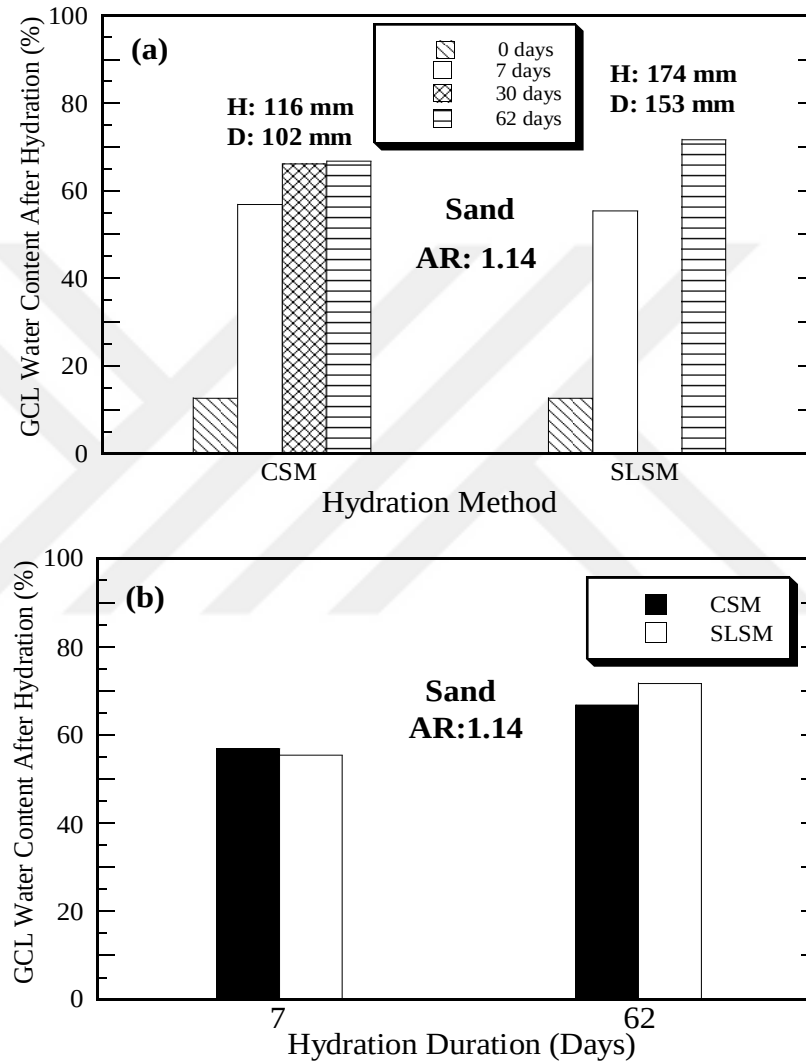


Figure 3.1 Comparison of water contents of GCL-1 after hydration depending on: a) the hydration duration and b) hydration method

The changes on bentonite after 62 days of hydration were also investigated visually on both applied hydration methods. Fibers between the geotextiles were detached with a sharp razor knife and bentonite layer were photographed (Figure 3.2). Figure 3.2a

and Figure 3.2b show the bentonite in GCL-1 after 62 days of hydration using CSM and SLSM, respectively.



Figure 3.2 The picture of GCL-1 after 62 days of hydration with: a) CSM and b) SLSM (Personal archive, 2017)

It can be clearly seen from Figure 3.2a, bentonite particles tended to form an impervious layer by swelling during the hydration with CSM. However, there were still fiber bundles induced gaps between the particles. The distribution and the size of these gaps had an importance on the hydraulic behavior of the GCL-1.

The picture of GCL-1 hydrated for 62 days with SLSM is also shown in Figure 3.2b. Because sample was taken for the hydraulic conductivity test, there is an empty space in the center of the GCL. It can be seen from Figure 3.2b that the bentonite particles tended to fill the gaps by swelling. However, it is observed that there were more gaps in the bentonite layer with this method instead of CSM. This might have been generated from the difficulties during the detachment of fibers. Since the width of the remaining portion of the GCL is narrow (about 20 mm), GCL was inevitably bent while cutting, resulting in unnatural planar crack formations over bentonite layer (Figure 3.2b).

On the other hand, the surface area of the remaining portion of the GCL-1 in SLSM (Figure 3.2b) is greater than the area of the same GCL in CSM (Figure 3.2a) (i.e. 9800 mm² versus 7900 mm²). This surplus area means that more bentonite can be obtained with SLSM compared to CSM for the determination of some other properties of bentonite in addition to the water content such as swell index, cation exchange capacity, exchangeable cations and specific surface area.

3.3 Influence of Hydration Method on the Water Content Profiles of the Subsoils

GCLs whose water contents increase by suction during the hydration processes result in some changes in the water contents of the subsoils as well. The determination of this variation in the subsoil water content is very important for the evaluation of GCL water uptake. To determine the water content changes in the soil profiles, subsoils were divided into 5 layers for CSM and 7 layers for SLSM. Except for the bottom layer, layer thicknesses were taken as 25 mm. The residual thickness at the bottom layers of subsoils were taken as 16 mm in CSM and 24 mm in SLSM.

The influence of hydration method on the water content of sand subsoil for 7 days of hydration is demonstrated in Figure 3.3 in two ways. The water contents in Figure 3.3 are shown from the midpoints of the sublayers. In the first demonstration (Figure 3.3a), water content profiles are drawn by considering the total heights of the subsoils. However, it is seen that the subsoil heights were different (i.e. 116 mm versus 174

mm) depending on the hydration method. To compare the results, subsoil heights were normalized by dividing the sublayer height to corresponding subsoil height as shown in the second demonstration (Figure 3.3b).

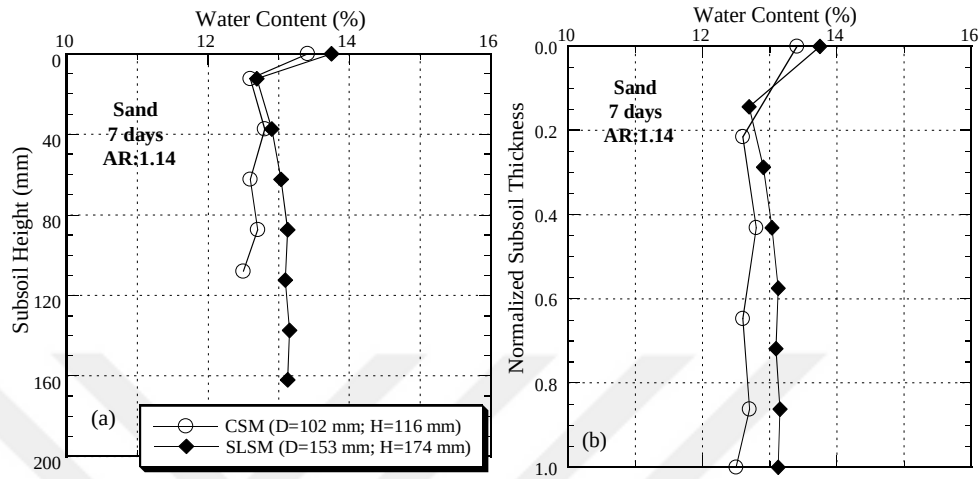


Figure 3.3 Changes in the water contents of subsoils after 7 days of hydration depending on the GCL hydration method throughout the a) original and b) normalized thicknesses

It can be seen from Figure 3.3 that the traces of water content changes were very similar to each other with two methods. The water contents of the first sublayers in each method that were in contact with the GCL-1 suddenly decreased and became drier than the subsequent layers. GCL, that had drier (i.e. 12%) and finer particles with respect to the subsoil, was adsorbed much water from the compacted sand due to capillary forces. Therefore, the sublayer that was in contact with the GCL-1 decreased while the water content of GCL-1 increased (Figure 3.3). On the other hand, the subsoil water contents obtained from SLSM were somewhat higher than those of the water contents obtained from CSM (Figure 3.3). The reason of this difference may be sourced from the subsoil. That is the initial water content of the subsoil used for SLSM was slightly greater than that of the subsoil used for CSM (13.8% versus 13.4%). The other explanation is that the pore size distributions of the subsoils were possibly not resemble within each other when compacted, resulting different suction characteristics during hydration.

Changes in the subsoil water contents after 62 days of hydration is shown in Figure 3.4 as a function of subsoil height and normalized height. It can be seen that the subsoil water content profiles after 62 days of hydration quite similar to those of obtained from 7 days of hydration. Subsoil water contents obtained from SLSM were greater than the water contents obtained from CSM. The reason of this difference may be due to rather greater initial subsoil water content during the hydration with SLSM.

Furthermore, the subsoil water content profiles after 62 days of hydration were somewhat different from each other regarding to the applied hydration methods. The water content of the first sublayer (upper or top layer) of the subsoil decreased while the water contents of the subsequent layers increased for CSM. However, the subsoil water content decreased up to second sublayer and then started to increase below this layer with SLSM (Figure 3.4a). When normalized water content profiles are compared, however, similar water content paths across the sample height were obtained from both methods (Figure 3.4b). In other words, the changes in the subsoil water contents were initiated at around the same normalized thicknesses.

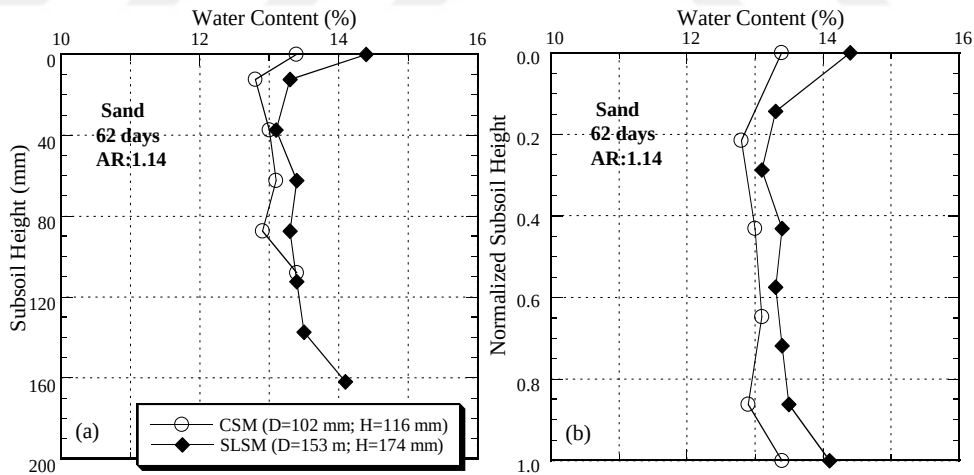


Figure 3.4 Changes in the water contents of subsoils after 62 days of hydration depending on the GCL hydration method throughout the a) original and b) normalized thicknesses

It is also obtained from both methods that the subsoil water contents increased in the bottom layers of the subsoils. The reason of this difference may be attributed to the migration of water through the subsoil due to gravity forces. Similar behavior was not seen for the subsoils hydrated for 7 days since the hydration duration was short.

Although the subsoil thicknesses were different within each other, the changes in the water content profiles of the subsoils which had the same ARs, were quite similar (Figure 3.3 and Figure 3.4). In addition to this, the water contents of the GCLs were in close ranges when they were subjected to 7 and 62 days of hydration by CSM and SLSM (i.e. 56.9% versus 55.4% and 66.7% versus 71.7%, respectively).

3.4 Influence of Subsoil Diameter on the Hydration of Geosynthetic Clay Liners

3.4.1 Hydration over Compacted Sand

The influence of sample diameter (or contact area) on the hydration of GCL was investigated first by hydrating over compacted sand which had different ARs (i.e. 1.14 for CSM and 0.76 for SLSM). For this purpose, sand subsoils were compacted in molds which had the same heights ($H=116$ mm) but different diameters ($D=100$ mm for CSM and $D=150$ mm for SLSM). To represent the short and long-term test durations, GCL-1 was hydrated over compacted sand for 7 days and 62 days. The influence of hydration methods on GCL-1 is shown in Figure 3.5.

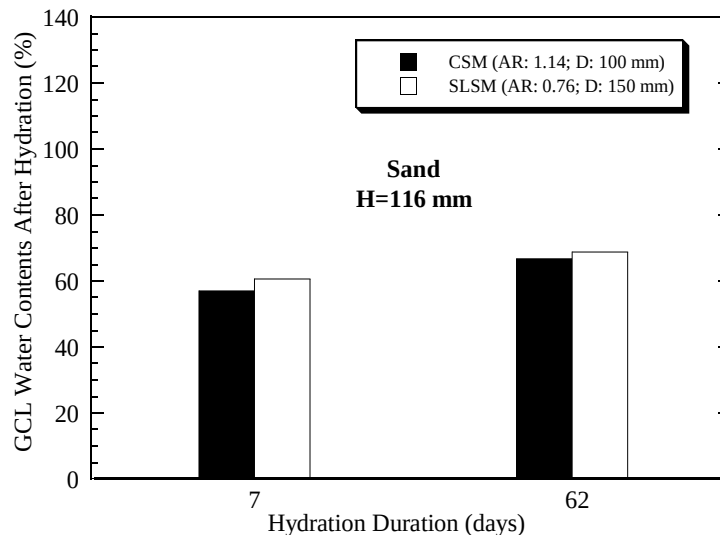


Figure 3.5 The influence of hydration method on the final water contents of GCL-1

Based on the hydration methods, increase in the subsoil diameter resulted 7% difference in the water contents of GCL-1 in short-term hydration (i.e. 7 days).

However, this difference decreased to 3% when the hydration duration was increased to 62 days. The difference between the water contents of GCL-1 possibly resulted from the subsoil water contents which were used for hydration. Subsoil water content profiles drawn as a function of sample height and normalized height is shown in Figure 3.6.

As seen in Figure 3.6, the paths of water content profiles for both methods are quite similar. However, the initial water contents of the subsoils used for SLSM were greater than those of water contents used for CSM (Figure 3.6a-b). The differences between the initial water contents of the subsoils were 1.1% for 7 days of hydration and 0.6% for 62 days of hydration. Hence, the water contents of GCL-1 became greater when SLSM was used [56.9% versus 60.6% for 7 days of hydration and 66.7% versus 68.8% for 62 days of hydration (Figure 3.5)].

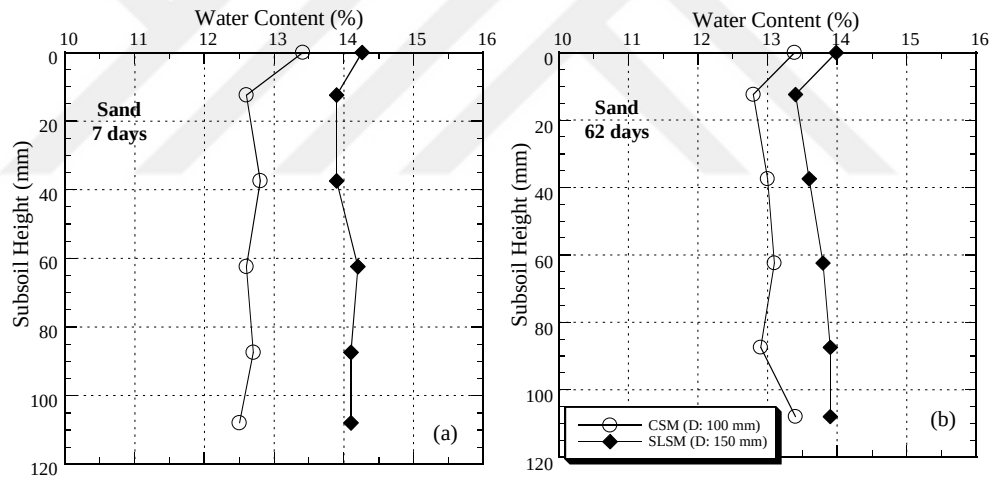


Figure 3.6 Influence of hydration method on the subsoil water content profile depending on the subsoil diameter for a) 7 days of hydration and b) 62 days of hydration

3.4.2 Hydration over Compacted Zeolite-1

It is known that the increase in the subsoil water content has a positive effect on the hydration of GCLs. Several researchers have investigated this effect for clayey sands and silty sands in the literature (Anderson, Rayhani & Rowe, 2012; Chevrier et al., 2012; Sarabian & Rayhani, 2013). However, compaction of these subsoils with greater

water contents are not practical. Therefore, zeolite which has greater compaction water contents than silty sands and clays was used in this study as the second subsoil. The comparison of the hydration methods regarding to the subsoil diameters were made using zeolite-1. Regarding to the heavy testing program, GCL-1 was hydrated over zeolite-1 just for 17 and 30 days. The results are shown in Figure 3.7 as a function of water contents of GCL-1 after hydration.

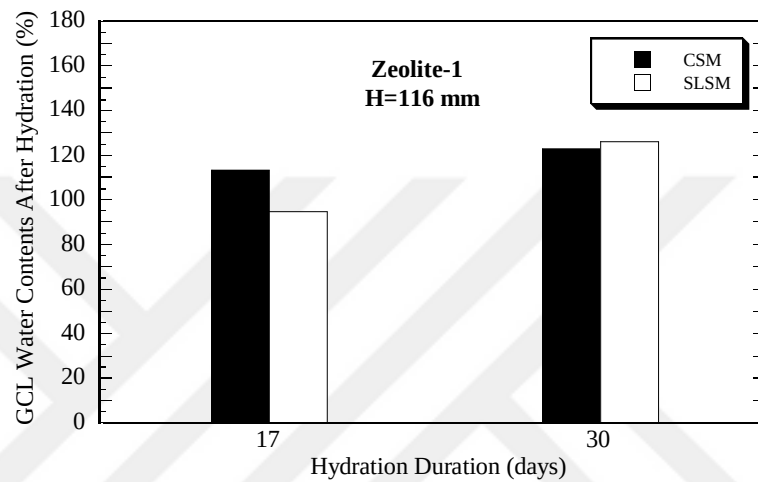


Figure 3.7 Comparison of the hydration methods on GCL-1

The water contents of GCL-1 after hydration were 113.1% and 94.7% after 17 days of hydration. Then, they increased to 122.8% and 126.1% after 30 days of hydration with CSM and SLSM, respectively. The GCL water contents after hydration over compacted zeolite were significantly greater than those of the water contents obtained after hydration over compacted sand (i.e. 66.7% for CSM and 68.8% for SLSM after 62 days of hydration). In other words, water contents of GCL-1 increased up to two times when zeolite-1 was used as the subsoil instead of sand.

Hydration over sand subsoil which were compacted with the same and different ARs resulted up to 8% greater GCL water contents with SLSM than with CSM (Figure 3.1 and Figure 3.5). Similar situation was observed for the GCL-1 when hydrated over compacted zeolite for 30 days. At this time, 3% greater GCL water contents were obtained with SLSM than with CSM. Although there were some differences in the water contents of GCL-1 after hydration depending on the hydration methods and

hydration durations, it is noteworthy that hydration over compacted zeolite had greater effect on the GCL water content than hydration over compacted sand.

The influence of hydration method on the subsoil water content profile was also investigated for zeolite subsoil (Figure 3.8). As seen in Figure 3.8a, the subsoil water content profiles for 17 days of hydration were similar with those profiles obtained with compacted sand. In other words, subsoil water contents decreased in the GCL contact layers. Then, water content increased in the subsequent layers and became stable. In addition, lower subsoil water contents were obtained for 17 days of hydration which may be attributed to the difference between the initial water contents of the subsoils.

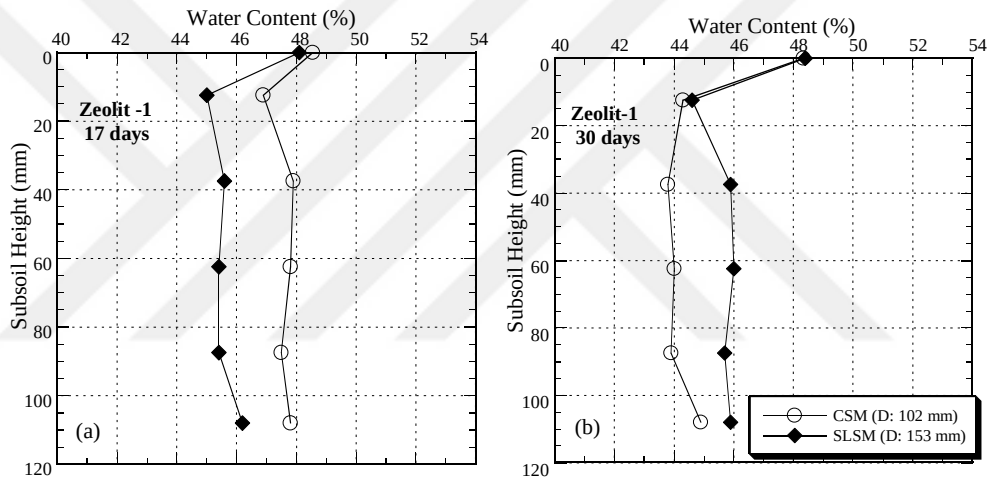


Figure 3.8 Subsoil water content profile with D=100 mm for a) 17 days of hydration and b) 30 days of hydration

The subsoil water content profiles for the longer hydration duration (i.e. 30 days) are shown in Figure 3.8b. The water contents of the subsoils which had almost the same (i.e. 48%) initial water contents decreased to 44.5% for both methods and showed some differences across the sample height. The subsoil water content decreased to 43.8% after first layer and then kept constant in the following sublayers when CSM was used. In contrast, the subsoil water content increased to 45.9% in second layer and became stable through the bottom of the sample for SLSM. Since subsoil initial water contents were the same, the differences in the subsoil water content profiles cannot be related with the initial compaction water contents of the subsoils. The reason of this

difference may be attributed to the GCL properties such as the mass per unit area (MPUA) of bentonites. The MPUA of GCL-1 hydrated for 30 days over zeolite-1 were 3.92 kg/m² for SLSM and 4.05 kg/m² for CSM. This means that if the mass of water is divided to lower bentonite mass, then greater water contents can be achieved at lower MPUA. Because of this, greater GCL water contents were obtained with SLSM than those obtained with CSM (126.1% to 122.8%).

3.5 Influence of Subsoil Height on the Hydration of Geosynthetic Clay Liners

The influence of subsoil height (thickness) was investigated with SLSM in terms of water contents of GCL-1 after hydration. For this purpose, sand subsoils were compacted in 150 mm diameter molds with different heights (from 59 mm to 174 mm). The blow counts and number of layers were arranged to achieve the same dry density as previously obtained from compaction test (Table 3.1).

Table 3.1 Compaction conditions for sand for different molds

Subsoil Diameter	Subsoil Height	Number of layers	Blow counts per layer
D (cm)	H (cm)		
15.3	5.9	2	36
15.2	11.6	3	56
15.3	17.4	5	52

GCL-1 was hydrated for over 59 mm in height of compacted sand for 7 days, 30 days and 62 days and over 116 mm and 174 mm in height of the same subsoil for 7 days and 62 days. The influence of subsoil heights on the water contents of GCL-1 is shown in Figure 3.9. The changes in the subsoil height had no significant effect on the hydration of GCL-1. That is, the water contents of all GCL samples increased significantly after 7 days of hydration and further hydration resulted in a slight increase in the water contents of GCL-1.

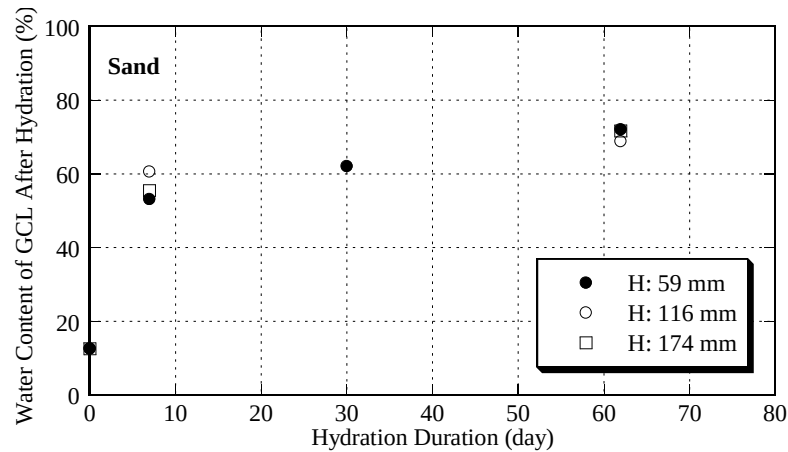


Figure 3.9 Influence of subsoil height on the hydration water content of GCL

The comparison of the water contents of GCL-1 as a function of subsoil height is shown in Figure 3.10. In the case of 7 days of hydration, the final water content was 53.1% when GCL-1 was hydrated over the 59 mm in height of subsoil and 60.6% when hydrated over the 116 mm in height. However, the final GCL water content decreased to 55.4% when the subsoil height was increased to 174 mm. The water content differences were 7.5% at most when GCL-1 was hydrated for 7 days. In contrast, the final GCL water contents changed rather negligibly in the case of 62 days of hydration. The lowest water content was obtained for subsoil of 116 mm in height. Depending on the subsoil heights, the differences in the water contents of GCL-1 was around 3.2%. The reason for these differences may possibly be related to small deviations in the initial subsoil compaction water contents.

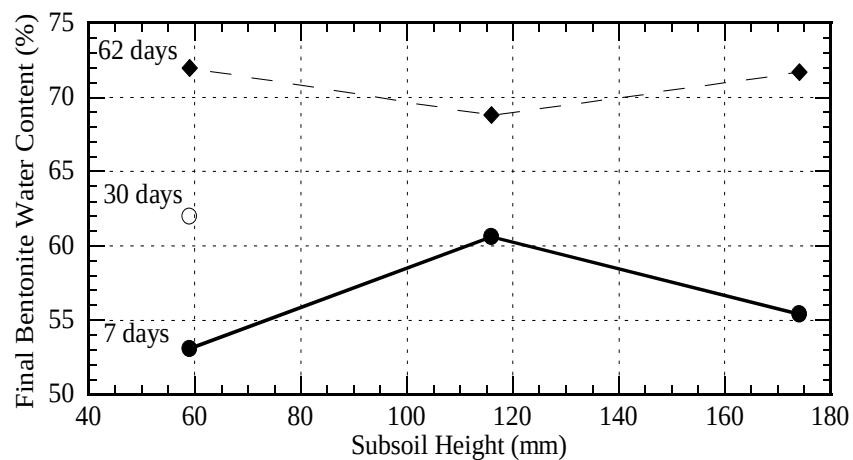


Figure 3.10 Influence of subsoil height on the hydration water content of GCL-1

After hydration the subsoils were divided into sub-layers (4 to 7 layers) to determine the water content changes across the soil profiles (Figure 3.11). The water content profiles of the subsoils are demonstrated in a similar way as previously described.

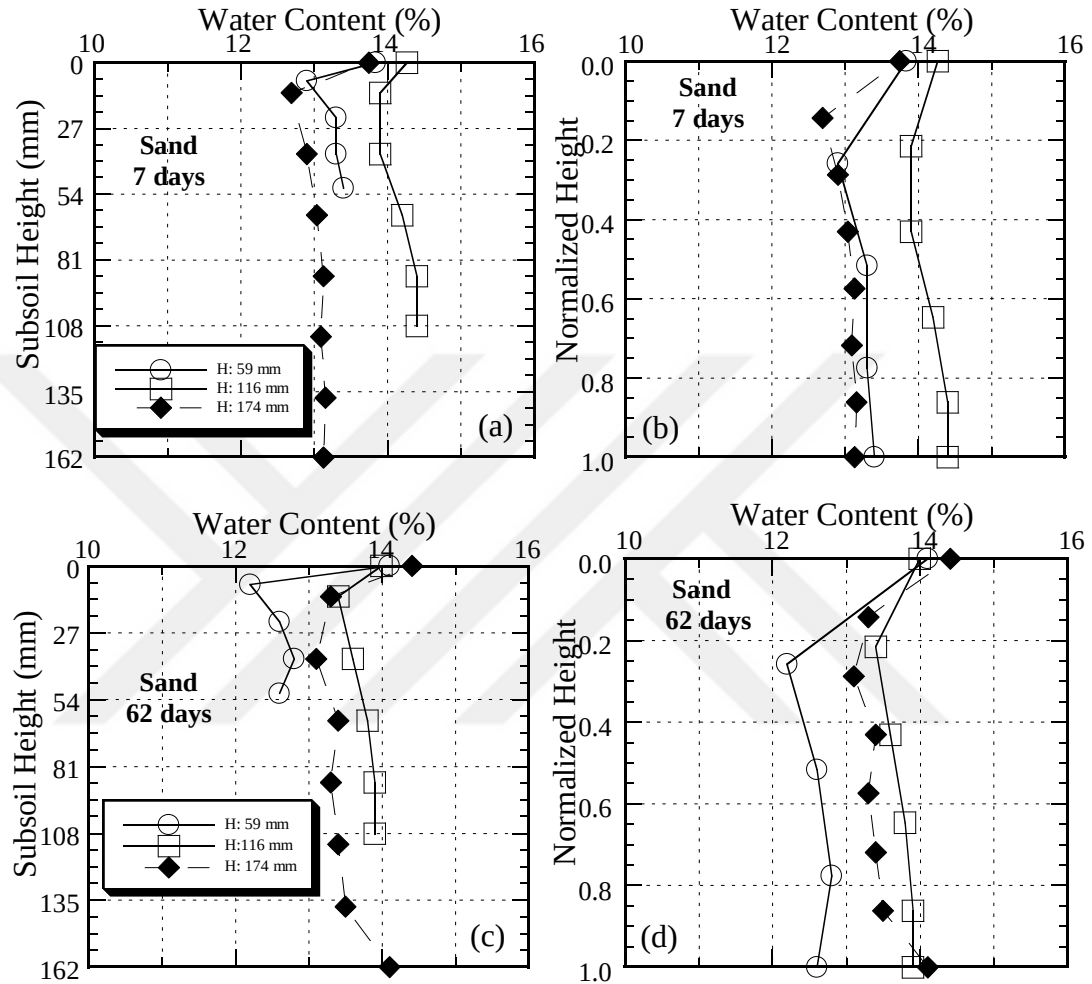


Figure 3.11 Water content distributions across the subsoil in terms of: a) total height and b) normalized height for 7 days of hydration; c) total height and d) normalized height for 62 days of hydration

Regardless of the hydration duration and subsoil height, general appearance of water content distribution across the subsoils were the same. Water content of the subsoil decreased in the first layer where GCL-1 was overlying the subsoil. This reduction in the water content can be attributed to the high suction potential of bentonite. In the subsequent layers, water contents of the subsoil slightly increased but still almost the same with the initial compaction water content. The migration of the

pore water due to gravity led to have greater water contents through the bottom of the samples (Barclay & Rayhani 2013; Chevrier et al., 2012).

In contrast, although the profile of water content distribution is the same for all subsoils, the profiles are somewhat different within each other. There are small differences in the initial compaction water contents of the subsoils. However, these differences are being more pronounced in the proceeding layers. In other words, water content profiles are apart from each other but almost parallel within each other. Thus, the differences in the final water contents of GCL-1 can be attributed not only to the initial compaction water content of subsoil, but also to suction characteristics of both the GCL-1 and subsoil. Thus, subsoil height can be accepted as one of an important factor that influences the hydration of GCLs while performing such tests in the laboratory.

3.6 Influence of Hydration Method on the Hydraulic Conductivity

The influence of hydration method on the long-term hydraulic conductivity of GCL-1 was investigated in terms of hydration methods. For this purpose, GCL-1 was hydrated over compacted sand and zeolite-1 then, hydrated GCL samples were subjected to the hydraulic conductivity tests with deionized water (DIW). The test results are summarized in Table 3.2.

Table 3.2 The summary of the hydraulic conductivity tests conducted on GCL-1

Test No	Subsoil Type	Subsoil Height (mm)	Subsoil AR	Hydration Duration (days)	Hydration Method	Test Duration (days)	Hydraulic Conductivity (m/s)
1	Sand	116	1.14	7	CSM	162	2.3×10^{-11}
2	Sand	174	1.14	7	SLSM	80	1.7×10^{-11}
3	Sand	116	0.76	7	SLSM	107	3.2×10^{-11}
4	Sand	116	1.14	62	CSM	92	2.6×10^{-11}
5	Sand	174	1.14	62	SLSM	90	3.1×10^{-11}
6	Zeolite-1	116	1.14	17	CSM	137	1.8×10^{-11}
7	Zeolite-1	116	0.76	17	SLSM	165	5.7×10^{-11}
8	Zeolite-1	116	1.14	30	CSM	92	4.1×10^{-11}
9	Zeolite-1	116	0.76	30	SLSM	191	2.5×10^{-11}

Regardless of the subsoil aspect ratio, hydration method and hydration duration, the final hydraulic conductivities of GCL-1 hydrated over compacted sand varied between 1.7×10^{-11} m/s and 3.2×10^{-11} m/s. Similarly, the hydraulic conductivities of GCL-1 hydrated over compacted zeolite were between 1.8×10^{-11} m/s and 5.7×10^{-11} m/s. As depicted in Table 3.2, slightly greater hydraulic conductivities were obtained when GCL-1 was hydrated over zeolite. This difference may be resulted from small deviations in the testing conditions such as effective stress and hydraulic gradient or MPUA of GCL-1. Although the final hydraulic conductivities of GCLs were close to each other, the long-term hydraulic behaviors are rather different. The initial hydraulic conductivities of all samples were around 2.0×10^{-8} m/s. Then, the hydraulic conductivities started to decrease after permeation with several PVFs and reached to the average of 2.2×10^{-11} m/s (Figure 3.12). However, this hydraulic behavior was obtained independent from the hydration method. In other words, hydration method had no significant effect on the hydraulic conductivity behavior of GCL-1 (or at least for low performance (LP) GCL).

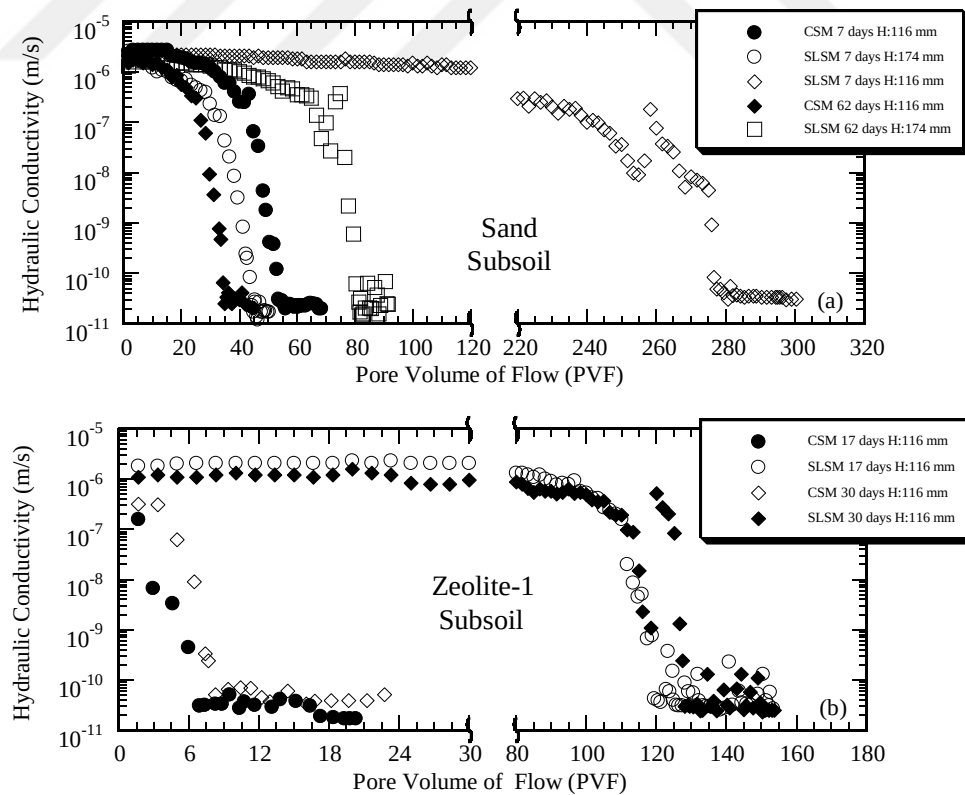


Figure 3.12 The hydraulic conductivities of the GCLs hydrated over compacted: a)sand and b)zeolite-1

The changes in the long-term hydraulic behaviors of GCL-1 mainly resulted from the hydration duration and hence the differences in the water contents of GCL samples after hydration. Since the water contents of GCL-1 were low after hydration, GCLs continued to uptake water and swelling during permeation. At the end of the hydraulic conductivity tests, the fibers that bound the geotextile parts together were detached with a sharp razor knife and bentonite layer was observed (Figure 3.13). Then, the visual conditions of the bentonite layers were compared with the bentonites observed after hydration (Figure 3.2a-b). It was seen that the bentonite particles flocculated during the hydration process. However, there were still some gaps between the bentonite particles after hydration (Figure 3.2b). These gaps were getting closed due to swelling of bentonite in the permeation phase (Figure 3.13a-b). This results also confirmed with the water contents of GCLs after hydraulic conductivity. The water contents of the GCLs hydrated over compacted sand and zeolite increased from 72% to 186% and 126% to 152%, respectively, when the hydraulic conductivity tests were terminated.

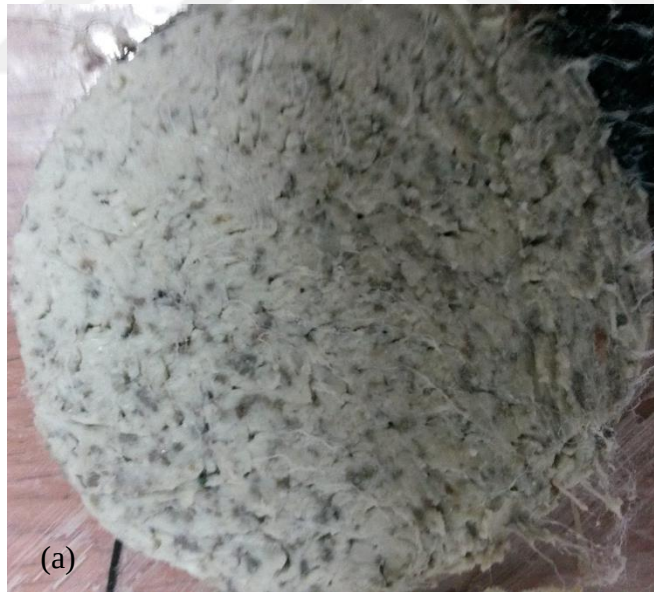


Figure 3.13 The photographic images of GCL-1 hydrated with a) control sample method (CSM) and b) single large sample method (SLSM) (Personal archive, 2017)



Figure 3.13 continues

3.7 Conclusions

Hydration methods using flexible wall permeameters were compared based on the bentonite water contents for GCL-1 (LP). Two different methods (i.e. Control Sample Method, CSM, and Single Large Sample Method, SLSM) were used for the hydration tests and the advantages/disadvantages of the systems were discussed. The conclusions of the experiments are given below:

- Independent from the subsoil aspect ratio, greater final water contents (up to 8%) were obtained for the GCL-1 (LP) hydrated over compacted sand with SLSM rather than CSM. When subsoil heights were kept constant (i.e. $AR=1.14$ for CSM and $AR=0.76$ for SLSM), up to 7% greater final water contents were obtained with SLSM than with CSM.
- Using compacted zeolite as the subsoil (with different aspect ratios) increased the final water contents of GCL-1 (LP) to ~125% after 30 days of hydration with both methods. This value is almost twice of the water content of GCL-1 (LP) hydrated over compacted sand for 62 days (i.e. around 65-70%).

- The impact of subsoil height on the final bentonite water contents for GCL-1 (LP) is more pronounced at lower hydration durations (i.e. 7 days). Depending on the subsoil heights, the differences between the final bentonite water contents were about 7.5%. This influence is less pronounced when the hydration duration was 62 days. These differences in the final water contents of GCLs are possibly due to initial water contents of subsoils.
- Subsoil height has significant effect on the subsoil water content profile. Although water content distributions across the subsoils were the same regardless of hydration duration, the subsoil water content profiles were apart from each other. This can be attributed not only to the small deviations in the initial compaction water contents but also to the height of the subsoils.
- The hydration profiles of the subsoils were quite similar for both sand and zeolite subsoils. The water content of the first sublayer which was in contact with the GCL significantly decreased and the water contents of the subsequent layers slightly increased after hydration. Increase in the water contents of lower layers were attributed to the movement of pore water due to gravity forces.
- The visual comparison showed that the swelling of bentonite or gaps between particles can be clearly seen with CSM. In contrast, it is hard to monitor the bentonite conditions in GCL hydrated with SLSM due to the hardness of sampling. Actually, the swelling of bentonite can be seen with SLSM; however, unnatural cracks are inevitably occurred during sampling.
- Hydration duration, subsoil type, hydration method had no influence on the final hydraulic conductivities of GCLs. The final hydraulic conductivities of GCL-1 (LP) hydrated over compacted sand and zeolite using CSM and SLSM were around 2.8×10^{-11} m/s. Although the final hydraulic conductivities of GCLs were close to each other, their hydraulic behaviors were different. The differences between the hydraulic behaviors of GCLs were attributed to the increase in the water contents of GCL-1 (LP) during the hydraulic conductivity

testing. The slight increase in the water contents of GCL-1 (LP) resulted in a decrease in the hydraulic conductivity. This conclusion visually supported with the comparison of bentonite conditions after hydration and hydraulic conductivity.

- The difference between the water contents of GCL-1 (LP) hydrated with CSM and SLSM were insignificant. One of an advantage for SLSM is to use of less permeameters with respect to CSM. Since the sample diameter was greater in SLSM, it is possible to get samples from one GCL for both water content determinations and the hydraulic conductivity tests. In addition, after sampling for the hydraulic conductivity tests, the remaining area of GCLs hydrated with SLSM is 25% greater than those of the GCLs hydrated using CSM. The remaining portion can be used to determine the swell index and exchangeable cation concentrations of bentonite after hydration. Although swollen bentonite can be visualized better with CSM, it is rather expensive and labor-intensive method due to requiring two permeameters.

CHAPTER FOUR

LIQUID LIMIT BASED ASSESSMENT OF GEOSYNTHETIC CLAY LINERS SUBJECTED TO HYDRATION AND HYDRAULIC CONDUCTIVITY TESTINGS

4.1 Background

Due to practical reasons, GCLs are generally installed at their initial water contents (around 10-15%). Then, GCLs become hydrated by water adsorption from the underlying or surrounding soil depending on the installation conditions. Hydration from the subsoil improves the hydraulic performance of GCLs. Hydration duration, subgrade soil (or subsoil) type and mineralogy, the water content of subsoil, GCL type, the effective stress acting on the GCLs and environmental conditions such as site temperature are some of the factors that influence the hydration of GCLs (Anderson, Rayhani & Rowe, 2012; Benson & Meer, 2009; Scalia & Benson, 2010, 2011; Bouazza et al., 2017; Meer & Benson, 2007; Rayhani et al., 2011; Rowe, 2012; Rowe & Abdellaty, 2012; Sarabian & Rayhani 2013). Many studies were conducted to determine the hydration behavior of GCLs on different subsoils so far. However, neither of these studies evaluated the hydration behavior as a function of the liquid limit of GCL.

Lee & Shackelford (2005) made quality-based denotation for GCLs such as lower or higher quality (LQ or HQ) depending on their mineralogical (i.e. montmorillonite content), physical (i.e. plasticity index) and chemical (i.e. cation exchange capacity, CEC) properties of bentonite. However, determining especially the mineralogical compositions and chemical properties of bentonite is rather complex and thus, different types of equipment and chemicals are needed for these analyses. For example, X-Ray diffractometer and Inductively Coupled Plasma (ICP) are required for mineralogical and chemical analyses, respectively. These devices are expensive and therefore, not available in most geotechnical engineering laboratories. Thus, a simple identification is desirable for the expression of GCL quality.

Regardless of mineralogical and chemical properties, index properties may be sufficient alone for the quality description. For example, liquid limit and swell index can be used for this purpose. These tests are quick, simple and cheap in comparison to mineralogical and chemical analyses, and they can be usually executed in geotechnical laboratories. In addition, the hydraulic conductivity of GCLs correlates well with liquid limit and swell index of bentonites. It is well documented that the lower the liquid limit or swell index, the greater is the hydraulic conductivity of the bentonite and vice versa (Hosney & Rowe, 2014; Jo et al., 2001; Katsumi 2008b; Kolstad, Benson & Edil, 2004; Lee et al., 2005; Mishra et al., 2011).

Despite these advantages, the liquid limit can be preferable with respect to swell index for some reasons. The amount of soil required for the swell index test is significantly lower than that of the soil required for the liquid limit test. Swell index test is conducted only with 2.0 g of dry bentonite, while the liquid limit test is carried out with about 500 g of bentonite. The test which uses more mass may successfully represent the general properties of bentonite and hence, GCL. Moreover, solid to liquid ratio in swell index test is much lower than that in the liquid limit test. The lower solid concentration increases the intact surface between the bentonite and water molecules, resulting in a larger swell volume than it should be. Therefore, it may be better if the liquid limit is used instead of swell index for the specification of GCL quality.

The liquid limits of bentonites from GCLs used in the hydration studies are within the range of 216-630% (Anderson, Rayhani & Rowe, 2012; Barclay & Rayhani, 2013; Katsumi et al., 2008a; Rowe & Abdellatty, 2012; Sarabian & Rayhani, 2013). In the case of polymer treatment, the liquid limit is as much as 743% (Emidio et al., 2015). However, there is no information about the hydration performance of GCLs which have liquid limits lower than 216% or higher than 630%. Moreover, the hydration of GCLs in these studies was not evaluated in terms of bentonite properties such as liquid limits. Mostly, compaction water contents of subsoils were the used as the variable that influences the water content of GCLs (Anderson, Rayhani & Rowe, 2012; Barclay & Rayhani, 2013; Chevrier et al., 2012; Rayhani et al., 2011; Sarabian & Rayhani, 2013 U.S. Environmental Protection Agency (USEPA), 1996). There are also scarce

studies in the literature that focused on the hydration and hydraulic conductivity of GCLs together. These studies were generally conducted on a single GCL (Bradshaw, Benson & Scalia, 2012; Rowe & Abdelatty, 2012) or two GCLs containing granular or powdered bentonite (Katsumi et al., 2008a). Similarly, the hydration and hydraulic conductivity of these GCLs were not evaluated in terms of the liquid limit. In other words, liquid limit-based assessment of hydration and hydraulic conductivity of GCLs have not been made in these studies.

The objective of this study is to investigate and discuss the hydration and hydraulic conductivity behaviors of GCLs as a function of their quality expressed by the liquid limit. Quality based assessment has been generally made with the montmorillonite content of GCLs. Since polymer treatment does not change the quality of GCL, and in order not to allow any confusion, performance-based denotation will be used henceforth. For this purpose, three GCLs (GCL-1, GCL-2 and GCL-8) with wide a range of liquid limit were hydrated over compacted sand and subsequently subjected to hydraulic conductivity tests. The performance descriptions of GCLs were made based on the liquid limits of bentonites. Hence, GCL-1, GCL-2 and GCL-8 were named as low performance (LP), medium performance (MP), and high performance (HP), respectively.

4.2 Water Content of Geosynthetic Clay Liner After Hydration

The water contents of GCLs were determined after 7 and 62 days of hydration for GCL-1 (LP) and 7, 30 and 90 days of hydration for GCL-2 (MP) and GCL-8 (HP) GCLs. The water contents after hydration are shown in Figure 4.1 as a function of hydration duration. Figure 4.1 indicates that water contents of GCLs increased from 13 to 69% for GCL-1 (LP), from 18 to 84% for GCL-2 (MP) and from 11 to 120% for GCL-8 (HP) as the hydration duration increased. This increasing trends of water contents with the hydration durations are also consistent with the findings reported in the literature (Anderson, Rayhan & Rowe, 2012; Bradshaw, Benson & Scalia 2012; Rayhani et al., 2011; Rowe & Abdelatty, 2012).

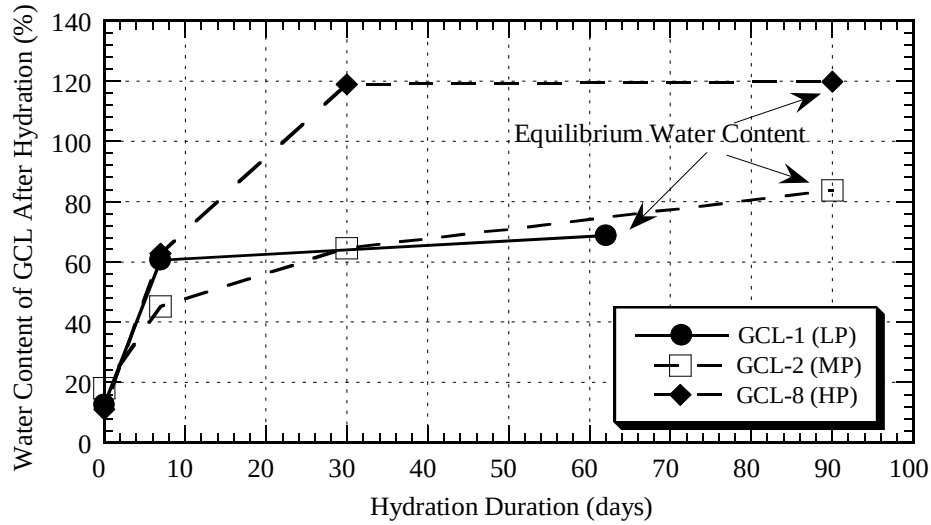


Figure 4.1 Influence of hydration duration on the water uptake of GCL hydration

Final water content was identified as the equilibrium water content that bentonite reached its maximum. The greatest water contents were achieved at the last step of applied hydration durations (Figure 4.1). Although water content of GCL-1 (LP) increased from 13 to 61% within 7 days of hydration, it increased slightly to 69% at the end of 62 days of hydration (Table 4.1). Thus, 69% was selected as the final water content for GCL-1 (LP). The water content after 30 days of hydration was 119% for HP-GCL and increased negligibly at the end of 90 days of hydration (by only 1%). The final water content for GCL-8 (HP) was accepted as 120% (Figure 4.1 and Table 4.1).

The trend of water content versus hydration duration was slightly different for GCL-2 (MP) than that for GCL-1 (LP) and GCL-8 (HP) (Figure 4.1). The water content of GCL-2 (MP) increased rapidly in the first 7 days of hydration and kept increasing until the end of 90 days of hydration. Since the water content had still an increasing trend at the 90 days of hydration and no data was available at further hydration durations, 84% was accepted as the equilibrium or final water content for GCL-2 (MP) (Table 4.1).

Table 4.1 Water contents and heights of geosynthetic clay liners after hydration

Testing Material	MPUA Mass/area (kg/m ²)	Hydration Duration (days)	Initial Height (mm)	Hydrated Height (mm)	Change of Height (mm)	Water Content of GCL (%)	
						Initial	Final
GCL-1 (LP)	3.41	7	3.1	3.1	0.0	13	61
GCL-1 (LP)	3.36	62	3.5	3.5	0.0	13	69
GCL-2 (MP)	4.27	7	5.3	5.6	0.3	18	45
GCL-2 (MP)	4.34	30	5.3	5.7	0.4	18	65
GCL-2 (MP)	3.57	90	4.9	5.5	0.6	18	84
GCL-8 (HP)	2.76	7	3.8	3.9	0.1	11	63
GCL-8 (HP)	2.84	30	3.7	4.7	1.0	11	119
GCL-8 (HP)	2.68	90	3.6	4.6	1.0	11	120

The performance-based comparison is initially made between the final water content of GCL and smectite content or CEC of bentonite (Figure 4.2). In Figure 4.2, open symbols show the smectite contents, whereas closed symbols indicate the CEC. The smectite contents of LP, MP and HP GCLs were 68, 64 and 66% and the CEC were 76, 80 and 79 meq/100g, respectively. The narrow ranges for smectite content and CEC gave no information about the GCL performance (Figure 4.2). At least, performance-based evaluation of final water contents could not be made when these mineralogical and chemical parameters were used.

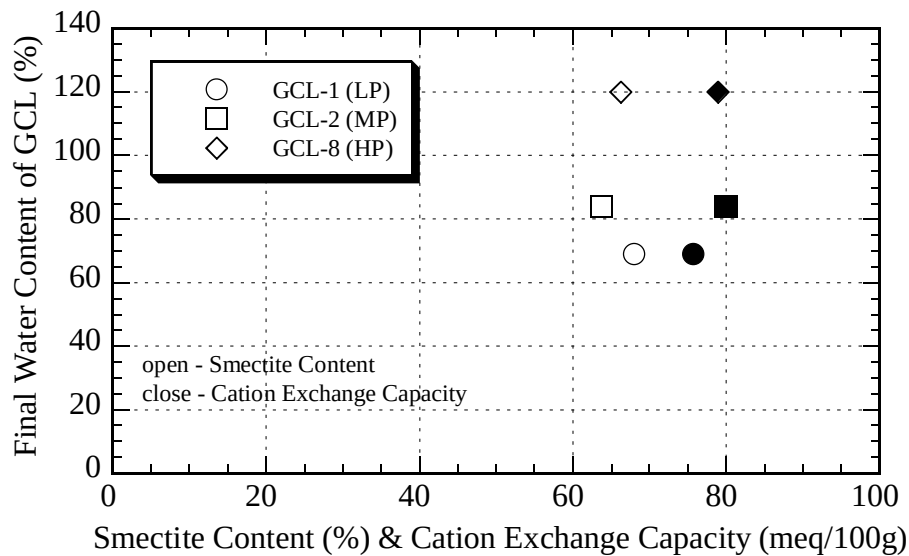


Figure 4.2 Influence of smectite content and cation exchange capacity on the final water contents of geosynthetic clay liners

It was also checked if there are any possible relationship between final water contents of GCLs and some physical parameters of bentonite such as swell indices and liquid limits (Figure 4.3).

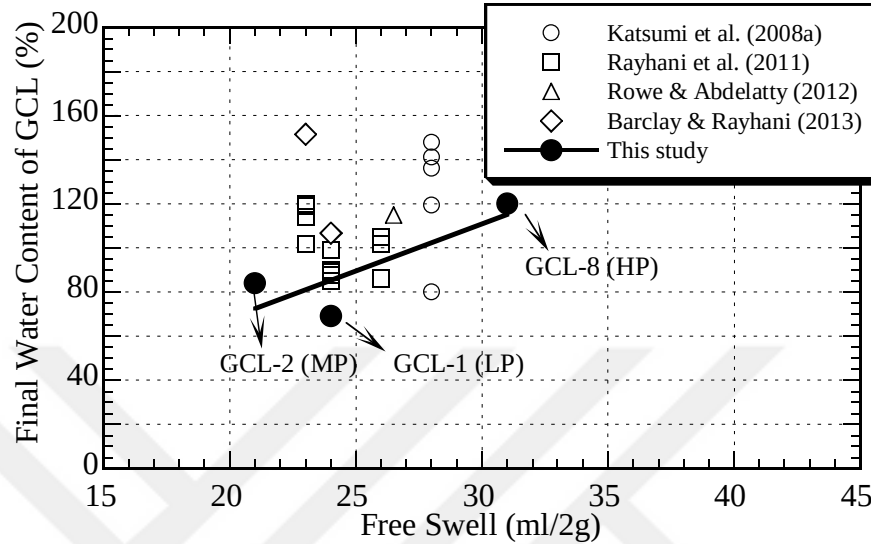


Figure 4.3 The relationship between the final water contents and swell indices for various geosynthetic clay liners subjected to hydration tests

Figure 4.3 shows the linear increasing trend between final water contents and the swell indices. However, although final water content of GCL-1 (LP) was lower than that of GCL-2 (MP) (69% vs. 84%), the swell index of GCL-1 (LP) was greater than the swell index of GCL-2 (MP) (24 mL/2g vs. 21 mL/2g). Thus, the plot for GCL-1 (LP) is slightly out of the general tendency. The greater swell index value for GCL-1 (LP) than for GCL-2 (MP) is possibly due to the abundance of monovalent cations in bentonite. The mole fractions of monovalent cations (Na^+ and K^+) were 0.87 and 0.65 and divalent cations (Ca^{2+} and Mg^{2+}) were 0.13 and 0.35 for GCL-1 (LP) and GCL-2 (MP), respectively. The abundance of divalent cations in GCL-2 (MP) suppresses the thickness of adsorbed water layer surrounding the bentonite particles, resulting in lower swell index value for GCL-2 (MP). Although mole fractions of GCL-8 (HP) were similar to GCL-2 (MP), the greatest swell index (31 mL/2g) and final water content were measured for GCL-8 (HP) due to the use of polymer treated bentonite in this GCL. These findings were evaluated together with the findings of previous studies of where GCLs were hydrated under similar conditions. Table 4.2 summarizes the test

conditions (soil type, bentonite form in GCLs, contact faces of GCL with subsoil, hydration durations) and final water contents of GCLs reported in Barclay & Rayhani (2013); Katsumi et al. (2008a), Rayhani et al. (2011) and Rowe & Abdelatty (2012).

Table 4.2 Summary of the test conditions and measured final water contents reported in the literature and in this study

Reference	Subsoil Type	Subsoil W_{opt} (%)	Subsoil water content (%)	Bentonite Form	Contact Face	Hydration Duration (days)	Final Water Content (%)
Katsumi et al. (2008a) ‡	Toyoura Sand	17	15	Granular	NW/W	31	80-148
Rayhani et al. (2011)	Silty Sand	11.4	10	Granular	W/NW	210	85-102
Rayhani et al. (2011)	Silty Sand	11.4	16	Granular	W/NW	210	88-120
Rowe & Abdelatty (2012) ¥	Silty Sand	13.9	13.9	Granular	NA	700	115
Barclay & Rayhani (2013)	Sand	10	12	Granular	NA	110	107-152
This Study	Sand (SM)	12	14	Granular	NW	62-90	69-120

NW:Non-woven; W:Woven; NA:Not available

‡ 1 cm of static water level existed at the bottom of the mold which supplied water to subsoil during hydration.

¥ data for control sample

The data from this study and from the literature are plotted in Figure 4.3 as a function of the swell index. Figure 4.3 shows that the data of Katsumi et al. (2008a) are more scattered than those of others. They used 10 mm static water level at the bottom of the compacted subsoil during hydration. Although compaction water content of subsoil is 2% dry side of optimum (Table 4.2), water supply from the bottom increased not only the water content of the subsoil but also the water content of the GCL. As an overall behavior, it is clearly seen from Figure 4.3 that the literature data consistently indicate an increasing trend of final water content with swell index. That is, the higher the swell index values, the greater is the final water contents of GCLs.

On the other hand, the amount of soil and solid to liquid ratio used for swell index test is significantly lower than that of the soil used for the liquid limit test. Thus, the liquid limit-based comparison may be more appropriate to evaluate the GCL performance. To do this, the final water contents are drawn as a function of liquid limit (Figure 4.4). It is obvious in Figure 4.4a that increasing the liquid limit caused an increase in the final water content of GCL. However, when this trend was evaluated

together with the data reported in the literature, two distinct tendencies were observed depending on the liquid limit value (Figure 4.4b). The final water content of GCL increased up to the liquid limit of 500%. However, the further increase in the liquid limit had no influence on the final water content of GCL. It means the performance-based assessment of GCLs can be made up to the liquid limit of 500% or values above 500% may be directly considered as high performance (HP) GCL.

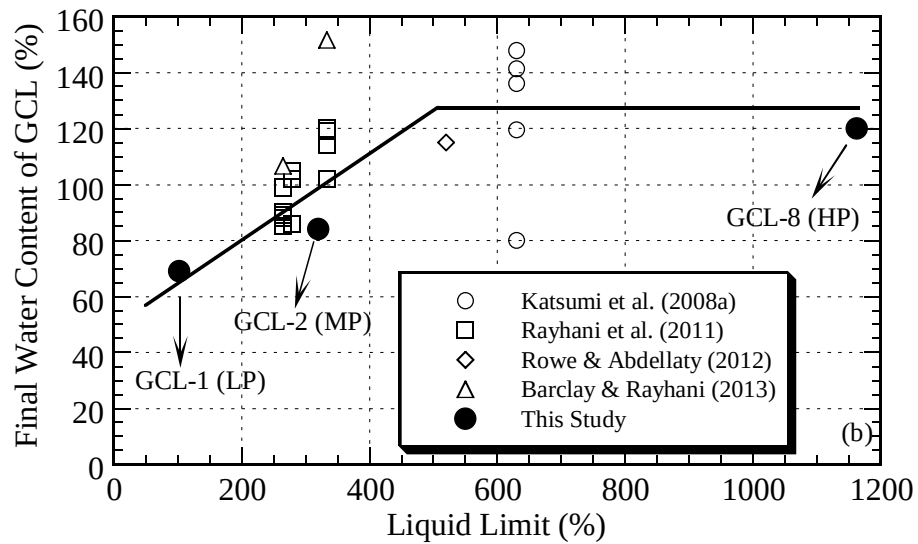
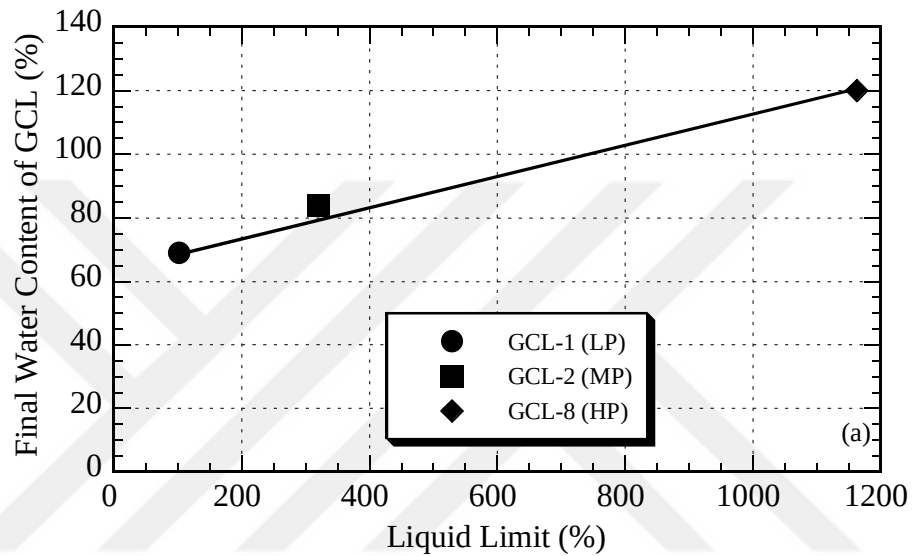


Figure 4.4 a) The general trend between final water contents and liquid limits and b) comparison of findings of this study with those of the literature

4.3 Heights of Geosynthetic Clay Liner After Hydration

GCLs are generally moistened during the manufacturing process. However, drying induced desiccation may occur in GCLs before getting into service. This results in more pores between dried aggregates of bentonite particles. Then, bentonite swells during subsoil hydration to reduce pore spaces and hence, hydraulic conductivity. Under any effective stress applied on GCLs during hydration, it is easy for bentonite to swell laterally first. If the swell pressure of bentonites overcomes the effective stress, then it tends to swell vertically as well. Thus, it should be expected that the bentonite in GCL swells in both directions during hydration: lateral and vertical.

The bentonites in GCL-1 (LP), GCL-2 (MP), and GCL-8 (HP) were in aggregate form and these aggregates were dislocated from each other in their initial state. When GCL-1 (LP) was subjected to hydration, the heights did not change even this GCL adsorbed appreciable amount of water. It was observed from the remaining part of GCL-1 (LP) (after sampling for hydraulic conductivity test) that the inter-aggregate pores were nearly closed during hydration (Figure 4.5a). Although this confirms the lateral swelling of GCL-1 (LP), bentonite was not able to swell vertically during hydration because of applied vertical stress and thus, the heights were unchanged. The picture of GCL-2 (MP) after hydration is given in Figure 4.5b. Similar to GCL-1 (LP), inter aggregate pores were nearly closed after water uptake of GCL from the subsoil.

However, unlike GCL-1 (LP), the height of GCL-2 (MP) slightly increased (Table 4.1). The difference between the swelling properties of LP and MP GCLs may be related to the differences in the MPUA of GCLs. On average, GCL-2 (MP) had greater MPUA than GCL-1 (LP) (i.e. 4.06 kg/m^2 versus 3.39 kg/m^2), resulting in greater heights for GCL-2 (MP) than for GCL-1 (LP). In contrast, the greatest increase in the height was measured on GCL-8 (HP) (Table 4.1). In this case, the lower MPUA for GCL-8 (HP) (i.e. 2.76 kg/m^2) was compensated by the presence of polymers. From Figure 4.5c, there were no visible pores observed on the hydrated GCL and the state of bentonite seemed to be drier than GCL-1 (LP) and GCL-2 (MP) even if GCL-8 (HP) had greater water content. If the picture is checked with care, then the polymers shining

on the bentonite can be seen. This shows the hydration of polymers as well. As an overall behavior, the heights of GCL-2 (MP) and GCL-8 (HP) increased with hydration, indicating the lateral and vertical swelling of bentonite in these GCLs (Table 4.1).

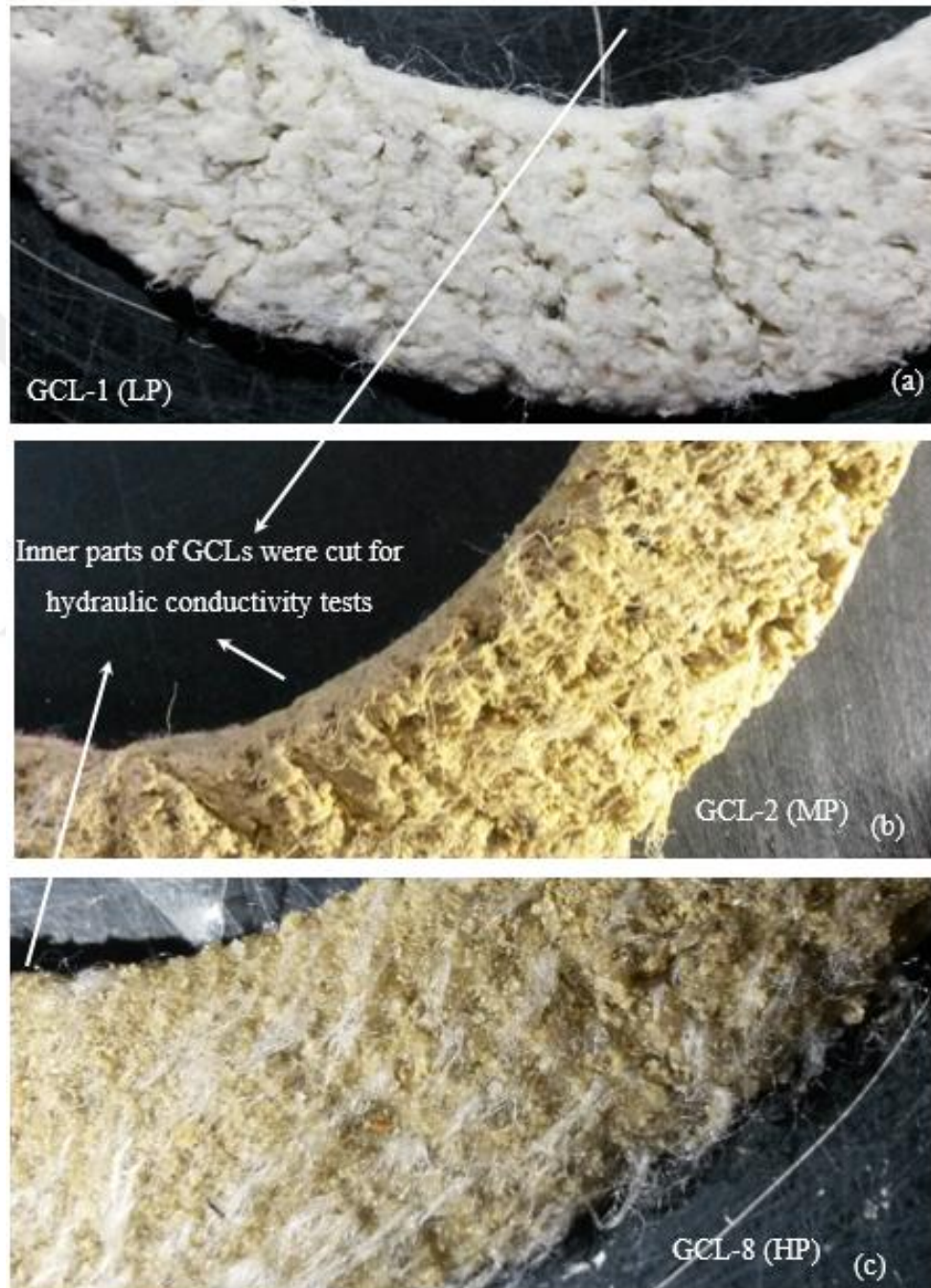


Figure 4.5 General overview of: a) GCL-1 (LP) after 62 days of hydration, b) GCL-2 (MP) after 90 days of hydration and c) GCL-8 (HP) after 90 days of hydration (Personal archive, 2017)

4.4 Hydraulic Conductivity of Hydrated Geosynthetic Clay Liners

At the end of the hydration processes, hydraulic conductivity tests were performed on GCLs to determine the influence of hydration on the long-term hydraulic behavior. Table 4.3 summarizes the final hydraulic conductivities of hydrated GCLs. Note that the final hydraulic conductivities in Table 4.3 are the average of the last five readings for each test. Regardless of the hydration durations, the final hydraulic conductivities were within the range of 1.6×10^{-11} – 3.6×10^{-7} m/s for GCL-1 (LP), 2.2×10^{-11} – 1.6×10^{-6} m/s for GCL-2 (MP), and 1.6×10^{-11} – 2.3×10^{-11} m/s for GCL-8 (HP), (Table 4.3). However, the long-term hydraulic conductivity behaviors were quite different depending on the GCL performance.

Table 4.3 Summary of the hydraulic conductivities of hydrated geosynthetic clay liners

Testing Material	Hydration Duration (days)	Water Contents of GCLs (%)		GCL Height (mm)		Required PVF for low hydraulic conductivities	Hydraulic conductivity		
		Initial	Final	Initial	Final		Time (days)	PVF	k (m/s)
GCL-1 (LP)	7	61	160	3.1	3.2	280	135	300.4	3.2×10^{-11}
GCL-1 (LP)	62	69	171	3.5	3.2	*	8	261.1	3.6×10^{-7}
GCL-2 (MP)	7	45	117	5.6	7.0	*	3	261.9	1.6×10^{-6}
GCL-2 (MP)	30	65	132	5.7	7.6	109	45	113.0	2.2×10^{-11}
GCL-2 (MP)	90	84	127	5.5	6.4	77	75	84.5	3.1×10^{-11}
GCL-8 (HP)	7	63	286	3.9	8.0	2	135	9.7	1.9×10^{-11}
GCL-8 (HP)	30	119	262	4.7	7.7	2	195	13.7	2.3×10^{-11}
GCL-8 (HP)	90	120	325	4.6	7.9	2	120	8.6	1.6×10^{-11}

*could not be determined

The hydraulic conductivity behaviors of hydrated GCLs are shown in Figure 4.6 as a function of pore volumes of flow (PVF). As seen in Figure 4.6a-b, greater hydraulic conductivities were obtained for GCL-1 (LP) and GCL-2 (MP) at the early stages of the permeation (i.e. 2.0×10^{-6} m/s). Bentonite was swollen via uptake of water from the subsoil during the hydration process. However, it was not sufficient to reduce the hydraulic conductivity of GCL-1 (LP) and GCL-2 (MP). This can be seen in Figure 4.5a-b which shows some minor pores existed on the GCL-1 (LP) and GCL-2 (MP) after hydration. Except for two GCL samples (GCL-1 (LP) hydrated for 62 days and GCL-2 (MP) hydrated for 7 days), the hydraulic conductivity of GCLs sharply

decreased and then became stable at 3.0×10^{-11} m/s, indicating continued swelling of bentonite during permeation phase.

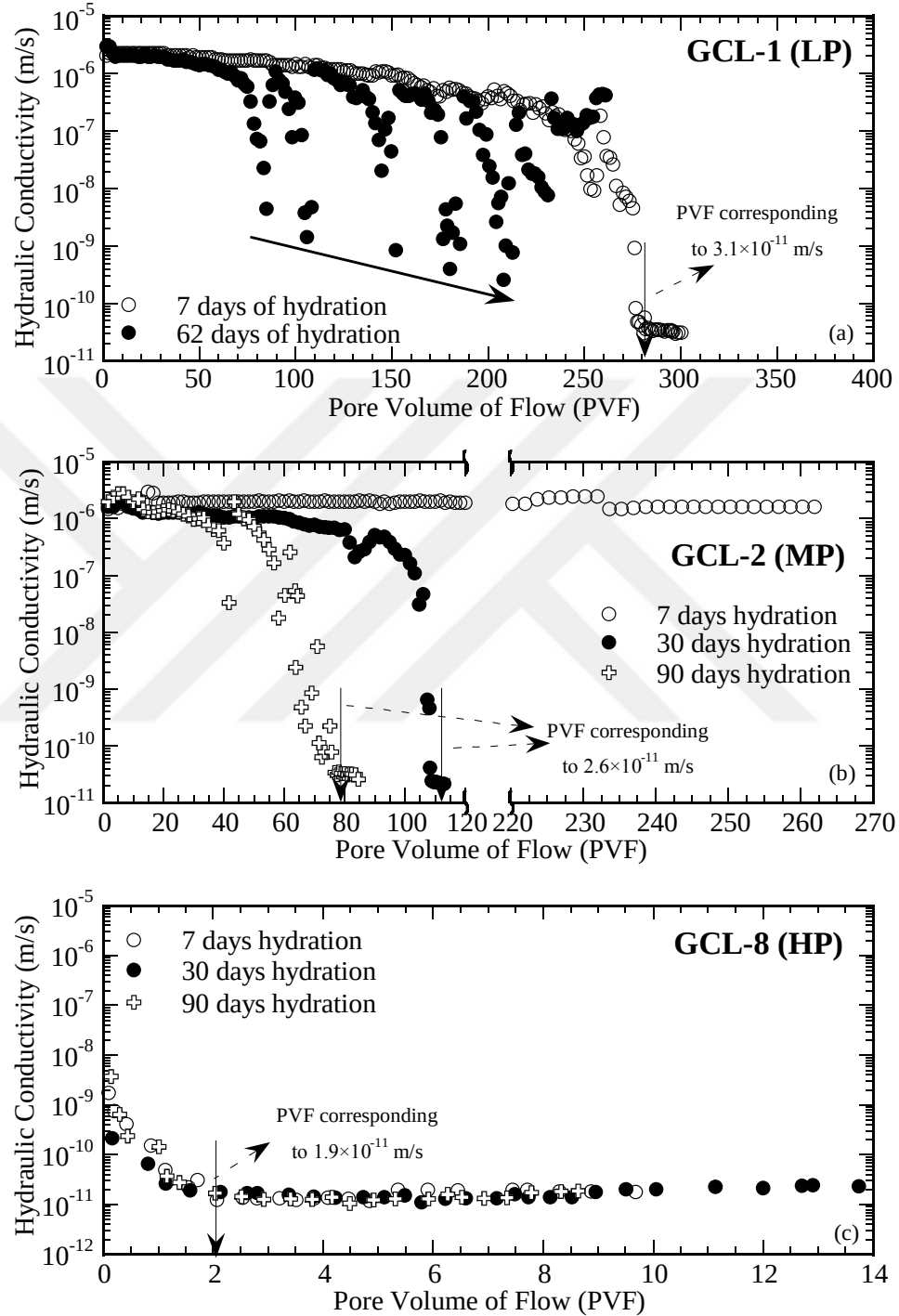


Figure 4.6 Influence of hydration on the hydraulic conductivity of a) GCL-1(LP), b) GCL-2 (MP) and c) GCL-8 (HP)

In contrast, some irregularities were observed in the hydraulic conductivity behavior of GCL-1 (LP) subjected to 62 days of hydration (Figure 4.6a). About four orders of magnitude greater final hydraulic conductivity was obtained for this GCL-1 (LP) (3.6×10^{-7} m/s). However, there were some traces in Figure 4.6a about the tendency of reduction in the hydraulic conductivity at 80, 100, 135, 170 and 200 PVF. The hydraulic conductivity decreased to 2.6×10^{-10} m/s at these PVFs due to gradual swelling of bentonite. The evidence of swelling can be seen from Table 4.3. The water content of GCL-1 (LP) increased from 69% to 171% during permeation. However, hydraulic conductivity increased because of the seepage forces and greater hydraulic gradient applied during the test (i.e. 185). This resulted in bentonite erosion within GCL. Similarly, GCL-2 (MP) hydrated for 7 days had constant and greater hydraulic conductivity (1.6×10^{-6} m/s) throughout the test duration (Figure 4.6b). The water content after hydration was 45% which is the lowest among other GCLs. This resulted in granular (or aggregated) appearance of bentonite in GCL-2 (MP) which means more open pores between aggregates prior to permeation (Figure 4.5b). When permeation was initiated, bentonite attempted to absorb water. However, particles were flushed out because of high hydraulic gradients, resulting loss of bentonite from GCL-2 (MP).

The evidence of bentonite erosion was found when woven and non-woven components of GCLs were detached by cutting with a sharp razor knife. It was observed that there was an eroded bentonite section which was across the inflow tubing (Figure 4.7a-b). Moreover, the outflows collected in graduated cylinders were blurred with the bentonite particles, indicating the erosion of bentonite from GCLs.

To some extent, particle erosion due to bentonite movement under high hydraulic gradients was seen for other hydration durations of GCL-1 (LP) and GCL-2 (MP). Although there were no eroded sections on these GCLs, the graduated cylinder that collects the effluent was blurred at the beginning of the hydraulic conductivity tests, indicating the loss of bentonite. The evidence of bentonite loss can be seen from hydraulic conductivity behaviors of GCLs shown in Figure 4.6a-b. As can be seen in Figure 4.6a and Figure 4.6b, the initial hydraulic conductivities were high until 80 PVFs and then, decreased finally to $\sim 3.0 \times 10^{-11}$ m/s. Since bentonite finds a chance to

swell and clogs the pores sufficiently, the loss of bentonite was not as much as those observed for damaged GCL-1 (LP) (62 days of hydration) and GCL-2 (MP) (7 days of hydration).

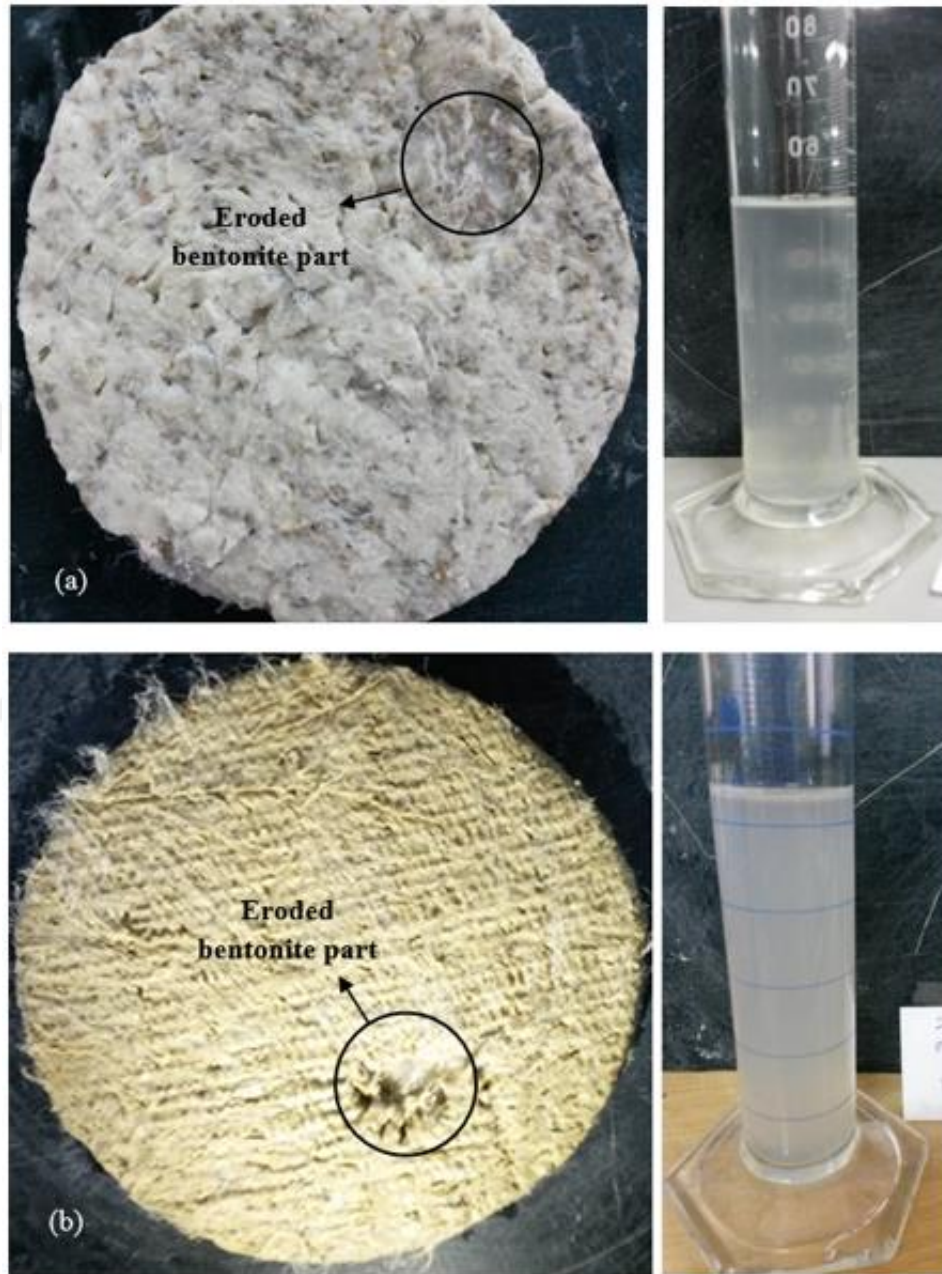


Figure 4.7 Evidence of bentonite loss from GCLs: a) GCL-1 (LP) hydrated for 62 days (left picture) and outflow water from hydraulic conductivity test (right picture) and b) GCL-2 (MP) hydrated for 7 days (left picture) and outflow water from the hydraulic conductivity (right picture) (Personal archive, 2017)

In contrast, the hydraulic conductivity of GCL-8 (HP) subjected to 7, 30 and 90 days of hydration was as low as 1.0×10^{-9} m/s since the beginning of the test. Then, hydraulic conductivity decreased to 1.9×10^{-11} m/s within a few PVF (Figure 4.6c). Use of the polymer treated bentonite resulted in greater water contents and lower hydraulic conductivities for GCL-8 (HP) at any hydration durations. It is the fact that the water content of GCL-8 (HP) at 7 days of hydration was close to those of GCL-1 (LP) at 7 and 62 days of hydrations and that of GCL-2 (MP) at 30 days of hydration (~65%). Even if they had similar water contents, the initial hydraulic conductivities of hydrated GCL-1 (LP) and GCL-2 (MP) were several orders of magnitude greater than that of hydrated GCL-8 (HP) which shows the significance of polymer treatment on the hydraulic conductivity behavior rather than water content. Thus, lower hydraulic conductivity values were obtained for hydrated GCL-8 (HP) throughout the test period.

GCL performance had also a significant role in achieving low hydraulic conductivity depending on the hydration durations. Figure 4.6 indicates that increase in the hydration duration led to decrease the PVFs needed to achieve lower hydraulic conductivity for GCL-1 (LP) and GCL-2 (MP) (i.e. $\approx 3.0 \times 10^{-11}$ m/s). The hydraulic conductivity of GCL-1 (LP) subjected to 7 days of hydration reduced to 3.0×10^{-11} m/s at 260 PVF. When this GCL was hydrated for 62 days, it attempted to decrease the hydraulic conductivity at 80, 100, 135, 170 and 200 PVFs due to gradual swelling of bentonite. At each attempt, the lowest hydraulic conductivity gradually decreased from 4.5×10^{-9} m/s to 2.6×10^{-10} m/s which is shown with an arrow in Figure 4.6a. Then, bentonite particles followed the preferential flow path to find an area of lower stress, resulting bentonite erosion from GCL. This led to increase the hydraulic conductivity up to 3.6×10^{-7} m/s. Similar findings were also obtained for the same GCL but taken from another roll. The GCL (LP) was hydrated over the same silty sand for 17, 62 and 90 days. They reported that the hydraulic conductivity decreased to 3.0×10^{-11} m/s at 53, 10, and 6 PVF after 17, 62, and 90 days of hydration, respectively.

The lower hydraulic conductivity for GCL-2 (MP) at 30 days of hydration was attained after 109 PVF passed across the GCL. However, required PVF for 3.0×10^{-11} m/s was 77 when the hydration duration was prolonged to 90 days. In contrast, PVF

required for lower hydraulic conductivity was not dependent on the hydration duration when GCL-8 (HP) is considered (Table 4.3 and Figure 4.6). The lower hydraulic conductivities were achieved even after 2 PVF for all hydrated samples of GCL-8 (HP). It can be attributed to the adequate swelling of polymerized bentonite within very short hydration duration (i.e. 7 days).

The influence of GCL performance on the hydraulic conductivity is illustrated by considering the initial and final hydraulic conductivity values as a function of liquid limits in Figure 4.8.

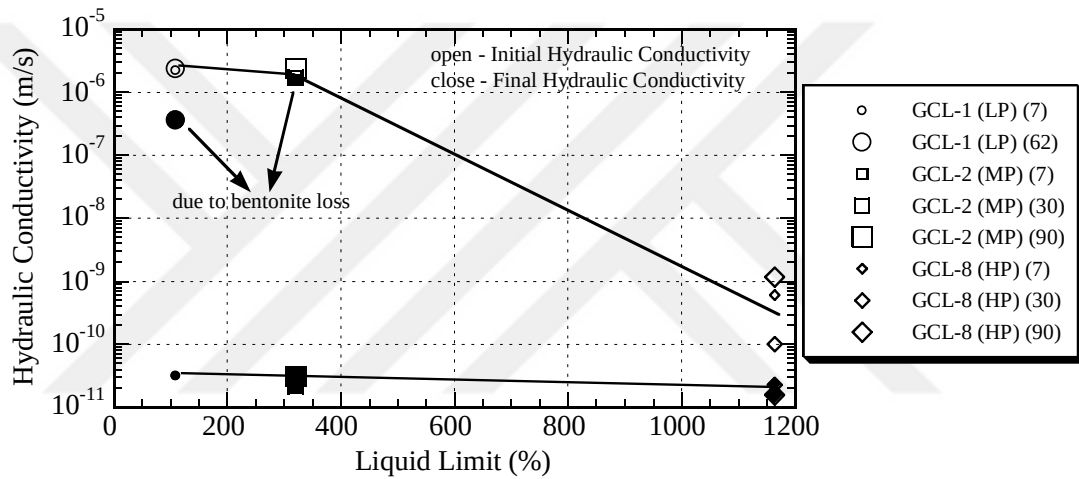


Figure 4.8 Initial and final hydraulic conductivities of GCLs as function of liquid limit

Initial hydraulic conductivity was taken as the average of readings up to 10 PVF for GCL-1 (LP) and GCL-2 (MP) and 1 PVF for GCL-8 (HP). It is clearly seen that the GCL performance had no significant effect on the final hydraulic conductivity. Except for two samples (GCL-1 (LP) hydrated for 62 days and GCL-2 (MP) hydrated for 7 days), the final hydraulic conductivities of hydrated GCLs were around 3.0×10^{-11} m/s. However, initial hydraulic conductivities showed some differences depending on the GCL performance. Increase in the liquid limit up to 320% slightly decreased the initial hydraulic conductivity from 2.3×10^{-6} m/s to 2.0×10^{-6} m/s and beyond this level, up to three orders of magnitude lower initial hydraulic conductivities were obtained (6.4×10^{-10} m/s). It means that if the GCL is high performance, all flow channels will be closed right after the hydration phase. In contrast, if GCL is low or medium performance

additional water uptake will be required to sufficiently block the pores between the particles.

4.5 Water Content of Geosynthetic Clay Liner After Hydraulic Conductivity

Determining water contents after hydraulic conductivity tests also gave some information about the water uptake of GCLs during permeation. Change in the water contents of GCLs between hydration and hydraulic conductivity period is plotted as a function of liquid limit in Figure 4.9. Regardless of GCL performance, water contents of GCLs increased further during the hydraulic conductivity tests, indicating GCLs were still being hydrated with the permeant water (Table 4.3). The water contents of GCL-1 (LP) samples hydrated for 7 and 62 days rose up to 160% and 171% after hydraulic conductivity, respectively (Table 4.3). It is interesting to note that these values were greater than the liquid limit of GCL-1 (LP) (108%) or the changes of water contents were as much as liquid limit value. Indeed, when hydraulic conductivity tests were terminated, and needle-punched fibers were cut to take samples, it was observed that bentonite was in liquid form and was sampled easily without showing any resistance at bentonite/geotextile interface.

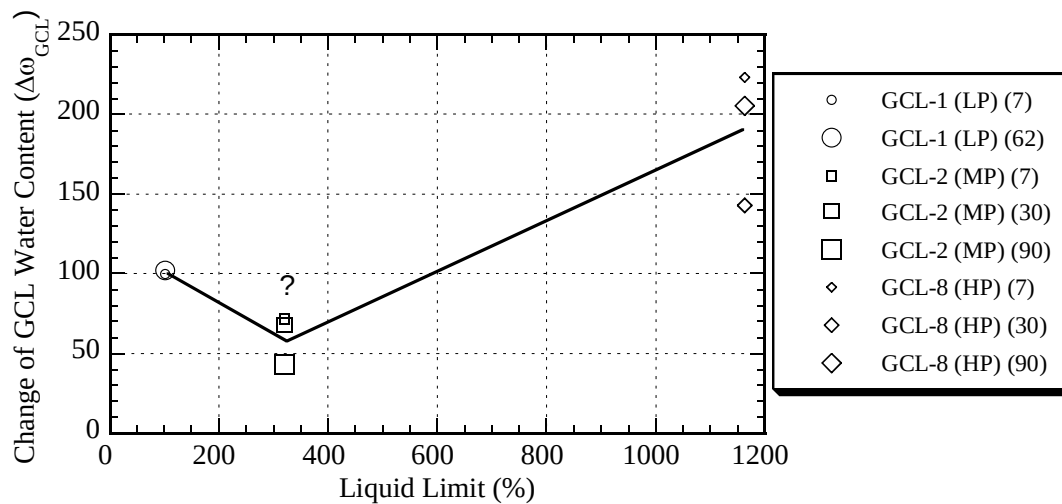


Figure 4.9 Demonstration of change of water content between hydration and hydraulic conductivity as a function of liquid limit

On the other hand, the water contents of GCL-2 (MP) samples were within the range of 117-132% and were less than GCL-1 (LP) samples (Table 4.3). Although an increasing trend existed between the change of water content of GCL and liquid limit, Figure 4.9 shows that the change of water content for GCL-2 (MP) was less than that for GCL-1(LP). There are three possible reasons for lower water contents of GCL-2 (MP) with respect to GCL-1 (LP): i) differences between the MPUA of GCLs, ii) short test duration applied for GCL-2 (MP) (Table 4.3) and iii) differences in the concentrations of cations in exchange complex of bentonite. Average MPUA of GCL-2 (MP) was greater than that of GCL-1 (LP). This may lead lower water contents for GCL-2 (MP) or higher water contents for GCL-1 (LP). The test duration applied for GCL-2 (MP) was less than GCL-1 (LP). The test duration was 8 days and 3 days for GCL-1 (LP) and GCL-2 (MP), respectively, when the hydraulic conductivity was greater ($\sim 10^{-7}$ m/s). The hydraulic conductivity tests were terminated at the end of 135 days for LP-GCL and 45 and 75 days for GCL-2 (MP) when the final hydraulic conductivities decreased to 3.0×10^{-11} m/s. Thus, it is believed that test duration applied on both GCLs would have an influence on the water contents after hydraulic conductivity. Another reason is the differences in the mole fractions of monovalent and divalent cations in the exchange complex of GCL-1 (LP) and GCL-2 (MP). The lower monovalent and higher divalent mole fractions in GCL-2 (MP) may have restricted the osmotic swelling of bentonite, resulting in lower water contents for GCL-2 (MP).

Although the average MPUA of GCL-8 (HP) was lower than GCL-1 (LP) and GCL-2 (MP) (Table 4.1), the greatest water contents were obtained for GCL-8 (HP) which contains polymerized bentonite. The water contents after hydraulic conductivity tests were within the range of 262-325% (Table 4.3). In addition to this, the change of water content of GCL-8 (HP) was significantly higher than those of GCL-2 (MP) (Figure 5.9), even GCL-8 (HP) had the same monovalent and divalent cation mole fractions as GCL-2 (MP) (0.65 and 0.35, respectively). It shows the significance of polymerization of bentonite on the water contents of GCL-8 (HP). That is, GCLs absorbed additional water due to additional water uptake of polymers during permeation.

4.6 Heights of Geosynthetic Clay Liner After Hydraulic Conductivity

GCL performance had a significant influence on the post-test GCL heights. Although water contents remarkably increased, the heights of hydrated GCL-1 (LP) samples negligibly changed during hydraulic conductivity testing (Table 4.3). It was expected because GCL-1 (LP) was not able to swell vertically and swelled only laterally during hydration. On account of lower MPUA for GCL-1 (LP) (i.e. 3.39 kg/m² on average), applying a greater effective stress (26 kPa vs. 10 kPa applied during hydration) and acting seepage induced forces in the opposite direction, bentonite could not swell during hydraulic conductivity. The change of GCL height is also plotted as a function of liquid limit in Figure 4.10. A negative value was obtained for GCL-1 (LP) hydrated for 62 days which is due to compression of GCL-1 (LP) with the applied stresses during hydraulic conductivity.

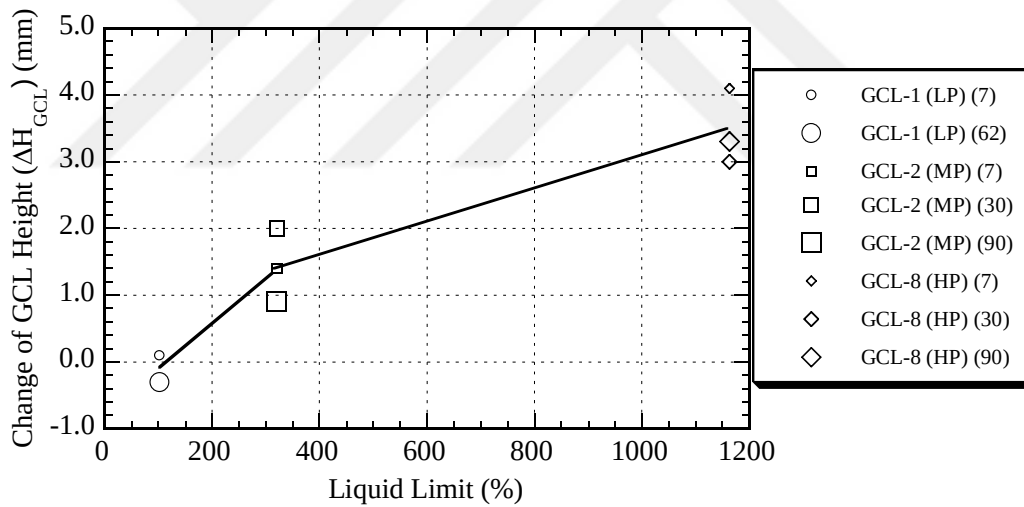


Figure 4.10 Demonstration of change of height between hydration and hydraulic conductivity as a function of liquid limit

In contrast, the heights of hydrated GCL-2 (MP) and GCL-8 (HP) samples increased with permeation (Table 4.3). Figure 4.10 shows that change of the GCL height reached up to 2.0 mm for GCL-2 (MP) samples. Further increase in the GCL performance (i.e. GCL-8 (HP)) increased the height almost twice of its initial height (around 3.5 mm).

4.7 Conclusions

The hydration and hydraulic performances of GCLs were investigated based on their performance. The performance term refers to the liquid limits of bentonites in GCLs. To determine the influence of liquid limit on the GCL performance the water uptake, swell index and hydraulic conductivity of three GCLs which had distinct liquid limits (GCL-1 (LP), GCL-2 (MP) and GCL-8 (HP)) were investigated. The conclusions of the test results are given below:

- The liquid limit-based assessment of GCL hydration over sand subsoil showed that the water contents of all GCLs rapidly increased in the first 7 days of hydration and became stable after 30 days for GCL-1 (LP) and GCL-8 (HP). GCL-2 (MP) had still an increasing trend even at 90 days of hydration.
- The final water contents differed depending on the GCL performance and were 65%, 84% and 120% for GCL-1 (LP), GCL-2 (MP), and GCL-8 (HP), respectively. Final water contents increased as the swell indices of bentonites increased. The findings were in agreement with the studies reported in the literature. A similar trend was also observed when the liquid limit was considered instead of the swell index. However, this trend changed slightly when evaluated together with the literature data. That is, GCL final water content increased up to the liquid limit of 500% and then leveled off beyond 500%.
- Hydraulic conductivity behaviors of hydrated GCLs were significantly affected by GCL performance. The initial hydraulic conductivities of hydrated GCL-1 (LP) and GCL-2 (MP) were around 2.0×10^{-6} m/s, whereas, except GCL-1 (LP) hydrated for 62 days and GCL-2 (MP) hydrated for 7 days, the final hydraulic conductivities were around 3.0×10^{-11} m/s. The reduction in the hydraulic conductivity is attributed to gradual swelling of bentonite during permeation. In contrast, GCL-1 (LP) hydrated for 62 days and GCL-2 (MP)

hydrated for 7 days were not able to decrease the hydraulic conductivity throughout the test duration.

- Observations on post-test GCLs and effluents showed that particle erosion took place during hydraulic conductivity. Increase in the hydration durations also decreased the required PVFs to achieve lower hydraulic conductivity (i.e. 3.0×10^{-11} m/s) for GCL-1 (LP) and GCL-2 (MP).
- The required PVFs to get lower hydraulic conductivities were 280 for GCL-1 (LP) subjected to 7 days of hydration. Many attempts on decreasing the hydraulic conductivity were observed for GCL-1 (LP) hydrated for 62 days. In each attempt (at 80, 100, 135, 170 and 200 PVFs), although hydraulic conductivity reduced more than the previous attempt, it finally increased to 3.6×10^{-7} m/s because of bentonite erosion. For GCL-2 (MP), the required PVF was greater for 30 days of hydration than for 90 days of hydration (109 versus 77 PVF). Unlike GCL-1 (LP) and GCL-2 (MP), GCL-8 (HP) had low hydraulic conductivities since the beginning of the tests. This is likely due to the activation of polymers during subsoil hydration and hydraulic conductivity.
- Water contents and heights of GCLs were also measured after hydration and hydraulic conductivity tests. Regardless of GCL performance, the water contents increased during hydration. Water contents increased further after hydraulic conductivity, indicating GCLs were still being hydrated during permeation. The greatest change of water content occurred for hydrated GCL-8 (HP), whereas the lowest change of water content was measured for hydrated GCL-2 (MP). Interestingly, water contents of hydrated GCL-1 (LP) were more than GCL-2 (MP). This is due to the amount of MPUA, long test durations applied for GCL-1 (LP) and abundance of monovalent cations in exchange complex of bentonite. Since water contents of hydrated GCL-1 (LP) were greater than its liquid limit, bentonite lost its strength and was unable to swell vertically. Only horizontal swelling occurred for GCL-1 (LP) which, in turn, reduced the hydraulic conductivity. The measurements on GCL heights also

proved this conclusion. GCL-1 (LP) preserved its initial height after hydration and hydraulic conductivity. However, the heights of GCL-2 (MP) and GCL-8 (HP) increased slightly after hydration but increased markedly after permeation.



CHAPTER FIVE

HYDRATION OF GEOSYNTHETIC CLAY LINERS ON COMPACTED ZEOLITE

5.1 Background

Hydraulic performance of GCLs not only depend on the mineralogical and physicochemical properties of bentonite but also depend on the degree of hydration that occurs after installation (Katsumi et al., 2008a; Rayhani et al., 2011; Rowe, 2005; Sarabian & Rayhani, 2013). To achieve low hydraulic conductivity, researchers have suggested that the water content of GCLs should be maintained at least 100% in the field (Chevrier et al., 2012; Fascicule n 12, 1998; Meer & Benson, 2007).

The impact of subsoil water content on the water uptake of GCLs has been simulated in the laboratory experiments (e.g., Anderson, Rayhani & Rowe, 2012; Chevrier et al., 2012; Sarabian & Rayhani, 2013; U.S. Environmental Protection Agency (USEPA), 1996). For this purpose, GCLs have been hydrated over subsoils that were compacted at various water contents. One of the common findings of these studies is that increase in the subsoil water content led to increasing the water content of GCLs (Anderson, Rayhani & Rowe, 2012; Chevrier et al., 2012; Sarabian & Rayhani, 2013). In addition, depending on the hydration duration, water contents of GCLs can be more than 100% if the subsoils were compacted at least 2% wet side of optimum. However, this conclusion depends totally on the subsoil and the GCL type.

Although valuable studies have been conducted so far, the influence of subsoil type on the hydration of GCLs is scarce. Commonly, poorly graded sand (SP), silty sand (SM), clayey sand (SC), low plastic clay (CL) and low plastic silt (ML) have been considered as the subsoils whose optimum water contents (w_{opt}) were within the range of 10-28% (Anderson, Rayhani & Rowe, 2012; Barclay & Rayhani, 2013; Chevrier et al., 2012; Rayhani et al., 2011; Sarabian & Rayhani, 2013). To observe the influence of subsoil water content on the hydration of GCLs, researchers increased the water

contents of the subsoils to far above their optimum (i.e. 10-15%). However, one can argue that excessive increment in the subsoil water content may lead to cause strength loss on the subsoil and thus, it becomes impractical.

The other way of increasing the subsoil water content may be the use zeolite. Since zeolite resembles physically to sand and chemically to clay, using zeolite as a subsoil would have many advantages. Thus, it was decided to use zeolite as the subsoil in this study. The influence of zeolite as a subsoil on the hydration were investigated for two GCLs (GCL-1 (LP) and GCL-8 (HP)) which have distinct characteristics within each other.

5.2 Zeolite

Zeolites are hydrated aluminosilicates of alkali and alkaline earth metals with unique crystal structures consisting of a three-dimensional framework of SiO_4 and AlO_4 . There are many types of zeolites based on their mineral composition (Mumpton, 1999). The most common zeolite minerals are clinoptilolite, chabazite, phillipsite and mordenite (Birsoy, 2002). All of these minerals have open cages and many interconnected pore channels, resembling a honeycomb. This open structure allows zeolite to have lightweight when compared to natural soils. The engineering behavior of zeolites can be placed between sands and silts depending on the particle size (Ören & Kaya, 2014; Ören, Kaya & Kayalar, 2011). However, zeolites have some chemical advantages similar to clays.

Since zeolites have negatively charged surfaces, the heavy metal removal efficiency of zeolites is comparable to many other adsorbents (Blanchard et al., 1984; Cincotti et al., 2001; Peric et al., 2004, Ören & Kaya, 2006). Thus, they are used in wastewater treatment processes. In addition, zeolites have the ability to remove ammonia from the air (Kang & Wada, 1988; Rozic et al., 2000). This beneficial characteristic may be used to reduce malodors in landfills.

Zeolite is in the rock formations, but the particle size can be easily arranged on account of its brittle characteristics. Thus, zeolite can be found in the wide range of particle sizes in the markets. From a physical point of view, the compaction characteristics of zeolites are similar to silty sands. However, the optimum water content is significantly greater (i.e. $\sim 40\%$), whereas maximum dry unit weight is remarkably lower (12 kN/m^3) than those of many natural soils (Ören & Özdamar, 2013). Moreover, clinoptilolite type of zeolites has no or very little plasticity, resulting in comparable volumetric shrinkages with silty sands (Ören & Kaya, 2014). All of these physical and chemical abilities make zeolite a candidate subsoil material that can be used in landfills.

5.3 Water Uptake of GCLs from Different Subsoils

U.S. Environmental Protection Agency (USEPA, 1996) investigated hydration behavior of three GCLs (named as Claymax, Bentomat and Bentofix) over a low plastic clay (CL). GCLs were hydrated for 5, 25 and 75 days on compacted CL subsoil at different water contents (i.e. 16%, 20% and 24%). The authors concluded that a small increase in the subsoil water content had a significant effect on the water contents of GCLs. In addition to this, the highest water contents of GCLs were achieved after 75 days of hydration. The maximum water contents of GCLs were 70% for Claymax, 94% for Bentomat and 78% for Bentofix when the subsoil was compacted at 4% wet side of optimum (i.e. 24%).

Katsumi et al. (2008a) hydrated two GCLs with powdered and granular bentonites over Toyoura sand or decomposed granite soil. Soils were compacted at 15% and 20% water contents and GCLs were subjected to hydration from 7 days to 93 days. They also simulated rise of groundwater across the soil by standing compacted subsoil in 1 cm of water table and examined the influence of water supply on the water content of GCLs. They found greater final water contents for GCLs hydrated over the subsoil which stand in the water than the GCLs hydrated over subsoil without a water supply. For example, the water contents of GCLs with powdered bentonite hydrated for 31

days over decomposed granite at 20% water content were 266% versus 110% with and without water supply, respectively.

Rayhani et al. (2011) hydrated three needle-punched GCLs (GCL1, GCL2 and GCL3) over silty sand which was compacted at water contents of 5%, 10%, 16% or 21% and sand subsoil compacted at 2% and 10% water contents. Water contents of GCLs more than 100% were achieved when the subsoil water contents were 16% for GCL1, 21% for GCL2 and 10% for GCL3, respectively. However, the greatest final water contents were obtained with the subsoil compacted at 21%. After 30 weeks of hydration, water contents reached to 141%, 116% and 119% for GCL1, GCL2 and GCL3, respectively.

Anderson, Rayhani & Rowe (2012) hydrated the same GCLs used by Rayhani et al. (2011) over a clayey sand at various water contents (i.e. 5-20%) for 22 weeks. GCLs reached the lowest final water contents (i.e. 24% for GCL1, 22% for GCL2 and 23% for GCL3) after 22 weeks of hydration when the subsoils water contents were 5%. In contrast, the water contents of GCLs were 130% for GCL1, 106% for GCL2 and 174% for GCL3 within the same hydration duration when the subsoil water contents were increased to 20%.

Chevrier et al. (2012) investigated the hydration of a needle-punched GCL at various temperatures (i.e. 5°C, 20°C and 45°C) over a fine-grained silica sand and a plastic clay with different water contents (i.e. 5% and 10% for silica sand and 15% and 25% for plastic clay). The authors reported that increasing the subsoil water content and temperature resulted to increase in both hydration water content and hydration rate of GCL. The highest water contents of GCLs were obtained with silica sand at 45°C (i.e. 175%).

Barclay & Rayhani (2013) determined the influence of elevated temperatures on the hydration of two GCLs hydrated over sand and clay subsoils. It was revealed that the elevated temperatures restricted the GCLs to reach the acceptable water content levels in the field. That is the greater than 100% GCL water contents can be obtained

at room temperature. In other words, the water contents of GCLs decreased around 13% with clayey subsoil at 55°C.

Sarabian & Rayhani (2013) examined the hydration of two GCLs (GCL1 and GCL2) on a foundation soil of Navan Landfill in Ottawa which had 10%, 30%, 45% and 65% water contents. After 20 weeks of hydration, final water contents of GCLs were within the ranges of 48-86% for GCL1 and 48-106% for GCL2. The highest final water contents of GCLs (i.e. 86% for GCL1 and 106% for GCL2) were achieved with the subsoil which had 65% water content. Similar results were also obtained from Barclay & Rayhani (2013). The authors hydrated the same GCLs (GCL1 and GCL2) around 110 days on a compacted poorly graded sand (SP) and low plastic clay (CL) at 2% wet side of optimum. The final water contents of GCLs were 60% versus 106% for GCL1 and 65% versus 152% for GCL2 regarding hydration over CL and SP subsoils, respectively. However, both GCLs reached greater final water contents (i.e. $\geq 100\%$) when hydrated on SP subsoil which was compacted at 2% wet side of optimum.

Bouazza et al. (2017) investigated the influence of mineralogy-based effects of subsoil types on the hydration of an Australian GCL. GCL samples were hydrated over compacted SM (S1), SC (S2), CL (S3) and CH (S4) subsoils at 2% wet of optimum water contents. The authors reported that the hydration of the GCL strongly depend on the smectite content of the subsoil. The maximum water contents of the GCL samples were between 28% and 122% regarding the smectite contents of the subsoils. That is, the greater smectite content of the subsoils, the greater is the hydration water content of the GCL.

5.4 Water Uptake of GCLs After Hydration

The water contents of GCLs hydrated over compacted zeolite subsoil (zeolite-2) were determined after 7, 30, 62 and 90 days of hydration for GCL-1 (LP) and 7, 30 and 90 days of hydration for GCL-8. Figure 5.1 indicates that the water content of GCL-1 (LP) increased from 13% to 120% within 30 days of hydration and then slightly

increased to 147% at the end of 62 days of hydration when hydrated over zeolite-2. Further hydration caused to decrease the water content of GCL-1 (LP) (i.e. 117% for 90 days of hydration). Similarly, the water content of GCL-8 (HP) increased from 11% to 65% over zeolite-2 in 7 days of hydration. After 30 days of hydration, the water contents reached to 117% and kept increasing until the end of 90 days of hydration (i.e. 149%). This increasing trends of water contents with the hydration durations are also consistent with the findings reported in the literature (Anderson, Rayhani & Rowe, 2012; Bradshaw, Benson & Scalia, 2012; Rayhani et al., 2011; Rowe & Abdelatty, 2012).

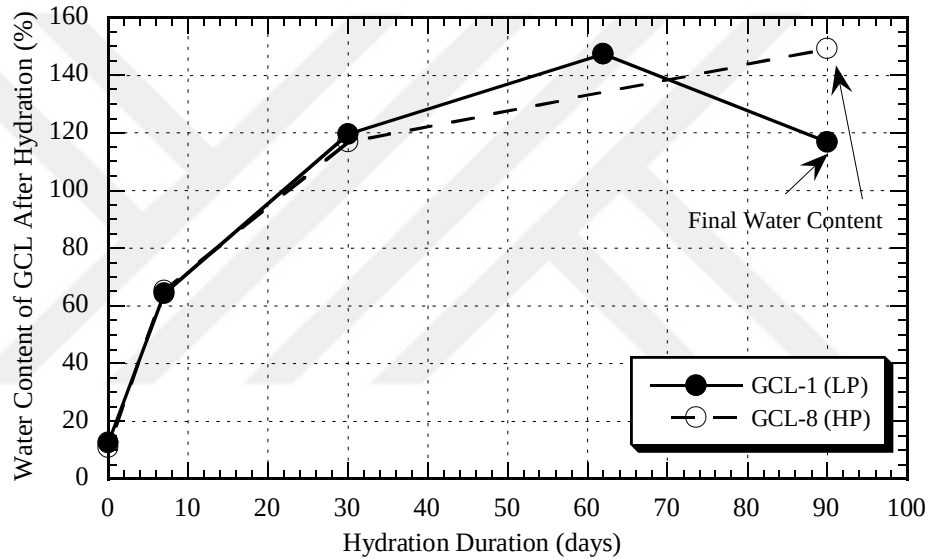


Figure 5.1 Influence of hydration duration on water content of GCLs

GCL type has no significant influence on the water content of GCLs in the short-term hydration durations (i.e. ≤ 30 days). The water contents are more or less the same in this time period. However, it becomes significant in the long-term (> 62 days). The difference between the water contents of GCL-1 (LP) and GCL-8 (HP) is about 30% after 90 days of hydration (Figure 5.1).

The final water content of GCL is identified as the equilibrium water content that bentonite reached its maximum at the final step of hydration duration (it is 90 days for this study). Although it varies depending on GCL and subsoil type, most GCLs reached equilibrium state around 30 days of hydration. The final water contents of data reported

in the literature are compared with those of GCL-1 (LP) and GCL-8 (HP) (at the end of 90 days of hydration) in this study as a function of subsoil water content relative to optimum in Figure 5.2. The increasing trend of final water contents of GCLs with increasing the subsoil water content is shown by two lines drawn on Figure 5.2. The final water content of GCL-1 (LP) is close to the upper limit; however, that of GCL-8 (HP) is out of the line. In general, the final water contents of GCL-1 (LP) and GCL-8 (HP) are above most of the final water contents reported in the literature, suggesting the efficiency of zeolite on increasing the water contents of GCLs.

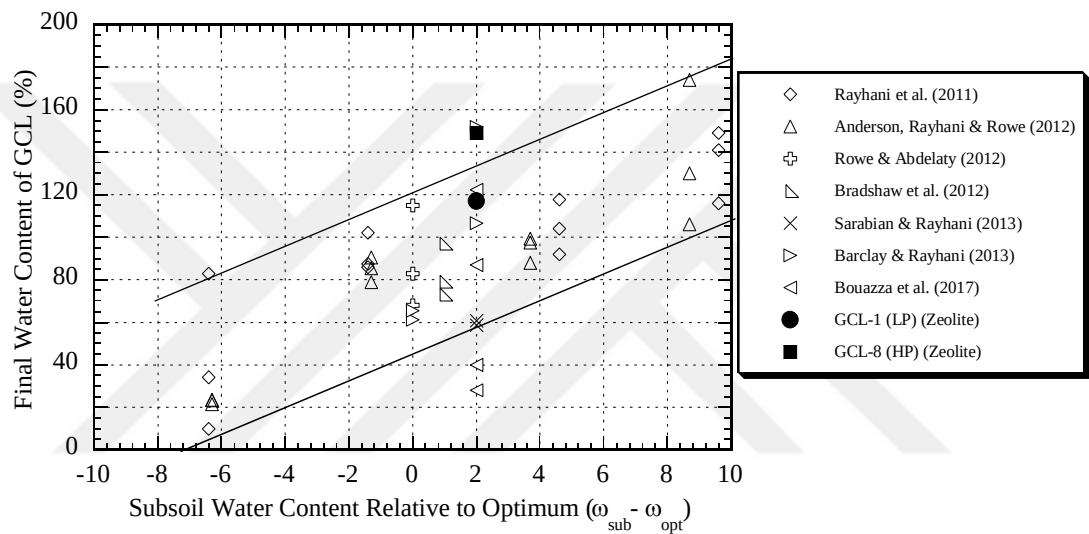


Figure 5.2 Influence of subsoil water content on the final water content of GCL

Another thing that should be emphasized is that the water content of GCL-1 (LP) decreased from 147% to 117% when hydration duration was increased from 62 days to 90 days. Unlike GCL-1, such kind of decrement was not observed for GCL-8 (HP), but note that GCL-8 (HP) was not hydrated for 62 days on the zeolite. The reduction in the water content of GCL-1 (LP) after 90 days of hydration may be due to cation exchange that might have been occurred between GCL and zeolite. Although Na^+ is the most abundant cation type in the pore water of zeolite, concentrations of other cations are appreciably high as well (Table 2.3). Thus, cation analyses were conducted on hydrated GCLs to see if there is any cation replacement took place between GCLs and the subsoil.

5.5 Cation Exchange During Hydration

The major bound cations (Na^+ , K^+ , Ca^{++} , Mg^{++}) were determined for both new and hydrated GCLs. The exchangeable cations of GCLs are expressed in terms of mole fractions in Table 5.1. Mole fractions were calculated as the ratio of each cation concentration to the total concentrations of all exchangeable cations.

Table 5.1 Influence of subsoil hydration on the exchangeable complex of GCLs in terms of mole fractions

GCL Type	Subsoil Type	Hydration Duration (Days)	Exchangeable Mole Fractions			
			X_{Na}	X_{K}	X_{Ca}	X_{Mg}
GCL-1 (LP)	None	0	0.86	0.01	0.12	0.01
		7	0.86	0.02	0.11	0.01
	Zeolite-2	30	0.73	0.03	0.21	0.04
		62	0.70	0.03	0.22	0.05
		90	0.58	0.03	0.29	0.11
GCL-8 (HP)	None	0	0.65	0.01	0.24	0.11
		7	0.70	0.01	0.19	0.09
	Zeolite-2	30	0.68	0.02	0.21	0.09
		90	0.65	0.02	0.22	0.12

Mole fractions of monovalent cations (Na^+ and K^+) and divalent cations (Ca^{++} and Mg^{++}) were 0.88 and 0.13 for brand-new GCL-1 (LP) and 0.65 and 0.35 for brand-new GCL-8 (HP), respectively (Table 5.1). There was no cation replacement between GCL-1 (LP) and zeolite-2 within 7 days of hydration. Indeed, mole fractions of all exchangeable cations were more or less the same as with brand new GCL-1 (LP) at 7 days of hydration. However, the mole fraction of Na^+ (X_{Na}) gradually decreased to 0.58 at the end of 90 days of hydration for GCL-1 (LP). The mole fraction of K^+ (X_{K}) was very low in GCL-1 (LP) with respect to other cations, and thus the hydration induced change in the K^+ mole fraction is neglected. In contrast, mole fractions of divalent cations (X_{Ca} and X_{Mg}) started to increase after 7 days of hydration. Finally, X_{Ca} and X_{Mg} increased to 0.29 and 0.10, respectively, after 90 days of hydration for GCL-1 (LP) (Table 5.1).

The mole fractions of exchangeable cations in GCL-1 (LP) are plotted as a function of hydration duration in Figure 5.3a. Here it is depicted depicts that the changes in the

mole fractions of bound cations with hydration duration are almost linear (Figure 5.3a). Although cation replacement undoubtedly occurred, the exchange complex of GCL-1 (LP) is still majorly occupied by Na^+ . However, when compared to brand new GCL-1 (LP), the mole fractions of monovalent cations reduced from 0.86 to 0.61, whereas those of divalent cations increased from 0.13 to 0.39 after 90 days of hydration (Table 5.1).

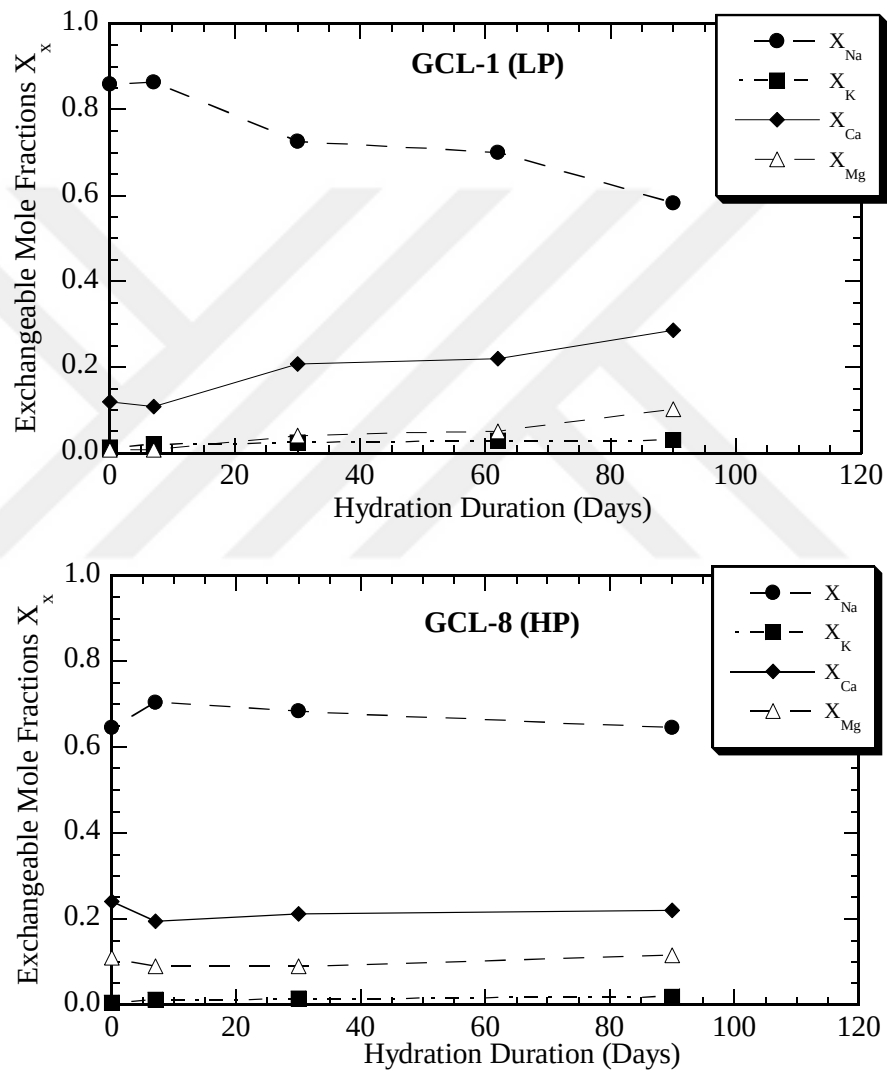


Figure 5.3 Mole fractions of bound cations on GCLs after hydration over compacted zeolite as a function of hydration duration: a) GCL-1 (LP) and b) GCL-8 (HP)

The changes in the mole fractions of exchangeable cations in GCL-8 (HP) are rather different than that occurred in GCL-1 (LP). The mole fractions of X_{Na} , X_{Ca} and X_{Mg} of brand new GCL-8 (HP) are 0.65, 0.24 and 0.11, respectively (X_{K} was neglected

because of very low mole fraction). However, X_{Na} increased to 0.70 and X_{Ca} and X_{Mg} decreased to 0.19 and 0.09, respectively, at 7 days of hydration (Table 6.1). Thereafter, X_{Na} started to decrease and X_{Ca} and X_{Mg} started to increase until 90 days of hydration. It is interesting to note that the mole fractions of exchangeable cations were almost the same as with the brand new GCL after 90 days of hydration. The changes of mole fractions of exchangeable cations are also shown in Figure 5.3b as a function of hydration duration.

The rapid changes in the mole fractions after 7 days of hydration can be attributed to polymer elution from GCL-8 (HP). The basic mechanism governing the hydraulic conductivity of polymer GCLs is dissolution of polymers and clogging the pores of bentonite when faced with water (Hosney & Rowe, 2013; Scalia & Benson, 2017). It is hypothesized that polymers started to elude from GCL-8 (HP) immediately after placing the GCL over zeolite-2. The eluded polymers were then stocked on the pores of GCL. Hence, when cation analysis was conducted, more Na^+ was transferred from GCL to extract solution, resulting in a greater X_{Na} for GCL-8 (HP). This also led to calculate lower mole fractions for Ca^{2+} and Mg^{2+} . This tendency, however, changed again after 30 days of hydration. That is, X_{Na} decreased, whereas X_{Ca} and X_{Mg} increased until 90 days of hydration. The main reason for this change may be the movement of polymers from GCL through the subsoil. In other words, the concentration of polymers, and hence Na^+ , in the GCLs decreased with the hydration duration. This hypothesis is proved by Scalia & Benson (2017). They hydrated a polymer GCL on clayey subsoil for 50 and 125 days and observed polymer diffusion at the 3-4 mm uppermost layer in the subsoil. They also concluded 54% of polymer loss from GCL after 125 days of hydration.

To observe the influence of cation replacement, swell index tests were conducted on the clay components of GCL-1 (LP) and GCL-8 (HP). Swell index test is a rapid method that measures the swell characteristics of bentonites in water and gives good information about the response of swell changes when cation exchange occurred (Bradshaw, Benson & Scalia, 2012; Hosney & Rowe, 2013; Meer & Benson, 2007; Ören & Akar, 2017; Scalia & Benson, 2011, 2010).

5.6 Swell Indices of GCLs

The influence of zeolite hydration on the swell indices of GCLs is shown in Figure 5.4 in terms of hydration duration. The swell index of GCL-1 (LP) decreased from 24 to 13 mL/2g with the hydration. In contrast, swell indices of GCL-8 (HP) increased from 31 to 36.5 mL/2g until 30 days of hydration and then decreased to 33 mL/2g after 90 days of hydration. Increase in the swell indices of GCL-8 (HP) until 30 days of hydration is due to the polymers in bentonite. Dissolution of polymers during hydration improves the swelling performance of GCL-8 (HP). However, this tendency changed after 30 days of hydration possibly because of polymers' transport from GCL-8 (HP) to zeolite-2, resulting in polymer loss on GCL-8 (HP).

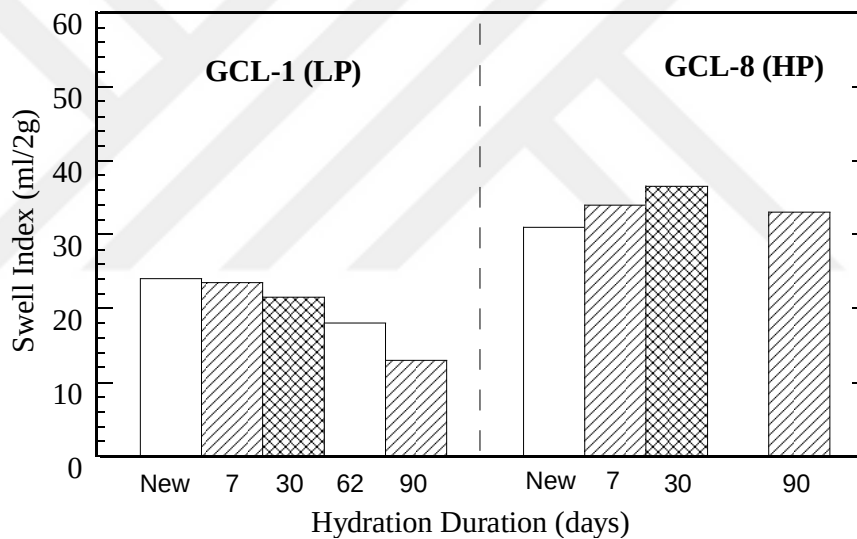


Figure 5.4 Influence of subsoil hydration on the swell index of GCL

Changes in swell indices with hydration duration are evaluated together with the cation exchange analyses. Figure 5.5a-b show that X_{Na} of GCL-1 (LP) and GCL-8 (HP) increases whereas X_{Ca} and X_{Mg} decreases as the swell indices increase. Although no correlation coefficients are given, the tendencies for both GCLs are almost linear. However, the slopes of these lines for GCL-1 (LP) are steeper than those for GCL-8 (HP). It means that the swell indices of GCL-1 (LP) are sensitive to the changes in the exchange complex more than GCL-8 (HP).

Use of zeolite beneath GCLs had an advantage on increasing the water content of GCL. In contrast, X_{Na} of GCLs decreased and X_{Ca} increased as a result of cation exchange occurred between GCLs and zeolite. So, another question that should be examined is whether this cation exchange has an influence on the hydraulic conductivity of GCLs or not. To demonstrate this effect, hydrated GCLs were subjected to hydraulic conductivity tests.

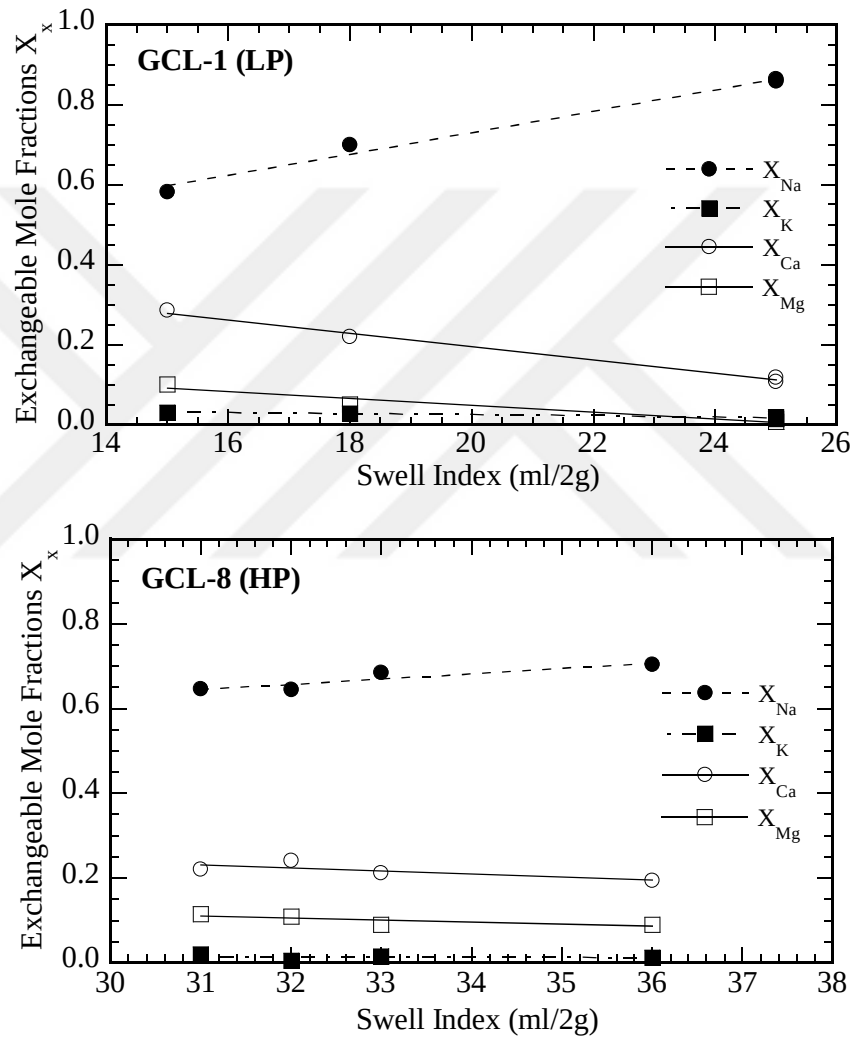


Figure 5.5 Relationship the between exchangeable mole fractions and swell indices of: a) GCL-1 (LP) and b) GCL-8 (HP)

5.7 Hydraulic Conductivity of GCLs

The hydraulic conductivities of GCL-1 (LP) and GCL-8 (HP) are summarized in Table 5.2. Although final hydraulic conductivities of GCLs are more or less the same and thus, independent of GCL type, the long-term hydraulic conductivity behaviors of GCL-1 (LP) are somewhat different than those of GCL-8 (HP) (Figure 5.6). The initial hydraulic conductivities of GCL-8 (HP) samples were low for all hydration durations. That is probably due to polymer enhancement which quickly dissolved and clogged the pores even at 7 days of hydration. However, the initial hydraulic conductivities of GCL-1 (LP) were high for all hydration durations. The gradual reduction in the hydraulic conductivity shows that GCL-1 (LP) continued hydration during permeation phase, resulting in comparable final hydraulic conductivity values with GCL-8 (HP) (Figure 5.6).

Table 5.2 Final hydraulic conductivities of GCL-1 and GCL-8

GCL Type	Hydration Duration (days)	Test Duration (days)	PVF	Final Hydraulic Conductivity (m/s)
GCL-1 (LP)	7	120	111	2.0×10^{-11}
	30	136	54	2.6×10^{-11}
	62	nd	-	-
	90	76	62	3.5×10^{-11}
GCL-8 (HP)	7	131	10	1.8×10^{-11}
	30	120	10	1.7×10^{-11}
	90	112	9	2.1×10^{-11}

In addition to this, the required PVF to achieve the hydraulic conductivity of 2.0×10^{-11} m/s is around 100 for GCL-1 (LP) which was subjected to 7 days of hydration. The same hydraulic conductivity level is measured at 40 and 50 PVF when GCL-1 (LP) was hydrated over zeolite-2 for 30 and 90 days, respectively. The reduction in the required PVF with the hydration duration is due to increase in the water content of GCL in the long term (Figure 5.1).

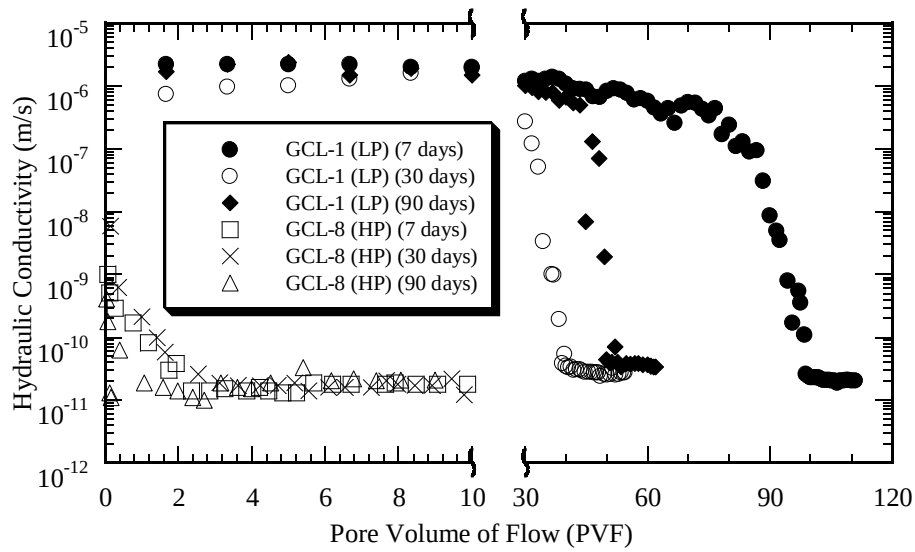


Figure 5.6 Hydraulic conductivity of GCL-1 (LP) and GCL-8 (HP) after hydrating over compacted zeolite-2

The water content of GCL-1 (LP) in 30 days of hydration was almost twice of the water content in 7 days of hydration (120% vs. 64%). Since the final water contents of GCL-1 (LP) at 30 and 90 days of hydration are almost equal (120% vs. 117%), the difference between the required PVF for low hydraulic conductivity was low as well (40 PVF vs. 50 PVF). However, it is obvious that increase in the hydration duration led to decrease the required PVF from 100 to less than 50 PVF.

5.8 Discussion of Test Results

The obtained results showed that three stages can be suggested for the hydration of GCLs over zeolite. In the first stage (Stage I), which has been commonly seen by other researchers, the water contents of GCLs rapidly increased within 7 days of hydration (< 7 days). This is because of high suction applied by the GCLs to subsoil. At Stage I, there was no evidence of cation exchange occurred between GCL-1 (LP) and zeolite-2. Since GCL-8 (HP) is polymer treated, X_{Na} increased and mole fractions of divalent cations (i.e. X_{Ca} and X_{Mg}) decreased slightly. In the second stage of hydration between 7 and 30 days (Stage II), the water contents of GCL-1 (LP) and GCL-8 (HP) continued increasing; however, cation replacement started between both GCLs and zeolite-2. Suction performances of GCLs at this stage were less than those observed at Stage I

(Figure 5.1). At the third stage between 30 and 90 days of hydration (Stage III), water contents of GCL-1 (LP) initially increased (at 62 days of hydration) and then decreased (at 90 days). However, the water content of GCL-8 (HP) kept rising until 90 days of hydration. But the slope, which shows the increment rate of water content, significantly decreased at Stage III with respect to the slope at Stage II. This means, suction of both GCLs stopped or came to end in Stage II. In contrast, cation replacement continued at Stage III and was more pronounced for GCL-1 (LP) than GCL-8 (HP) (Table 5.1 and Figure 5.3a).

Pore water of zeolite-2 was the abundance of monovalent cations (Table 2.3). However, there were also an appreciable amount of divalent cations which may govern the cation exchange observed between GCL and zeolite-2. At the first glance, it may serve a problem for the hydraulic conductivity. Indeed, the impact of cation replacement can be observed from swell index test data (Figure 5.4 and Figure 5.5a-b). However, the final hydraulic conductivities of neither GCL-1 (LP) nor GCL-8 (HP) were not affected by cation exchange. Practically, it has no influence up to 90 days of hydration.

Zeolite possesses a critical role in increasing the water content of GCLs which is an important factor on the hydraulic conductivity. Indeed, Özdamar & Ören (2016a) showed that the water content of GCL-1 (LP) increased up to 65% after 62 days of hydration on compacted silty sand which is half of the water content obtained from this study. Thus, the water content may be more significant than the cation exchange for controlling the hydraulic conductivity, at least, in the short-term test durations (<90 days). Cation replacement may be important in the long-term (>1-2 years) and therefore, hydraulic conductivity of GCL may change undesirably. At this time, the influence of zeolite induced cation exchange can be minimized by homoionizing zeolite with sodium. Since the surface charge of zeolite is negative, it is possible to remove divalent cations and load monovalent cations onto zeolite. That is another advantage of zeolite against sands or silty sands. However, to highlight the importance of zeolite on the hydration of GCLs, more efforts should be spent in the future.

5.9 Conclusions

GCL hydrations were conducted on compacted zeolite-2 to determine the possible effects of the zeolite mineral on the hydration and hydraulic conductivity behaviors of GCLs. To do this, GCL-1 (LP) and GCL-2 (HP) were used for the test. The obtained results are summarized below:

- Hydration over Zeolite-2 resulted in an increase in the water contents of GCL-1 (LP) and GCL-8 (HP). The water contents of GCL-1 (LP) and GCL-8 (HP) reached the maximum of ~150% after hydration over compacted zeolite. This value is higher than most of the water contents of GCLs reported in the literature. Since zeolite has greater compaction water contents than many natural soils, GCLs adsorbed more water from the underlying zeolite via water movement from the high potential to low potential.
- The water content of GCL-1 (LP) after 90 days of hydration was less than the water content of the same GCL at 62 days of hydration with zeolite (117% vs 147%). Cation analyses were performed to investigate whether this reduction is due to cation exchange. Although zeolite pore water was abundance of monovalent cations (Na^+), divalent cations (Ca^{2+} , Mg^{2+}) in zeolite preferably replaced with sodium in GCLs. The replacement demand increased with the hydration duration with GCL-1 (LP). Since GCL-8 (HP) was polymerized, mole fractions of sodium (X_{Na}) increased and those of divalent cations (X_{Ca} and X_{Mg}) decreased in the first 7 days of hydration because of the dissolution of polymers. However, similar to GCL-1 (LP), X_{Na} started to decrease whereas X_{Ca} and X_{Mg} increase at subsequent hydration durations.
- The influence of cation replacement was initially assessed with the swell index tests. Swell indices of GCL-1 (LP) decreased as the hydration duration increased. In contrast, swell indices of GCL-8 (HP) increased until 30 days of hydration with zeolite and then, decreased at subsequent hydration durations. When this tendency is evaluated in terms of cation analyses, almost linear

relationships were obtained between mole fractions of exchangeable cations and swell indices, indicating the cation replacement had an influence on the swell indices of GCLs.

- The major role of GCLs is to limit the liquid flow through barriers. Thus, GCLs hydrated over compacted zeolite were subjected to hydraulic conductivity tests. Regardless of GCL type and hydration duration, the final hydraulic conductivities were almost the same. Unlike GCL-8 (HP), the initial hydraulic conductivities of GCL-1 (LP) were high at all hydration durations. However, it reduced to 2.0×10^{-11} m/s with the permeation. Increase in the hydration duration decreased the time required to achieve low hydraulic conductivity.
- It is suggested that additional studies should be encouraged to support the findings of this study and to increase the knowledge on LP-GCLs and polymer treated GCLs (HP-GCLs).

CHAPTER SIX

SUCTION PROPERTIES OF SUBSOILS AND GEOSYNTHETIC CLAY LINERS

6.1 Background

Over the last two decades, geosynthetic clay liners (GCLs) have been increasingly used in the geoenvironmental field due to the low permeability of bentonite component in GCLs (Acikel et al., 2018; Benson, Oren & Gates, 2010; Bouazza et al., 2017; Hosney & Rowe, 2014; Lake & Rowe, 2005; Mazzieri and Di Emidio, 2015; Rowe, 2005; Shackelford et al., 2000; Touze-Foltz et al., 2016). Recent studies showed that the barrier ability of GCLs strongly depends on how much hydration occurred on GCLs. Since GCLs have approximately 10% initial water content before installation, hydration induced water content should be more than 80% during the post construction stage (Acikel et al., 2018; Chevrier et al., 2012; Hornsey et al., 2010; Liu et al., 2015; Petrov & Rowe, 1997; Rayhani et al., 2011).

Based on the environmental conditions, GCLs are subjected to hydration from the subsoil after installation. Once GCLs are placed on the subsoil it tends to adsorb water from the underlying soil. The water content of the GCL increases whereas the water content of the subsoil decreases until the hydraulic potential (suction) forces become into equilibrium. The water transport between subsoil and GCL mainly depends on the water retention (WR) characteristics of the GCL and the subsoil (Acikel et al., 2018; Bouazza et al., 2017). The significance of this tendency during hydration has been emphasized in the previous chapters. However, the details about the suction performance of not only subsoil, but also GCLs are reported in this chapter.

The fundamental relationship between suction (total or matric) and water content (gravimetric/volumetric water content or degree of saturation) of the soil/GCL is known as a water-retention curve (WRC) (Fredlund & Xing, 1994). Suction term expresses the free energy state of the soil water (Fredlund & Rahardjo, 1993). The soil takes water by two types of suction which were held by capillary force (i.e. matric

suction) and chemical force (i.e. osmotic suction). The summation of matric and osmotic suction is also known as total suction. There are many techniques for measuring the soil/GCL suction, such as vapor equilibrium, high-capacity tensiometers, pressure plate or membrane extractors, thermocouple psychrometers, capacitive relative humidity sensors, filter paper etc. Among from these methods, filter paper is an inexpensive and simple method which promotes both total and matric suction measurements. However, it is classified under indirect measurement technique for suction.

Many studies were reported in the literature about the suction characteristics of different types of soils with filter paper method (Bai & Liu, 2012; Chen et al., 2012; Gardner, 1937; Munoz-Castelblanco et al., 2012). The applicability of this method on the GCLs were also investigated by several researches (Acikel et al., 2011; Barroso, Touze-Foltz & Saidi, 2006). Based on these studies, it was concluded that the suction measurements on GCLs can be performed with filter paper method in accordance with the ASTM: D5298-16.

ASTM: D5298-16 is a guide which helps to determine the suction values of the soil samples from the calibration curves of filter papers (i.e. Whatman No.42 or Schiecher and Schuell No.589). However, this standard gives only one calibration curve for both suctions by neglecting whether the suction is total or matric. However, Leong, He & Rahardjo (2002) reported that the calibration curves of filter papers were different for total and matric suction measurements especially at lower suction levels (< 1000 kPa). In addition, the authors reported the presence of hysteresis in the calibration curves when the filter paper is wetted up. Similar results have been also evaluated by other researches (Acikel et al., 2015; Munoz-Castelblanco et al., 2012). This hysteresis between the drying and wetting paths have been generalized by Acikel et al. (2015) as a conceptual model for the WRCs of filter paper with the assumption of filter paper had similar suction behavior with the soil.

To understand the water transfer from subsoil to GCL suction measurements were included to the study presented herein. Since no direct measurement techniques were

available in the laboratory, the use of filter paper method was the only way to simply measure the suction characteristics of subsoils (sand, zeolite-1 and zeolite-2) and GCLs (GCL 1-8). The suction characteristic of subsoils and GCLs were investigated with non-contact filter paper test method (NCFPT) for total suction whereas with contact filter paper test methods (CFPT) for matric suction (Acikel et al., 2011; 2015; Bulut & Leong, 2008; Bulut & Wray, 2005). The matric suction of GCLs were measured with two different methods [i.e. initially wet contact filter paper tests (IW-CFPT) and initially dry contact filter paper test (ID-CFPT)] (Acikel et al., 2015). By considering the presence of hysteresis, the suction values of GCLs were determined from the calibration curves suggested by ASTM D5298-16 and Parcevaux (1980) for ID-CFPT and IW-CFPT, respectively. Although it is suggested to use different calibration curve for total suction measurements, the same calibration curve suggested in ASTM D5298-16 was used for the determination of total suction by considering the GCLs have high suction levels. Finally, measured data were fitted with Fredlund & Xing (1994) equation to predict the parameters which can be used for the modeling of unsaturated behaviors of the materials.

6.2 Water Retention Curves

The gravimetric water contents of the soils/GCLs and suction values obtained from the filter papers were used to fit a curve which is known as “water retention curve (WRC)”. The total and matric suction curves were derived from Fredlund & Xing (1994) equation as given below:

$$\omega(\Psi) = \omega_s \times \left[1 - \frac{\ln\left(1 + \frac{\Psi}{\Psi_r}\right)}{\ln\left(1 + \frac{10^6}{\Psi_r}\right)} \right] \times \left[\frac{1}{\left[\ln \left[\exp(1) + \left(\frac{\Psi}{a_f}\right)^{n_f} \right] \right]^{m_f}} \right] \quad (6.1)$$

where;

$\omega(\Psi)$ is predicted water content in terms of either gravimetric or volumetric (g/g or m³/m³),

Ψ is suction (kPa),
 ω_s is saturated water content,
 Ψ_r residual suction fitting parameter,
 a_f (kPa), n_f , m_f are the curve fitting parameters.

Curve fitting technique was applied by minimizing the sum of squared errors between the measured and calculated gravimetric water contents. The Solver function in Microsoft Excel was used for the iteration of fitting parameters and best-fit parameters were determined for the suction data sets.

6.3 Suction Behaviors of Subsoils

To determine the water content-suction behaviors of subsoils, specimens of compacted subsoils prepared at different water contents were allowed to total and matric suction measurements using non-contact and contact filter paper methods, respectively. The suction measurements on the compacted subsoils were only conducted with initially dry contact filter paper test (ID-CFPT). The data points for the subsoils were represented by open symbols for total suction and by closed symbols for matric suction on Figure 6.1. Based on the equation of Fredlund & Xing (1994), lines of best fit through these data points are also presented as dashed lines for total suction and solid lines for matric suctions on the same graphs.

One difficulty arose during the curve fitting for the water retention characteristics of the subsoils is the limited suction ranges achieved by the filter paper method. The suction ranges obtained from total and matric suction measurements were within the range of 60-480 kPa and 6-200 kPa, respectively (Figure 6.1a – Figure 6.1c). Suction ranges less than 6 kPa and greater than 500 kPa could not be obtained from the measurements. Thus, the convergence of the fitting parameters would be hard. Fitting parameters calculated by the solver function in Microsoft Excel are given in Table 6.1 with saturated water contents for the subsoils.

Table 6.1 Fredlund & Xing (1994) curve fitting parameters for the subsoil water retention curves

Subsoil Type	Fredlund & Xing parameters					Fredlund & Xing parameters				
	Total Suction					Matric Suction				
	ω_{sat} (%)	α_f (kPa)	n_f	m_f	Ψ_r (kPa)	ω_{sat} (%)	α_f (kPa)	n_f	m_f	Ψ_r (kPa)
Sand	16	295.269	2.786	0.628	992	16	73.782	1.596	0.787	996
Zeolite-1	50	212.266	2.020	0.377	999	50	50.641	1.494	0.473	997
Zeolite-2	47	220.978	2.406	0.268	1000	47	94.101	1.201	0.450	1000

Air entry pressure (Ψ_{aev}), and residual suction (Ψ_r) values were also shown on the water retention curves of the subsoils in Figure 6.1. The air entry suction is the transition point between the saturated and unsaturated state that identifies the point where air enters between the largest pores of the soil whereas the residual suction is the point where large suction change is required to remove additional water from the soil after this point (Fredlund & Xing, 1994). These two points could be used to separate the WRC into three parts: i) boundary effect, ii) transition and iii) residual. Boundary effect part of the curve represents the saturated conditions which means all pores in the soils are filled with water. In the transition part, soil starts to loss its water significantly with the increase in the suction. At the end of the transition part, which corresponds to the residual suction point, the amount of water in the soil becomes quite low. Further increase in suction values lead to relatively low changes in the water content and soil goes towards the residual part (Acikel et al., 2018; Fredlund & Xing, 1994; Vanapalli, Sillers & Fredlund, 1998).

It can be seen from Figure 6.1 that the air entry pressures (Ψ_{aev}) of each subsoil were different based on the suction measurement type (total or matric). The air entry pressures of the subsoils were determined as 198 kPa and 33 kPa for sand (Figure 6.1a), 114 kPa and 24 kPa for zeolite-1 (Figure 6.1b) and 157 kPa and 50 kPa (Figure 6.1c) for zeolite-2 with non-contact and contact filter paper methods, respectively. The greater air entry pressures were obtained from the total suction measurements. This situation is expected because the total suction contains not only the matric suction component but also the osmotic suction component of the soil (Fredlund & Rahardjo, 1993).

Moreover, residual suction values for the subsoils were determined in two ways by: i) taking as fitting parameter during the curve fitting process and derived using solver function in Microsoft Excel and ii) by considering the intersection point of the lines of which are drawn through linear portions of the WRC. It can be seen from Table 6.1 and Figure 6.1 that the residual suction values obtained from both methods were almost the same and around 1000 kPa for the total and matric suction measurements. This results also compatible with the literature for silty sand type soils (Bouazza et al., 2017).

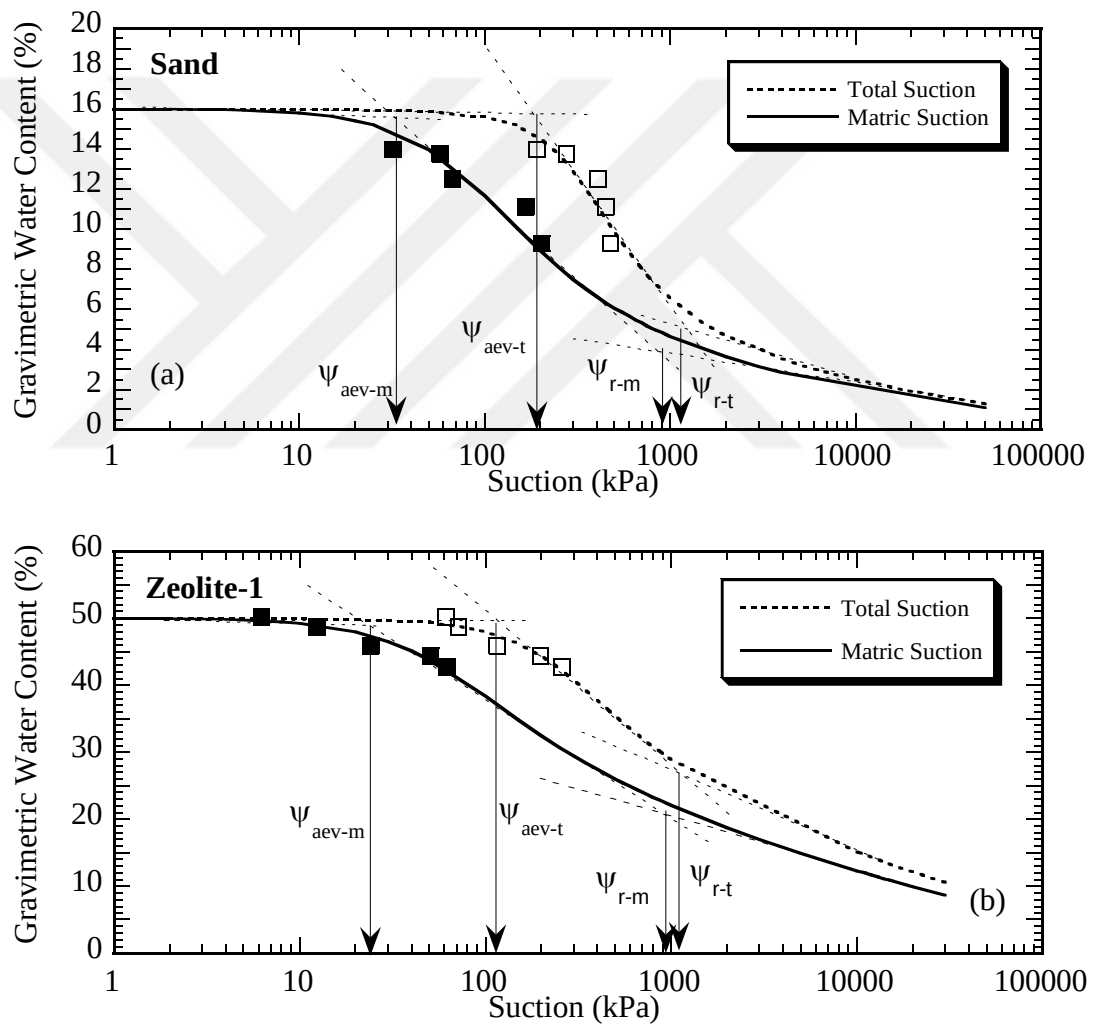


Figure 6.1 Water retention curves (WRC) of subsoils: a) sand; b) zeolite-1 and c) zeolite-2

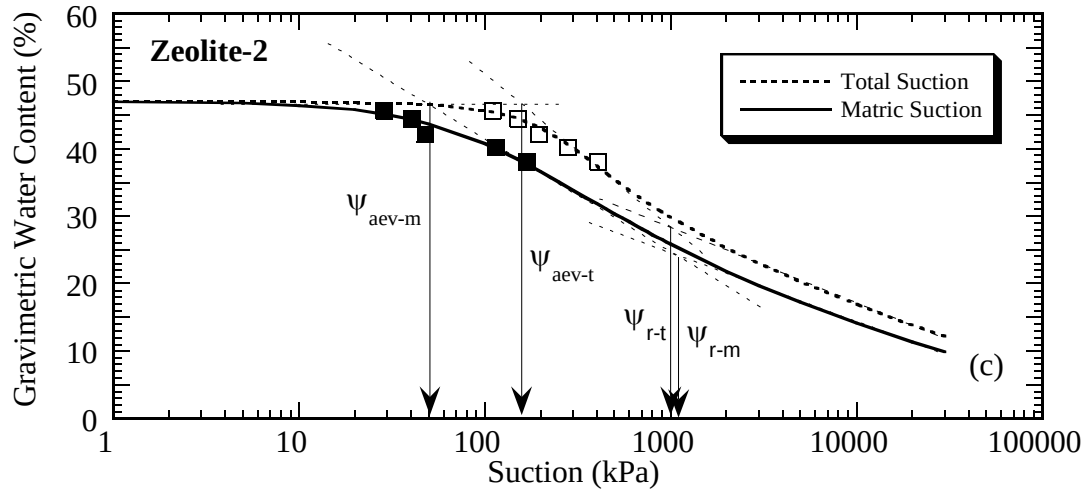


Figure 6.1 continues

6.4 Comparison of Suction Behaviors of the Subsoils

The suction behaviors of the subsoils obtained by contact filter paper method (i.e. matric suction) were drawn in terms of gravimetric water contents in Figure 6.2 for the comparison. It is clearly seen from Figure 6.2 that each compacted subsoil had unique WRCs although they were classified as silty sand (SM) in accordance with the Unified Soil Classification System (USCS).

The major difference between the WRCs of the compacted subsoils in Figure 6.2 are related with the saturated water content levels. The saturated water contents of compacted zeolites (zeolite-1 and zeolite-2) were around 50% whereas it was 16% for compacted sand. Therefore, although the shape of the WRCs are quite similar, the WRCs of compacted zeolites shifted over the WRC of the compacted sand (Figure 6.2).

The differences between the WRCs of the compacted subsoils possibly related with their particle size distributions as indicated by Fredlund, Wilson & Barbour (2001). Since most of the pores in coarse-grained soils are interconnected to each other, Fredlund, Wilson & Barbour (2001) stated that the desaturated tendencies of soils increase with the increase in the percentage of coarse grains or decreases with the increase in the fine contents of the soils. The particle size distributions of the subsoils

have been already given in Chapter 2 (Figure 2.5). As shows Figure 2.5 and Table 2.2 that the fine contents (< 0.075 mm) of zeolite-1 and zeolite-2 are greater than that of sand (48% and 46% versus 42%, respectively). Thus, the greater percent of fine particles in zeolite resulted in higher adsorption capacity (Figure 6.2). In contrast, although fine content of zeolite-1 is greater than that of zeolite-2, the latter had greater suction capacity at any water contents. This can be attributed to the difference between the clay-sized particles in zeolite-1 and zeolite-2 (i.e. 7% versus 20%). As suggested by Fredlund & Rahardjo (1993), greater percentage of clay-sized particles in zeolite-2 provided greater adsorption capacity.

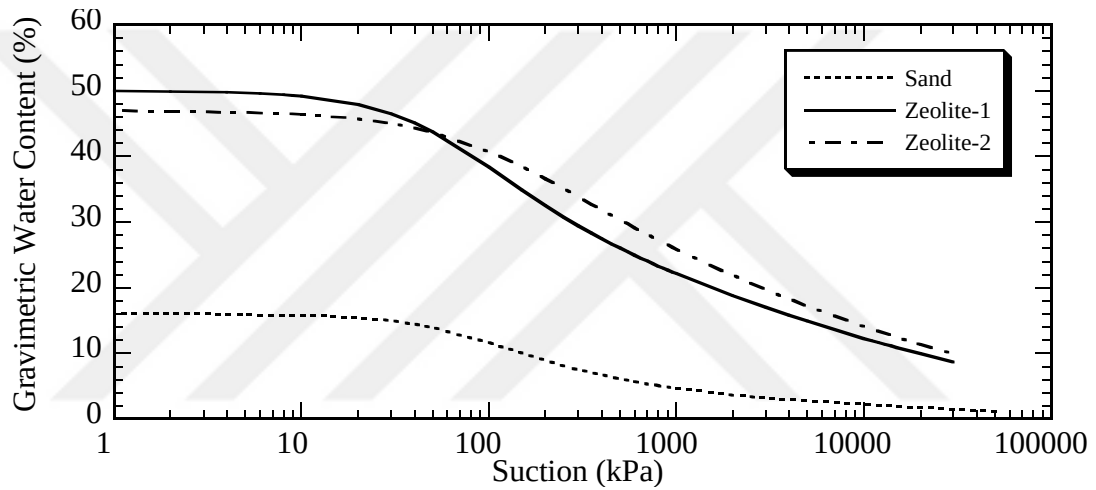


Figure 6.2 Comparison of water retention curves (WRC) of the subsoils in terms of matric suction measurements

Moreover, the difference between the suction characteristics of the compacted subsoils had also influence on the curve fitting parameters (Bouazza et al., 2017; Fredlund & Xing, 1994; Yang et al., 2004). Bouazza et al. (2017) showed that there is a linear increasing relationship between the air-entry pressure (Ψ_{aev}) and the curve fitting parameter α_f . Similar relationship between the Ψ_{aev} and α_f was also seen in this study. Compacted zeolite-1 has the lowest α_f (i.e. 50.641 kPa) and Ψ_{aev} (i.e. 24 kPa) values while compacted zeolite-2 has the greatest α_f (i.e. 94.101 kPa) and Ψ_{aev} (i.e. 50 kPa) values (Table 6.1 and Figure 6.1). Furthermore, Fredlund & Xing (1994) and Yang et al. (2004) proposed that the slope of the WRC is controlled by the parameter n_f . Greater n_f value results in steeper slope in the WRC. The descending order of n_f values are compacted sand, zeolite-1 and zeolite-2. Bouazza et al. (2017) also indicated

that the fitting parameter m_f is closely related with the residual suction value Ψ_r . They stated that the lower residual suction (Ψ_r) values corresponding to the greater m_f values. The results shown in Table 6.1 is in agreement with the findings of Bouazza et al. (2017) as well. Compacted zeolite-2 had the lowest m_f and highest Ψ_r , while compacted sand had the greatest m_f and lowest Ψ_r .

6.5 Suction Behaviors Geosynthetic Clay Liners

Like for the subsoils, the relationship between the water content and suction behavior was determined for eight needle-punched GCLs with filter paper method. For this purpose, GCL specimens with different water contents were subjected to both matric and total suction measurements. As previously described, initially dry contact filter paper test (ID-CFPT) and initially wet contact filter paper test (IW-CFPT) were used to determine the matric suction behaviors of the GCLs. The data points from the ID-CFPT and the IW-CFPT are shown in Figure 6.3 with open and closed circles, respectively. In accordance with the equation proposed by Fredlund and Xing (1994), the lines of best fit through these data points were derived and presented with a dashed line for ID-CFPT and a solid line for IW-CFPT measurements. Fitting parameters for WRCs of GCLs are also listed in Table 6.2.

Table 6.2 Fredlund & Xing (1994) curve fitting parameters for the subsoil water retention curves

GCL Type	Fredlund & Xing parameters					Fredlund & Xing parameters				
	Matric Suction-IDFM					Matric Suction-IWFM				
	$\omega_{\text{saturated}}$ (%)	Ψ_r (kPa)	n_f	m_f	Ψ_r (kPa)	$\omega_{\text{saturated}}$ (%)	α_f (kPa)	n_f	m_f	Ψ_r (kPa)
GCL-1	150	0.603	4.046	0.296	1115	150	0.513	3.419	0.356	1037
GCL-2	190	759.159	1.587	0.791	2127	190	695.349	2.080	0.582	2514
GCL-3	200	19.976	2.093	0.495	1002	200	12.353	1.916	0.653	1100
GCL-4	150	398.731	0.503	1.362	961	150	340.065	1.972	0.571	945
GCL-5	150	375.637	0.431	1.327	1000	150	94.213	0.767	0.851	1074
GCL-6	135	495.764	0.531	1.439	2523	135	136.022	0.574	1.279	2592
GCL-7	130	72.388	1.476	0.537	2561	130	27.951	0.446	1.266	2497
GCL-8	300	709.898	1.633	0.708	2838	300	185.367	0.598	1.744	2783

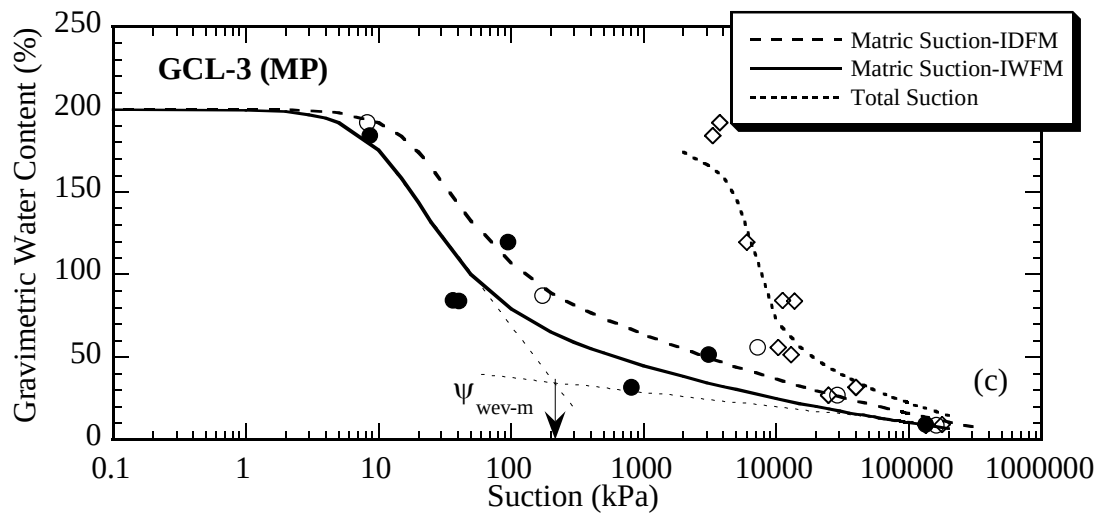
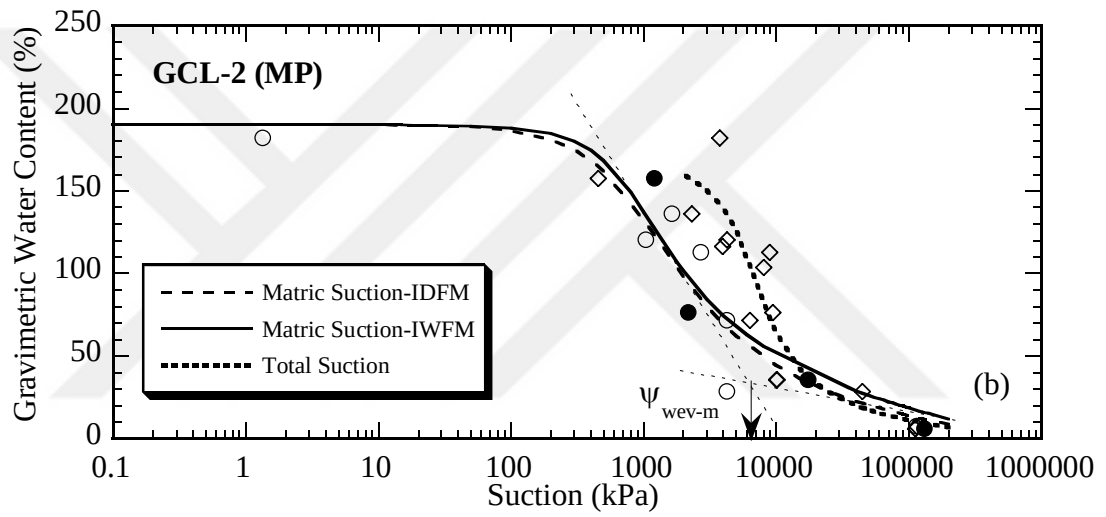
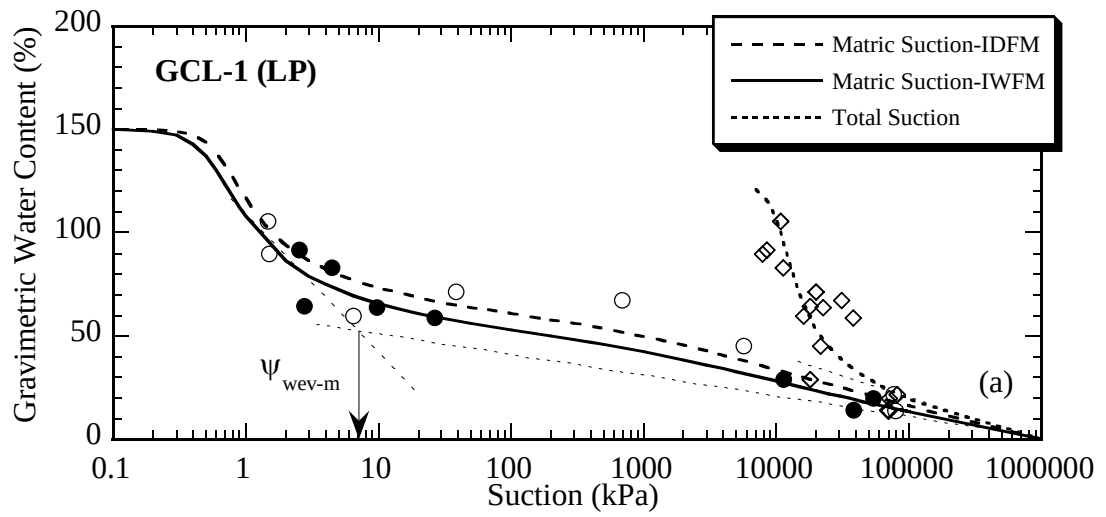


Figure 6.3 Water retention curves (WRC) of GCLs: a) GCL-1; b) GCL-2; c) GCL-3; d) GCL-4; e) GCL-5; f) GCL-6; g) GCL-7 and h) GCL-8

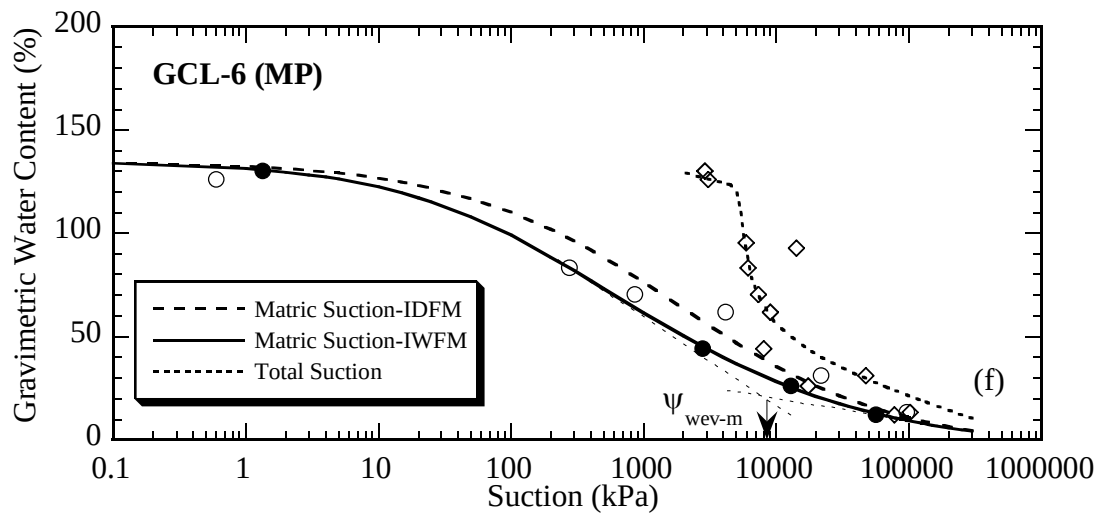
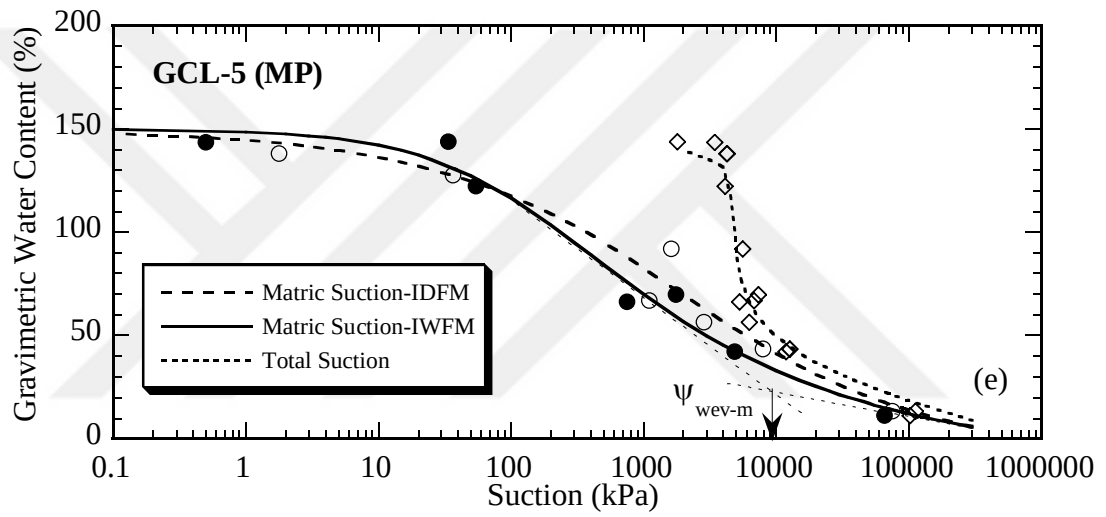
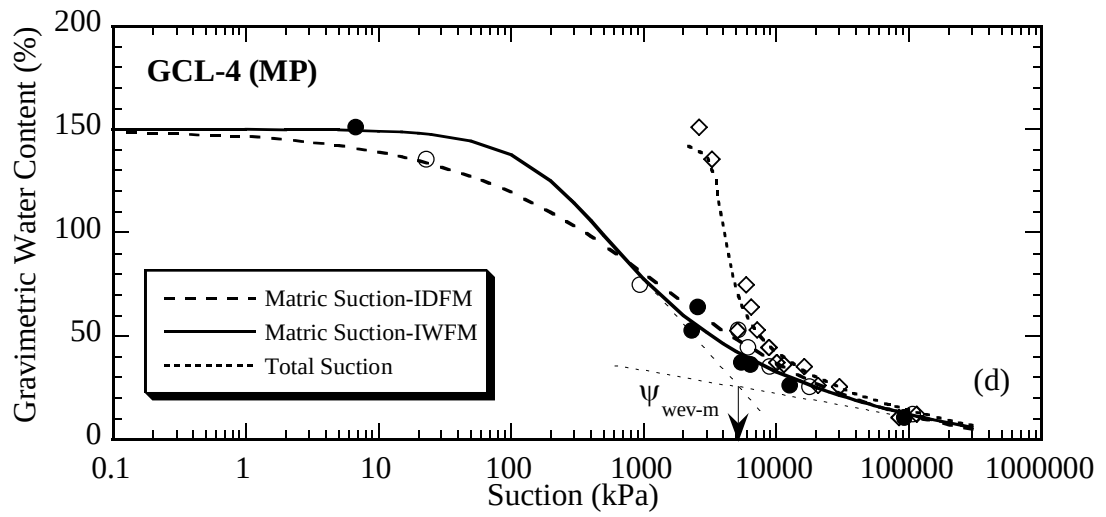


Figure 6.3 continues

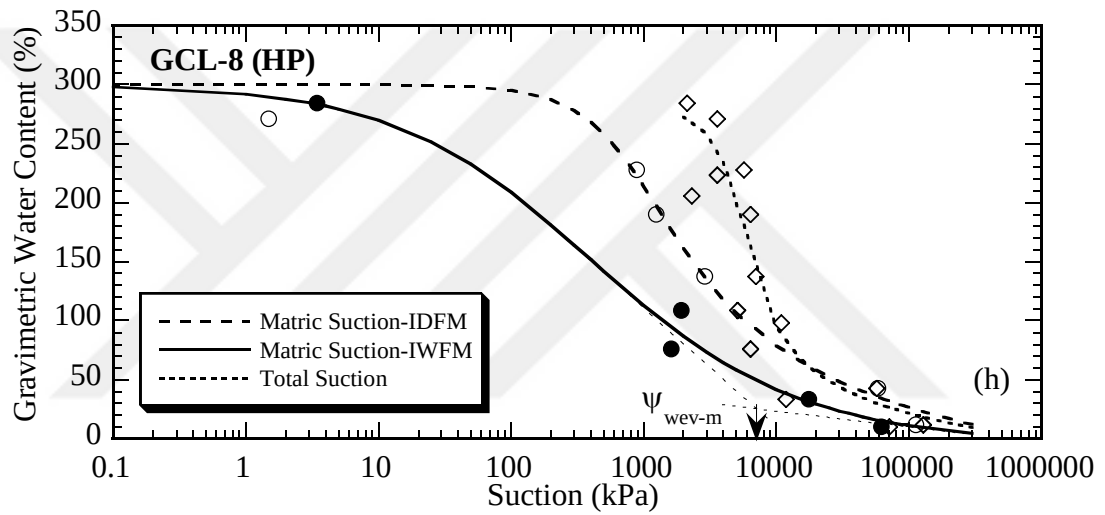
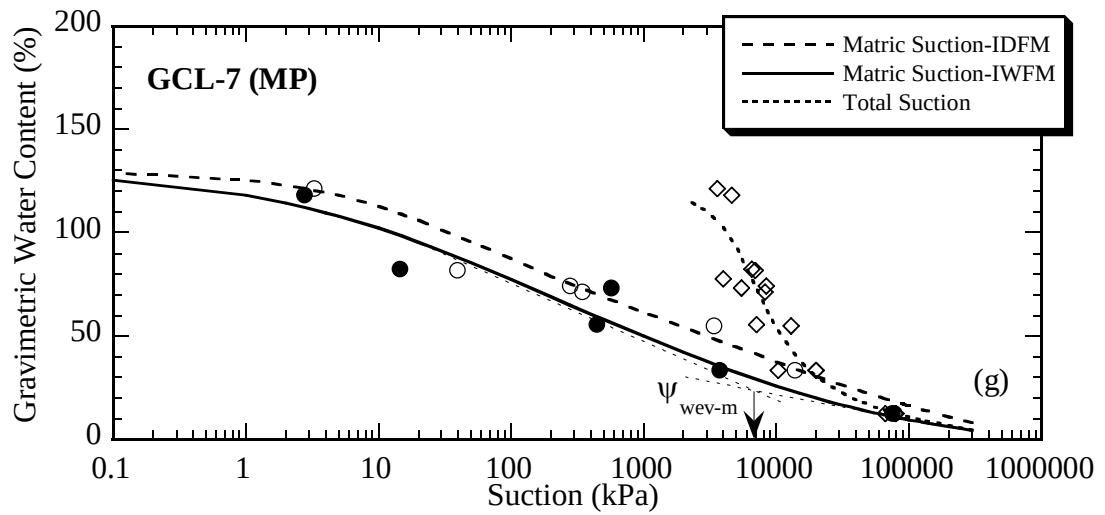


Figure 6.3 continues

The initial water content of GCL before hydration is low. Since the suction gradient between subsoil and GCL is remarkably high at the very early stage of hydration, GCL tends to adsorb water from the underlying soil. Thus, the GCL hydration can be represented by the wetting path of WRC. As seen in Figure 6.3, regardless of the applied suction technique (i.e. ID-CFPT or IW-CFPT), the suction pressure (or matric suction) of GCLs were high at low water contents and tended to decrease with an increase in the water contents of GCLs during hydration. Finally, GCLs reached the highest water contents at relatively low suction levels. This suction behavior gives a sigmoid shape to the WRCs of the GCLs (Figure 6.3a – Figure 6.3h).

Figure 6.3 shows that the water content levels reached by suction slightly change depending on the applied method (whether ID-CFPT or IW-CFPT). Muñoz-Castelblanco et al. (2012) proposed that the dry filter paper adsorbs water from the GCL in the ID-CFPT method whereas wet filter paper supplies additional water to the GCL in the IW-CFPT method. However, the water transfer between the GCL and the filter paper generally becomes stable before 7 days and compatible results could be obtained from both methods (Muñoz-Castelblanco et al., 2012). Except GCL-8, their observation is consistent with the findings of this study (Figure 6.3). In contrast, there is a significant difference between the suction values of GCL-8 obtained by ID-CFPT and IW-CFPT (Figure 6.3h). The matric suction values of the ID-CFPT were considerably higher than those of IW-CFPT when the suction values were within the range of 10-7000 kPa. Acikel et al. (2015) reported similar tendency between two methods for matric suction above 70 kPa. The reason for this difference between the ID-CFPT and IW-CFPT can be attributed to the accurate measurement limits of ID-CFPT. The capillary contact between the filter paper and the GCL was limited at the inflection (whether at residual suction or water entry) points (Acikel et al., 2015).

As previously mentioned in Chapter-2, the total and matric suction measurements were conducted on the same samples. Although the matric suction measurements were conducted with two different ways (ID-CFPT and IW-CFPT), the procedure applied for the total suction were the same and independent from the matric suction. Therefore, the total suction data were evaluated together (whether ID-CFPT or IW-CFPT). The results are shown with diamond symbols on Figure 6.3. As it is expected, the total suction values were greater than matric suctions (Figure 6.3). However, total suctions merged with the matric suction values at high suction level (>10000 kPa). This conclusion is consistent with the literature as well (Leong, He & Rahardjo, 2002)).

The water entry pressures (Ψ_{wev}) of GCLs were also shown in Figure 6.3. To avoid any confusion on the WRCs, the water entry pressures (Ψ_{wev}) were only drawn on WRCs obtained from IW-CFPT. The water entry pressure (Ψ_{wev}) represents the matric suction where the water content of the soil (i.e. GCL herein) starts to increase significantly (Yang et al., 2004). The water entry pressures (Ψ_{wev}) of GCLs were

between 7 and 7100 kPa for IW-CFPT and 7 and 12500 kPa for ID-CFPT (Figure 6.3). The difference between the Ψ_{wev} can be attributed to the physicochemical differences between GCLs.

6.6 Comparison of Suction Behaviors of GCLs

The matric suction characteristics of the GCLs obtained by IW-CFPT method are compared within each other in Figure 6.4. As seen in Figure 6.4, the shapes of all WRCs of GCLs were quite similar. However, the gravimetric water contents of GCLs show significant variation during the suction measurements of GCLs. The variation between the gravimetric water contents of GCLs were pronounced especially at matric suctions lower than 10000 kPa. The reason for this difference between the WRCs of GCLs may be due to smectite content in bentonite (or minerology), particle size, geotextile type or apparent opening pore size of geotextiles, fiber properties and manufacturing type (Beddoe, Rowe & Take, 2010; Beddoe et al., 2011). In contrast, independent from the type of GCL, the relationship between the gravimetric water content and suction became similar when suction values exceed 10000 kPa. As reported by Beddoe et al. (2011), the gravimetric water contents of GCLs and pure bentonite were similar at suctions greater than 10000 kPa. Thus, one can conclude that the bentonite portion of the GCLs dominated the suction characteristics of GCLs in high suction levels (> 10000 kPa). The WRCs of the GCLs in this study are also consistent with the findings of other researchers who reported the suction behaviors of GCLs (Acikel et al., 2015, 2018; Beddoe et al., 2011; Beddoe, Rowe & Take, 2010; Hanson, Risken & Yeşiller, 2013; Southern & Rowe, 2007).

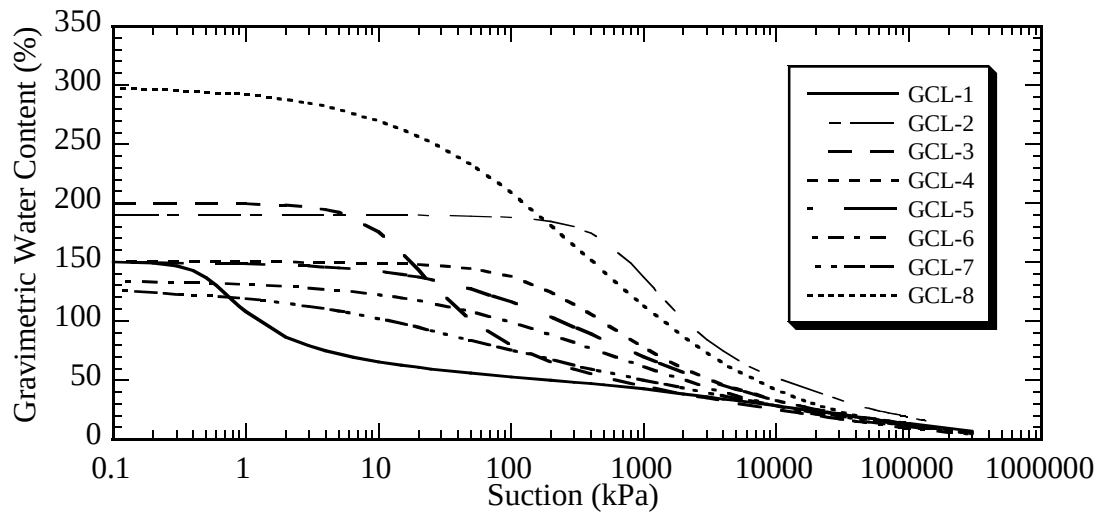


Figure 6.4 Comparison of water retention curves (WRCs) of GCLs used thought the study

6.7 Discussions

The suction tests with filter paper method showed that the matric suctions were between 10 kPa and 1000 kPa for the subsoils whereas they were between 1 kPa and 100000 kPa for the GCLs. Although reported measurable range of matric and total suction with filter paper method extends from 10 kPa to 100000 kPa (Beddoe, Rowe & Take, 2010), lower matric suction values were obtained especially for subsoils in this study. In this study, limited data exists for the suction measurements of the subsoils. The reason for the scarce data is mainly because of the difficulty encountered when samples were prepared on the dry sides of the optimum water contents. Unlike GCLs, the subsoil samples crumbled at low water contents and therefore limited number of samples could have been prepared for the suction tests. It should be noted that the lower water contents for the subsoils correspond to the higher suction levels on the drying path. In the lack of samples at lower water contents, the greater suction values were not achieved for the subsoils.

Furthermore, independent from the type of subsoil (i.e.), the matric suctions of compacted sand and zeolite were around 200 kPa at most during the hydration process. Thus, the matric suctions of GCLs during the hydration process should not be lower than the subsoil suction value. It is expected that the water transfer between the subsoil and the GCL terminates when the suction values of the materials come into equilibrium

or close to each other. However, when the water re-distributions between the GCL-1 (LP) and compacted subsoils are drawn together and the initial and final water contents of either GCLs or subsoils are plotted on WRC as proposed by Acikel et al. (2018), it is seen that the changes in suction values of GCL-1 (LP) during hydration was very interesting (Figure 6.5). The water re-distributions of other GCLs and subsoils are also drawn and presented in Appendix A.

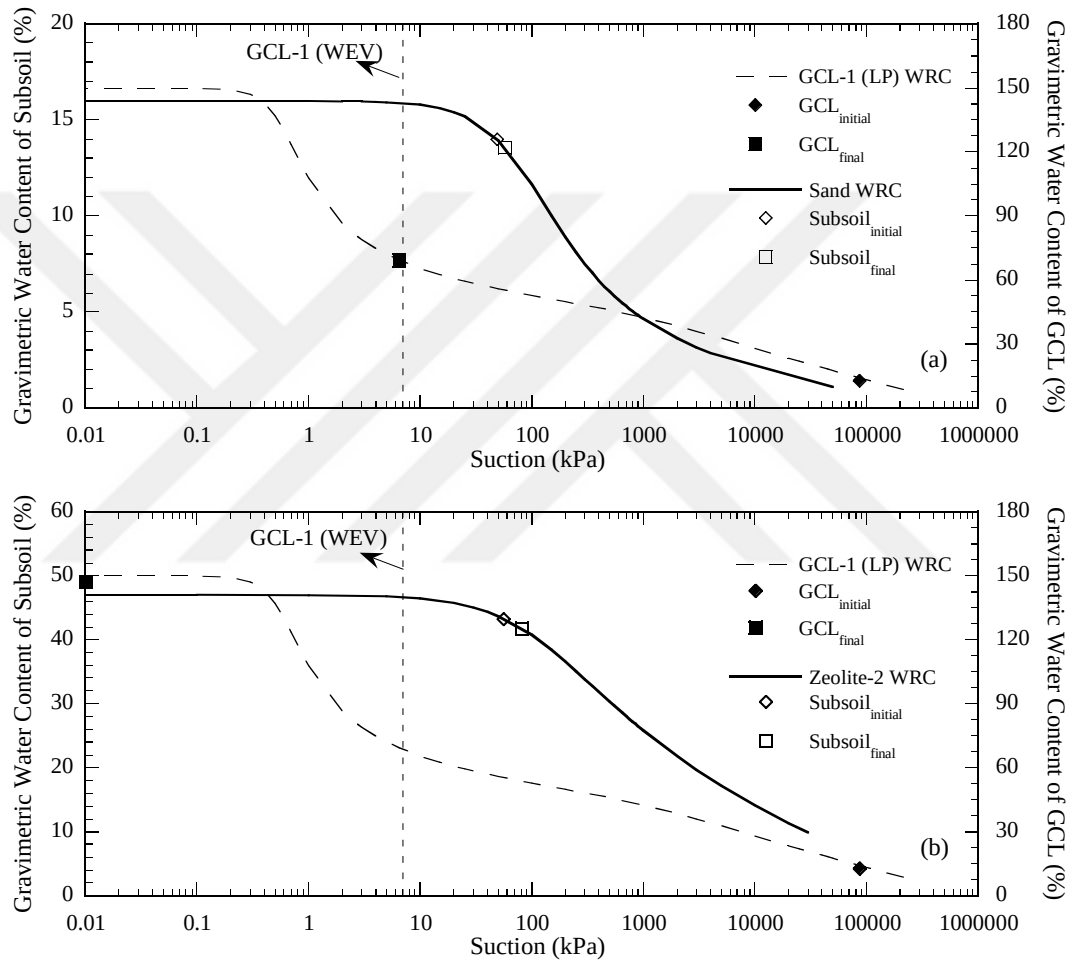


Figure 6.5 Water re-distribution between GCL-1 (LP) and compacted a) sand and b) zeolite-2

Figure 6.5 shows the WRCs of GCL-1 (LP) and subsoils (sand and zeolite-2) together. The diamond and square symbols plotted on the WRCs correspond to the water contents of GCL-1 (LP) and subsoils before and after hydration, respectively (Figure 6.5). As previously shown in Figure 4.1 and Figure 5.1 the water contents of GCL-1 (LP) increased from 13% to 69% and 147% when hydrated over compacted sand and zeolite-2, respectively. These final water contents of GCLs correspond to

very low matric suctions (i.e. <10 kPa) (Figure 6.5a and Figure 6.5b) or placed the final suction value of GCL on the left side of subsoil suction value (even initial or final). It is not logical because it is impossible to have lower matric suction for GCL-1 than for subsoil. The similar conclusion can be drawn between GCL-3 and compacted zeolite-2. The final suction value of GCL-3 was placed on the left side of final suction value of zeolite-2 (see also Appendix-A.2.a). The reason for this behavior may be attributed to: i) type of non-woven geotextile between the subsoil and bentonite, ii) the heterogeneity of bentonite in GCL-1 and iii) wide range of bentonite mass per unit area (MPUA) in GCL-1.

The geotextile part of the GCL which is in contact with the filter paper (i.e. non-woven side for this study) may result in capillary barrier effect during the suction tests. If the geotextile part governed the suction behavior of the GCL-1, similar results would be obtained for the other GCLs. Thus, it is believed that the geotextile component of GCL-1 has negligible or no effect on lower matric suction for GCL-1 than for subsoil.

The other reason may be attributed to heterogeneous characteristics of bentonite in GCL-1. The bentonite in GCL-1 might have been taken from different sources or different parts of borrow pit. During manufacturing, the bentonite might have not been mixed properly and hence, have not been homogeneously distributed over the woven geotextile. Thus, bentonite inside of GCL-1 might have different characteristics along the roll, resulting unexpected WRC for GCL-1.

The third reason, which is most probable among others, is that the GCLs in different MPUAs were used during filter paper method and thus, resulted in different characteristics of WRCs. The range of MPUA of each GCL was statistically analyzed and are shown in Figure 6.6 with box plot. In this kind of plots, the maximum and minimum MPUAs are shown outside of the box, whereas the median MPUAs are shown inside of the box with horizontal lines. The shape of the box shows the interquartile range of the data. The number of samples was also written on the bars for each GCL most of which were used during suction measurements (Figure 6.6). Figure 6.6 clearly shows that the range of MPUA significantly differs for each GCLs. For

example, GCL-1 and GCL-2 ranged from 2.17 to 5.63 kg/m², whereas GCL-6 and GCL-7 ranged from 5.01 to 10.30 kg/m². Only GCL-8 ranged slightly when compared to other GCLs (i.e. 1.68-2.98 kg/m²). Almost 16 samples were prepared for each GCL during matric suction measurements. If just these samples are evaluated in a similar manner as shown in Figure 6.6, the same MPUA ranges can be obtained. It means the MPUA ranges obtained by the whole GCL samples (Figure 6.6) can also be applicable to the MPUA ranges obtained by the GCLs used just in case of matric suction measurements. Thus, it should be expected that GCLs in different MPUAs used during filter paper method will inevitably have an impact on the suction measurements. Since GCL-1 and GCL-3 had wide range of MPUAs, the WRCs of these GCLs become questionable.

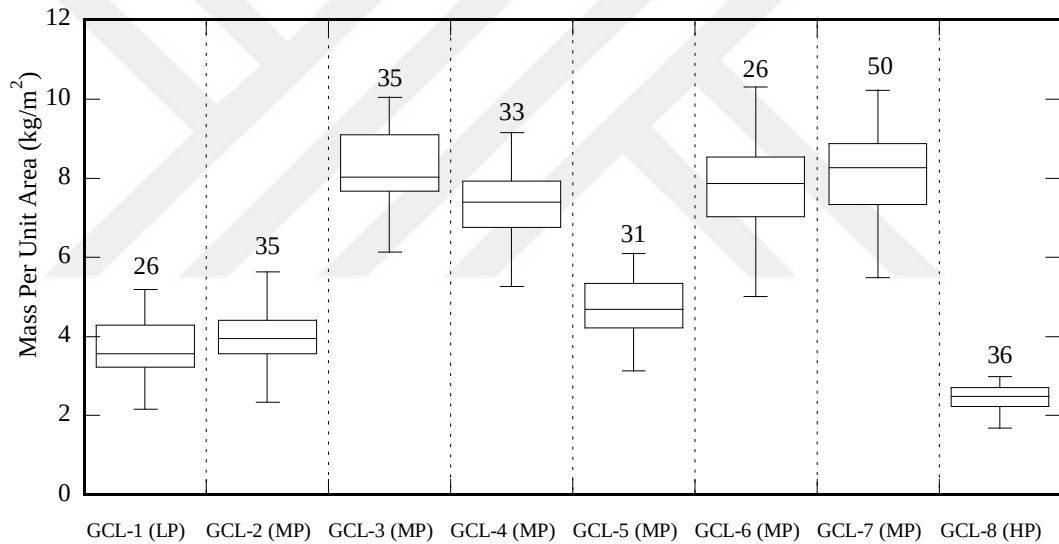


Figure 6.6 Bentonite mass per unit area distribution in the GCL rolls

On the other hand, the relationship between MPUA and the suction parameters of GCLs can be evaluated whether a general tendency exists. Since GCLs take up water from the underlying soil during hydration, suction parameters such as water entry pressure and water entry value were taken into consideration for the assessment. The relationship between these two parameters and the bentonite MPUA is shown in Figure 6.7. The data reported in Acikel et al. (2018), Beddoe et al (2011), Bouazza et al. (2017), Hanson, Risken & Yeşiller (2013), Risken (2014) and Rajesh & Khan (2018) are also plotted on the same figure as well.

Figure 6.7a shows that the water entry pressures were generally located between 1000 kPa and 10000 kPa depending on the types of GCLs. In addition to GCL-1, one more data was out of this range (GCL-3). Among others, the lowest water entry pressures were obtained for GCL-1 and GCL-3 (Figure 6.3). If WRC of GCL-3 given in Figure 6.3c is checked with care, then the scattered distribution of data points can be seen which is possibly due to the use of GCL-3 in different MPUAs (Figure 6.6). The WRC of the GCL-3 was drawn from the center of these separate data points and may be shifted above or below. Undoubtedly, the exact position of the WRC of GCL-3 will change suction parameters.

In addition, Figure 6.7b also shows relationship between the water entry values of GCLs and MPUA. It can be seen from Figure 6.7 that the bentonite MPUA had no effect on the water entry values of GCLs. Regardless of the bentonite MPUA, the water entry values of GCLs were within the range of 10-45%. Although all the data scattered, the data belongs to GCL-1 and GCL-3 are the uppermost of the whole set. This shows no clear relationship between the MPUA and suction parameters; however, it highlights the MPUA induced problems on the WRCs of GCL-1 and GCL-3 when determined with filter paper method.

Based on the experienced so far, it is believed that MPUA should have a significant influence on the suction measurements. However, this study shows that the accuracy of the filter paper method while determining the suction behavior of GCLs is questionable unless GCLs in the same MPUA are used throughout the test program. Therefore, the data set for GCL-1 and GCL-3 as well as other GCLs should be enlarged with additional tests. It will be better if such measurements are carried out with the GCLs in the same MPUAs (in the case of filter paper method) or with one of direct measurement technique like high capacity tensiometers (HCT).

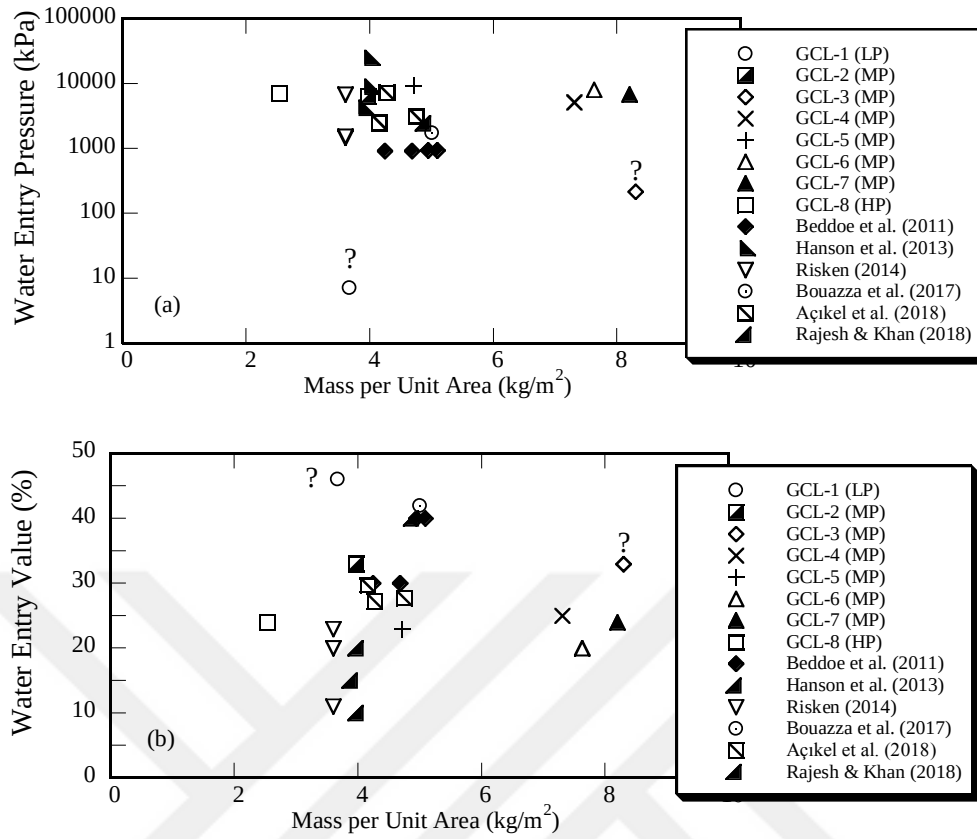


Figure 6.7 The relationship between the mass per unit area and a) water entry pressure and b) water entry value

6.8 Conclusions

The suction characteristics of subsoils and GCLs were investigated with filter paper method. The conclusions for the suction tests are summarized below:

- The gravimetric water content and suction relationship was significantly different for compacted sand and zeolite. The gravimetric water contents were between 2-16% for sand, 10-50% for zeolite-1 and 10-47% for zeolite-2 depending on the suction values.
- Among subsoils, compacted zeolite-2 had the greatest whereas compacted sand had the lowest suction capacity. The differences between the suction potentials of subsoils were attributed to their grain size distributions, fine contents and percent of clay-sized particles.

- Except GCL-8 (HP), the gravimetric water contents of GCLs slightly change depending on the applied technique (ID-CFPT or IW-CFPT) that is used during the matric suction measurements. The reason of this difference between the ID-CFPT and IW-CFPT may be attributed to the occurrence of capillary break.
- Matric suction behaviors of GCLs were product dependent. That is depending on the manufacturing properties and physicochemical properties of GCLs each GCL had different WRC within each other.
- The total suction values of GCLs became almost constant when the gravimetric water contents exceed 60%. Also, the total suction values overlapped with the matric suction values at high suction levels (>10000 kPa).
- The hydration induced decrease in the subsoil water content caused to an increase in the matric suction values. In contrast, increase in the water content of GCLs during hydration decreases the suction potential of GCLs.
- The suction values of GCL-1 (LP) and GCL-3 (MP) were lower than the suction values of subsoils after hydration. This tendency does not make any sense, because the water transfer between the subsoil and the GCL should terminate when the suction values of the materials come into equilibrium. The reason of this behavior can be attributed to the nature of filter paper method which uses more samples while determining WRC of a GCL. This study showed that these samples may have wide range of MPUAs which inevitably affect the determination of exact WRC.

CHAPTER SEVEN

HYDRATION OF GEOSYNTHETIC CLAY LINERS IN TERMS OF SUBSOIL WATER CONTENT AND BENTONITE MASS PER UNIT AREA

7.1 Background

Geosynthetic clay liners (GCLs) have been used as a liner or cover in many containment applications and faced with hydration from the adjacent soil. Hydration of GCLs from subsoils starts after installation and should be completed prior to facing with any fluids. The environmental conditions (i.e. confining stress, temperature, wetting and drying etc.), subsoil properties (i.e. type, initial water content, mineralogical composition etc.) and bentonite properties are the main factors which govern the in-service properties of GCLs.

The influencing factors on the hydraulic conductivity of GCLs have been investigated by many researchers so far (Anderson, Rayhani & Rowe, 2012; Barclay & Rayhani, 2013; Benson & Edil, 2004; Brashaw, Benson & Scalia, 2012; Bouazza et al., 2017; Chevrier et al., 2012; Katsumi et al., 2008a; Rayhani et al., 2011; Rowe & Abdelatty, 2012; Rowe & Hosney, 2013; Sarabian & Rayhani, 2013; Shan & Lai, 2002). However, little attention has been paid to investigate the influence of MPUA of bentonite on the hydration and hydraulic conductivity. As far as the author knows, only Rayhani et al. (2011) and Yu, El-Zein & Rowe (2018) compared the hydration water contents of GCLs based on their MPUA. Rayhani et al. (2011) reported a small difference between the water uptake of two GCLs which had 3.49 kg/m² and 4.88 kg/m² MPUA. Although the hydration rate over silty sand was faster for the GCL in higher MPUA, the final water content was 11% lower than that of the GCL in lower MPUA (i.e. 88% versus 99%). Similarly, Yu, El-Zein & Rowe (2018) hydrated two GCLs (GCL_A and GCL_B) which had 4.35 kg/m² and 4.77 kg/m² MPUA over a well graded compacted sand. Unlike Rayhani et al. (2011), the authors reported greater final water contents for GCLs in higher MPUA. It should be noted that the hydraulic conductivity behaviors of GCLs were not investigated in these studies.

There is one another study in the literature which reported the bentonite requirements for the GCLs. Maubeuge (2002) investigated the required MPUA of bentonite which allows the hydraulic conductivity less than 5×10^{-11} m/s. This study showed that increasing the bentonite MPUA from 2.70 kg/m² to 5.10 kg/m² result in 2.3 times decrease in the hydraulic conductivity. Although Maubeuge (2002) reported that the bentonite MPUA should be greater than 3.50 kg/m² at 10% water content, there is no comprehensive study on the influence of bentonite mass per unit area on the hydration and hydraulic conductivity behaviors of GCLs. Therefore, this study investigates and discusses the hydration and hydraulic conductivity of various GCLs in terms of subsoil water content and bentonite MPUA.

7.2 Hydration Behaviors of GCLs over Compacted Sand and Zeolite

The water uptake behaviors of all GCLs from two subsoils (i.e. sand and zeolite-2) were discussed herein. One of an important thing that should be emphasized is that the compaction water content of sand was 14% and zeolite was 43% prior to hydration. Thus, although they were classified as silty sand, they had distinct water contents within each other. Total of eight GCLs (i.e. from GCL-1 to GCL-8) categorized as low performance (LP), medium performance (MP) and high performance (HP) depending on their liquid limits were used for the hydration tests. The hydration durations were 7 and 62 days for GCL-1 (LP); 7, 30 and 90 days for GCL-2 (MP); 30 days for GCL-3, GCL-4 and GCL-6 (MP); 30 and 90 days for GCL-7 (MP) and 7, 30 and 90 days for GCL-8 (HP) when hydrated over compacted sand. The hydration durations were as follows: 7, 30, 62 and 90 days for LP GCL; 30 and 90 days for MP GCLs (from GCL-3 to GCL-7) and 30 and 90 days for HP when GCLs were hydrated over compacted zeolite-2. The water contents of GCLs are summarized in Table 7.1 and also shown as a function of hydration durations in Figure 7.1.

Table 7.1 and Figure 7.1 show that the water contents of GCLs considerably increased from their initial water contents within 30 days of hydration over both compacted subsoils. Further hydration generally caused slight increase in the water contents of GCLs. This increasing trends in the water contents of GCLs with the

hydration duration are consistent with the findings reported in the literature (Anderson, Rayhani & Rowe, 2012; Bradshaw, Benson & Scalia, 2012; Rayhani et al., 2011; Rowe & Abdelatty, 2012;). However, the water contents of GCL-1 (LP), GCL-5 and GCL-6 (MP) decreased up to 20% after 90 days of hydration over compacted zeolite-2. The decrease in the water contents of GCLs may be attributed to the cation exchange between the GCL and the zeolite-2 which has been explained in Chapter Five in detail.

Table 7.1 The water contents of GCLs after hydration over compacted sand and zeolite-2

Experiment No	GCL Type	MPUA (kg/m ²)	Subsoil Type	Hydration Duration (Days)	GCL Water Content (%)
1	GCL-1 (LP)	3.65	No subsoil	0	13
2	GCL-1 (LP)	3.41	SM	7	61
3	GCL-1 (LP)	3.36	SM	62	69
4	GCL-1 (LP)	4.34	Zeolite-2	7	64
5	GCL-1 (LP)	3.27	Zeolite-2	30	120
6	GCL-1 (LP)	3.22	Zeolite-2	62	147
7	GCL-1 (LP)	3.68	Zeolite-2	90	117
8	GCL-2 (MP)	4.15	No subsoil	0	18
9	GCL-2 (MP)	4.27	SM	7	45
10	GCL-2 (MP)	4.34	SM	30	65
11	GCL-2 (MP)	3.57	SM	90	84
12	GCL-3 (MP)	11.23	No subsoil	0	8
13	GCL-3 (MP)	9.29	SM	30	63
14	GCL-3 (MP)	9.89	Zeolite-2	30	66
15	GCL-3 (MP)	9.29	Zeolite-2	90	83
16	GCL-4 (MP)	9.56	No subsoil	0	9
17	GCL-4 (MP)	7.52	SM	30	80
18	GCL-4 (MP)	7.31	Zeolite-2	30	79
19	GCL-4 (MP)	6.75	Zeolite-2	90	88
20	GCL-5 (MP)	6.02	No subsoil	0	10
21	GCL-5 (MP)	6.10	Zeolite-2	30	79
22	GCL-5 (MP)	5.99	Zeolite-2	90	77
23	GCL-6 (MP)	8.94	No subsoil	0	12
24	GCL-6 (MP)	7.22	SM	30	77
25	GCL-6 (MP)	8.24	Zeolite-2	30	70
26	GCL-6 (MP)	7.80	Zeolite-2	90	65
27	GCL-7 (MP)	10.59	No subsoil	0	8
28	GCL-7 (MP)	8.50	SM	30	63
29	GCL-7 (MP)	6.55	SM	90	65
30	GCL-7 (MP)	9.17	Zeolite-2	30	62
31	GCL-7 (MP)	9.87	Zeolite-2	90	63
32	GCL-8 (HP)	2.85	No subsoil	0	11
33	GCL-8 (HP)	2.76	SM	7	63
34	GCL-8 (HP)	2.84	SM	30	119
35	GCL-8 (HP)	2.68	SM	90	120
36	GCL-8 (HP)	2.98	Zeolite-2	7	65
37	GCL-8 (HP)	2.82	Zeolite-2	30	117
38	GCL-8 (HP)	2.83	Zeolite-2	90	149

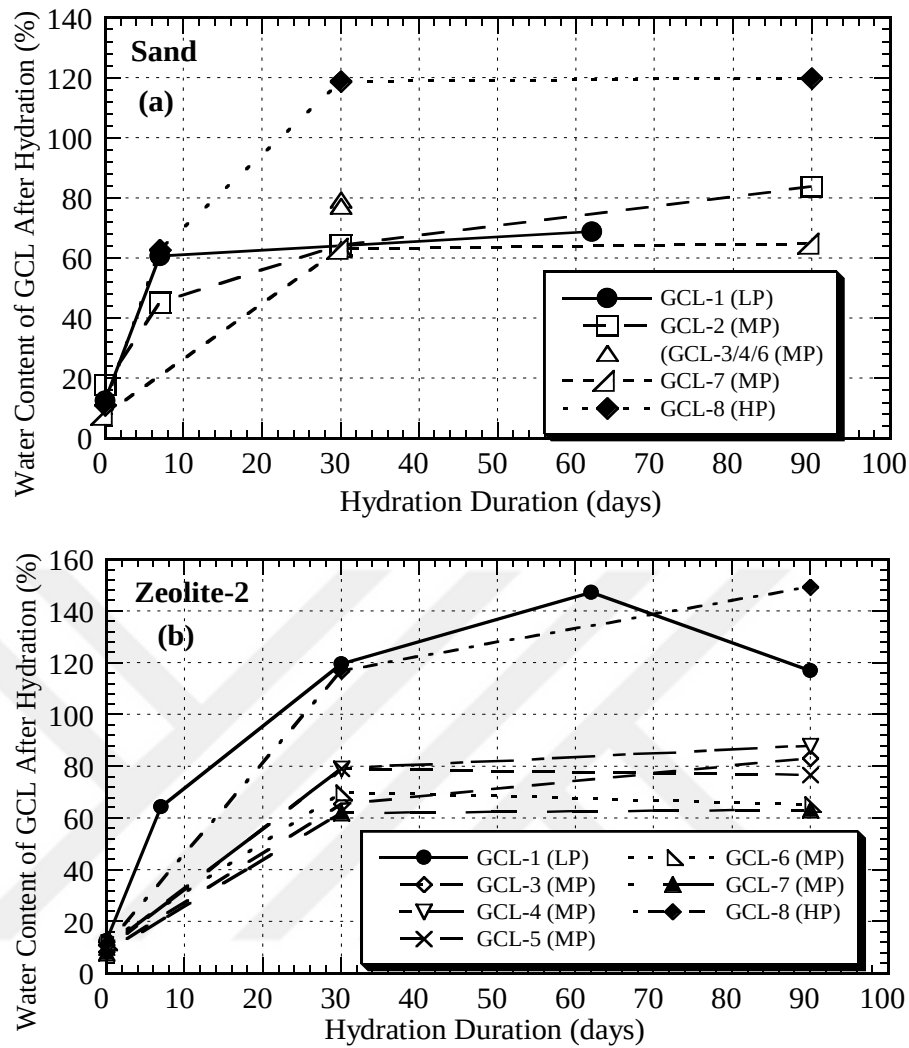


Figure 7.1 Change in water contents of GCLs with the hydration duration when hydrated over compacted: a) sand and b) zeolite-2

It is known that the subsoil type and subsoil water content had significant effect on the water contents of GCLs during hydration (Anderson, Rayhani & Rowe, 2012; Barclay & Rayhani, 2013; Bradshaw, Benson & Scalia, 2012; Bouazza et al., 2017; Chevrier et al., 2012; Rayhani et al., 2011; Sarabian & Rayhani, 2013). Although both subsoils (sand and zeolite-2) were classified as silty sand according to the Unified Soil Classification System (USCS), their compaction water contents and mineralogical properties were different within each other. Therefore, the water contents of GCLs showed some differences depending on the subsoil used for the hydration tests (Figure 7). Figure 7.1a shows that the water contents of LP and HP GCLs increased up to 69% and 120% when hydrated over compacted sand, respectively. However, hydrating the

GCLs over compacted zeolite-2 resulted in an increase in the water contents up to 147% and 149% for LP and HP GCLs, respectively (Figure 7.1b). In contrast, similar GCL water contents (i.e. between 63-88%) were obtained for MP GCLs hydrated over both sand and zeolite-2.

To show the influence of subsoil type on the water contents of GCLs in a appropriate way, the hydration water contents were normalized by dividing the waters content of GCLs hydrated over zeolite to the water contents of the same GCLs hydrated over sand at any hydration duration. For example, the normalized water content of GCL-1 (LP) at 7 days of hydration is 1.05 which was obtained by dividing 64% to 61% (Table 7.1). If the normalized values are greater than one (> 1.0), then the use of zeolite has an advantage on sand in terms of increasing the water content of the GCL. If the normalized values are lower than one (< 1.0), then it means there is no advantage of zeolite use with respect to sand. Normalized value of one ($= 1.0$) shows GCL hydration is independent of subsoil type.

Based on above definition, the influence of subsoil type on the normalized water contents of GCLs is drawn in Figure 7.2. One can expect that the water contents of GCLs hydrated over zeolite-2 should have been greater than those of GCLs hydrated over sand soil. This is due to greater compaction water content of zeolite-2 (i.e. 43% versus 14%). However, the normalized water contents of LP, MP and HP GCLs were around 1.0 up to 30 days of hydration (Figure 7.2). Then, increased to 2.1 and 1.3 with further hydration for LP and HP GCLs, respectively. In contrast the normalized water content of MP (GCL-7) was almost constant and around 1.0 after 90 days. It can be concluded that zeolite-2 had an increasing effect on the water contents of LP and HP GCLs which were hydrated longer than 30 days. This mechanism is possibly related with the difference between the suction gradient between the subsoil and the GCL. In other words, the suction capacities of GCLs control the amount of water which is adsorbed from the subsoil.

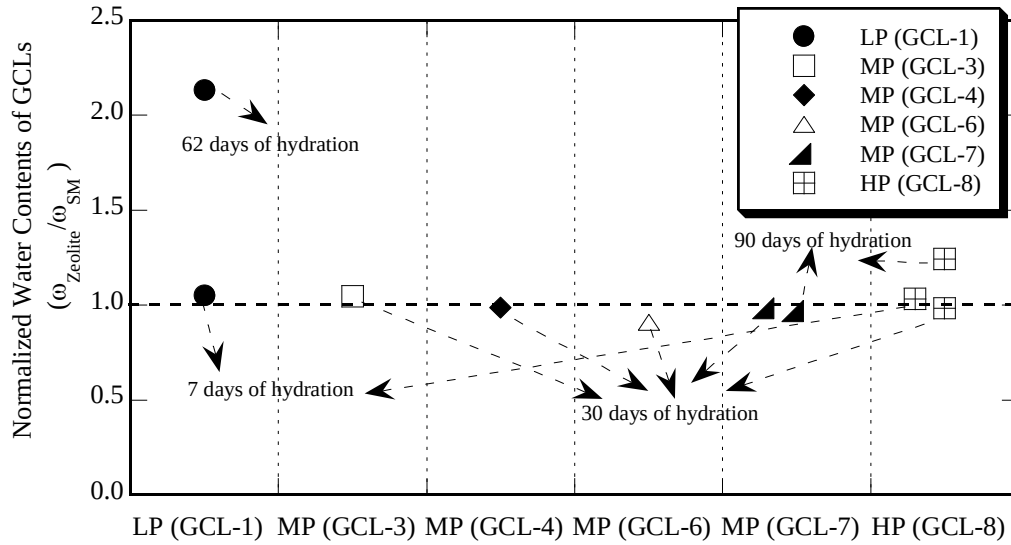


Figure 7.2 Influence of subsoil type on the hydraulic conductivity of GCL

7.3 Performance Based Comparison and Effect of Bentonite MPUA

The water contents of GCLs after hydration were compared based on their performance (i.e. liquid limits). The performance-based comparison of GCL water contents is shown in Figure 7.3. As previously mentioned in Chapter 4, there was a linear increasing trend between the final water contents and liquid limits of LP, MP and HP GCLs when hydrated over compacted silty sand (or sand). This tendency is still valid for the same subsoil when the data from different MP-GCLs were plotted on Figure 7.3. However, when zeolite-2 was used as the subsoil, this relationship became somewhat different. The final water contents of GCLs decreased up to 300% liquid limit and started to increase thereafter. In other words, the final water contents of MP-GCLs were lower than that of LP-GCL when hydrated over compacted zeolite-2.

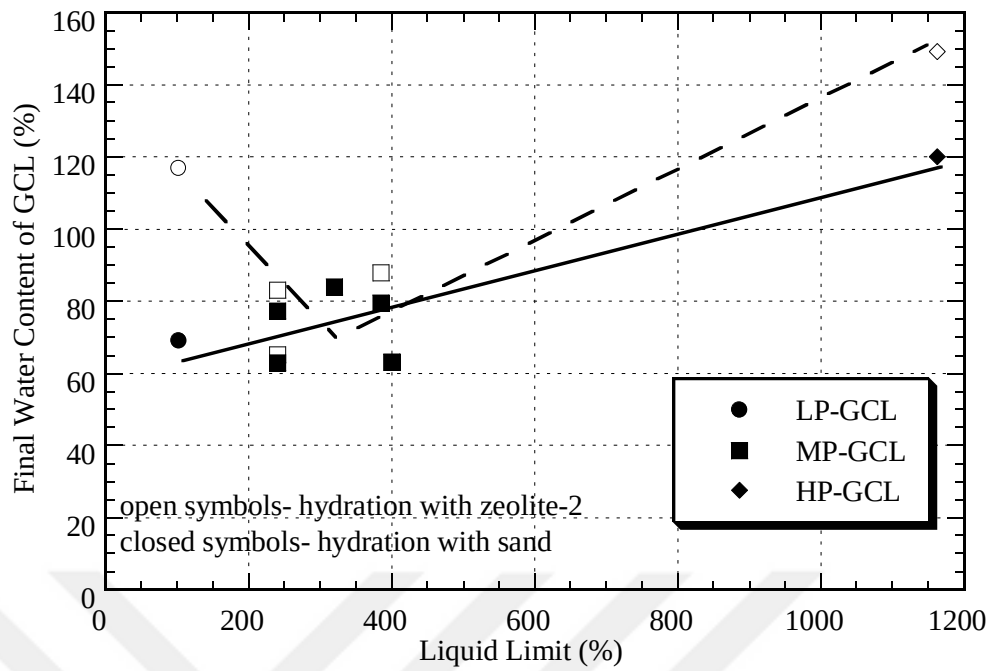


Figure 7.3 Relationship between the final water content of GCL and the liquid limit

The reason of lower final water contents for MP-GCLs with zeolite-2 may be related to the bentonite amounts in the GCLs. Table 7.1 presents that the bentonite MPUA of LP and HP GCLs were 3.68 kg/m^2 and 2.83 kg/m^2 , respectively. In contrast, the bentonite MPUA of most MP-GCLs were within the range of $6.75\text{--}9.87 \text{ kg/m}^2$. The tendency between the final water contents of GCLs and bentonite MPUA is shown in Figure 7.4 just in case of GCLs hydrated over silty sands (i.e. sand and zeolite-2). For this purpose, the final water contents of GCLs, which corresponds the longest hydration durations, were considered. Figure 7.4 shows that increase in MPUA up to 6.60 kg/m^2 resulted in a decrease in the final water contents of GCLs. However, bentonite MPUA greater than 6.60 kg/m^2 had no influence on the final water contents of GCLs hydrated over silty sand subsoils.

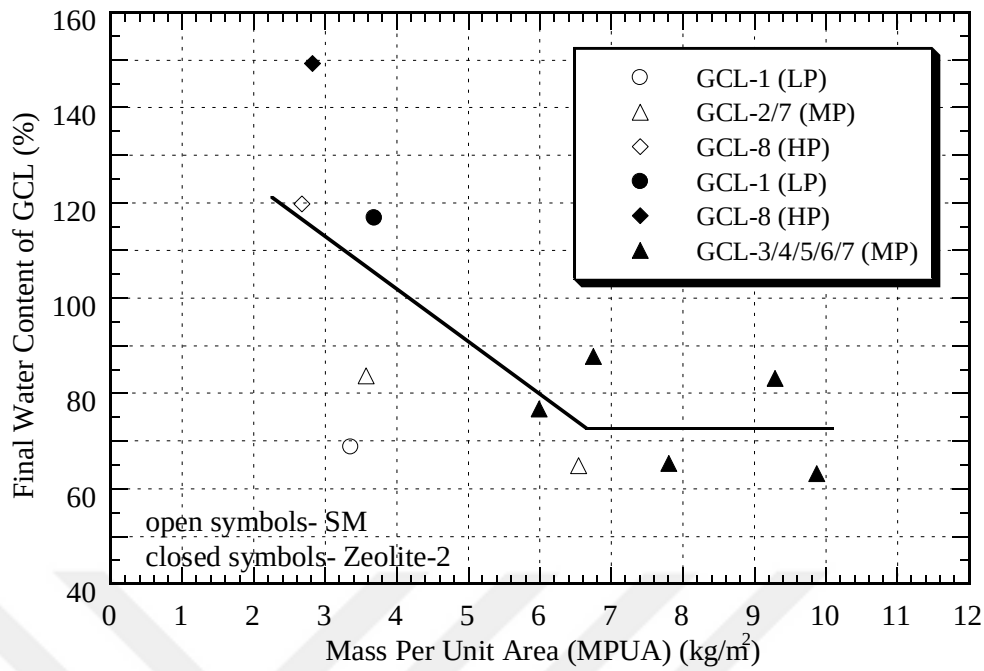


Figure 7.4 Relationship between the final water contents of GCLs and MPUA

It should be noted that the tendency given in Figure 7.4 was evaluated independent from the type of GCL. To investigate the validity of this tendency between the bentonite MPUA and final water content of GCLs, two GCLs [GCL-1 (LP) and GCL-7 (MP)] in low and high MPUAs had been selected and were hydrated over compacted sand for two different hydration durations. Since water contents of GCLs came to equilibrium after 30 days the hydration durations were selected as 62 days for GCL-1 (LP) and 30 days for GCL-7 (MP).

The changes in the final water contents of both GCL-1 (LP) and GCL-7 (MP) were shown in Figure 7.5 as a function of MPUA. Similar tendency shown in Figure 7.4 was also seen for GCL-1 (LP) and GCL-7 (MP). That is, the hydration water content of GCL-1 (LP) samples decreased when the MPUA of the samples increased from 3.19 kg/m² to 4.08 kg/m² whereas almost stable hydration water contents were obtained for GCL-7 (MP) whose MPUAs were ranged between 7.82 kg/m² and 10.02 kg/m².

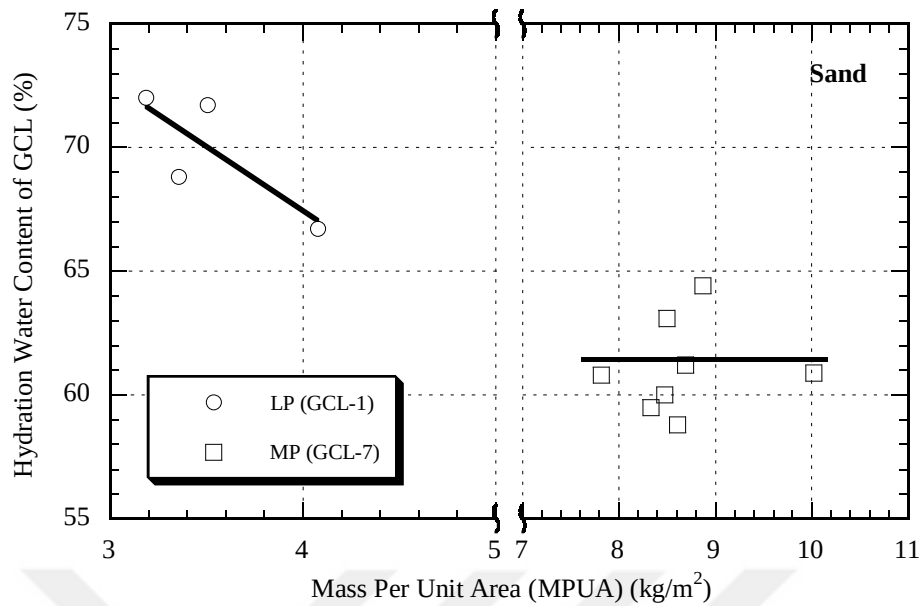


Figure 7.5 Relationship between the hydration water content of GCL and MPUA

The findings of this study were also evaluated with the data reported by several researchers in Figure 7.6 (Bradshaw & Benson, 2013; Bouazza et al., 2017; Katsumi et al., 2008a; Rayhani et al., 2011; Rowe & Abdelatty, 2012;). For the comparison, only the final water contents of GCLs which were hydrated over silty sand and sand subsoils compacted at wet sides of optimum water contents were considered from literature. Also, the contact face of GCLs were taken as both non-woven and woven geotextile during the interpretation of data.

As seen in Figure 7.6, the data reported in Bradshaw & Benson (2013), Bouazza et al. (2017), Katsumi et al. (2008a), Rayhani et al. (2011), Rowe & Abdelatty (2012) are consistent with the trend shown in this study. However, the data gathered from Katsumi et al. (2008a) had the greatest hydration water contents among others. The main reason of this highest hydration water contents was possibly because of the hydration conditions conducted in Katsumi et al. (2008a). Katsumi et al. (2008a) hydrated GCLs over the subsoil by supplying 10 mm of static water level from the bottom. This water supply possibly resulted to greater hydration water contents for the GCLs.

Moreover, except Bradshaw & Benson (2013), data gathered from the literature are closer to the data of this study given for the zeolite (Figure 7.6). This is possibly due to the difference in the particle and pore size distribution of the subsoils. In addition, applied confining pressure during the hydration were within the range of 2-5 kPa in the literature studies. Similar to this study, Bradshaw & Benson (2013) applied 10 kPa confining pressure for the hydration, resulting almost the same final water content of GCL obtained in this study. The greater confining pressure may restrict the swelling of bentonite and result in a lower hydration water content.

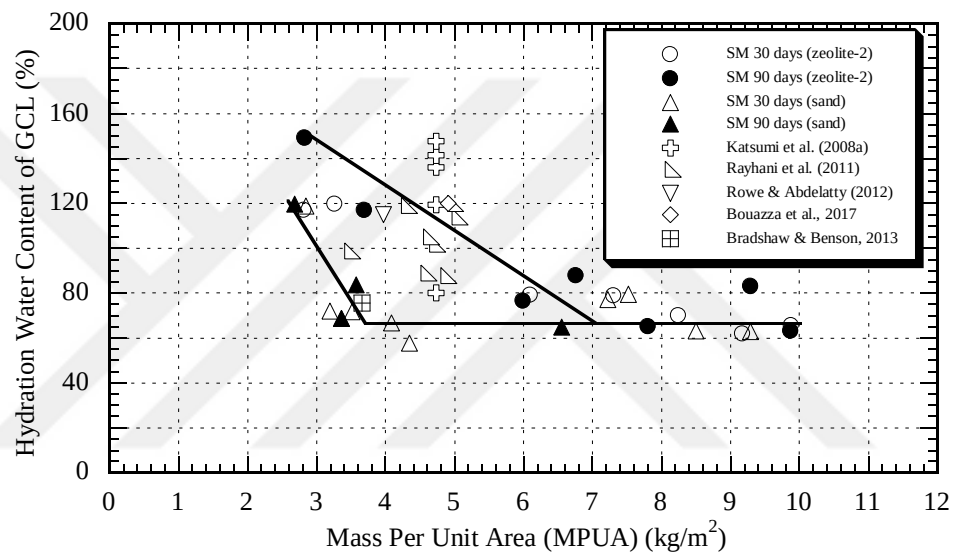


Figure 7.6 Comparison of the findings of this study with those of the literature depending on the hydration duration and the subsoil type

7.4 Hydration Induced Change in Subsoil Water Content

Hydration process resulted in some changes not only in the water contents of the GCLs but also in the subsoils. Hydration induced change in the sand has already been explained briefly for compacted sand in Chapter Three. It will be presented and discussed in terms of subsoil type in this chapter. Again, to show the influence of hydration on the water content profiles of sand and zeolite-2, subsoil water contents were observed across the soil body. The water content change of subsoils after hydration are shown in Figure 7.7 in terms of hydration durations.

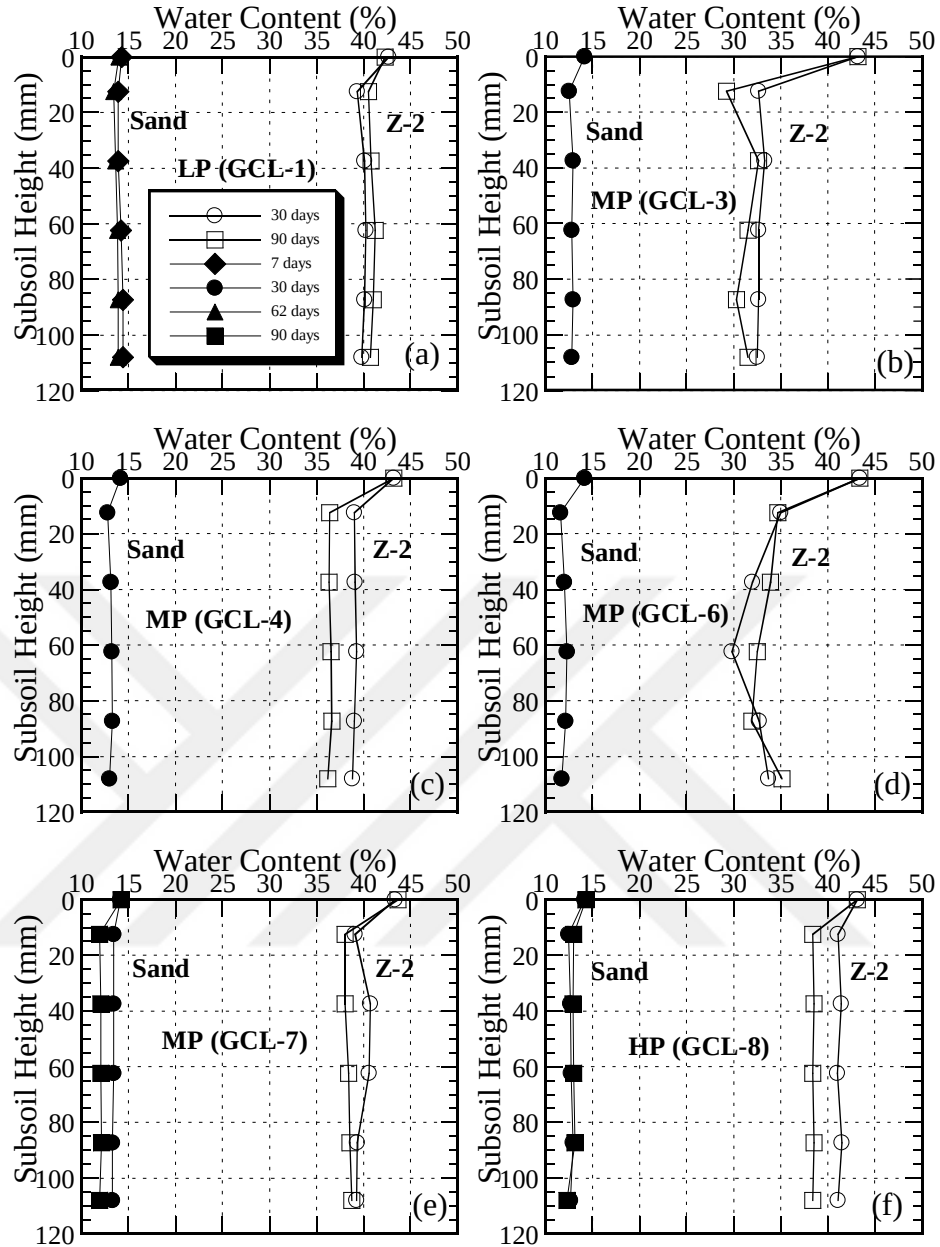


Figure 7.7 Water content profiles of subsoils after hydration with: a) LP (GCL-1), b) MP (GCL-3), c) MP (GCL-4), d) MP (GCL-6), e) MP (GCL-7) and f) HP (GCL-8)

Although the initial compaction water contents of sand and zeolite-2 were considerably different within each other (i.e. 14% and 43%, respectively) the water content profiles of the subsoils were similar regardless of the hydration duration. The traces of water content changes in both subsoils (i.e. sand and zeolite-2) were similar within each other (Figure 7.7a-f). That is, the water contents of the first sublayers, which were in contact with the GCLs, were significantly decreased and became drier than the subsequent layers. Since GCLs were drier when compared with the subsoils

their water contents increased during hydration due to capillary induced suction. Hence, the water content of the first sublayer decreased remarkably with respect to other layers, while the GCL water content increased (Figure 7.7). However, the changes in the water contents of the subsoils were dependent on the GCL type. Depending on the GCL type, the water contents of both subsoils decreased 3% (for sand) and 7% (for zeolite) at most, respectively, in the contact layer of subsoil (Figure 7.7). The variation in the adsorbed water amount is possibly related to the differences between the suction potentials of the subsoils and the GCLs.

As previously mentioned in Chapter 6, the suction ability of GCLs were affected from the bentonite MPUA. Therefore, the differences between the suction potentials of subsoils and GCLs could be different depending on the bentonite MPUA. These differences between the suction potentials may also result in some changes in the water content profiles of subsoils. To determine whether the bentonite MPUA had any influence on the water profiles of subsoils, the changes in the water content across the sand after hydration were plotted depending on the MPUAs of two GCLs (GCL-1 and GCL-7). The water content profiles of sand after hydration with GCL-1 (LP) and GCL-7 (MP) is shown in Figure 7.8 in terms of bentonite MPUAs of GCLs.

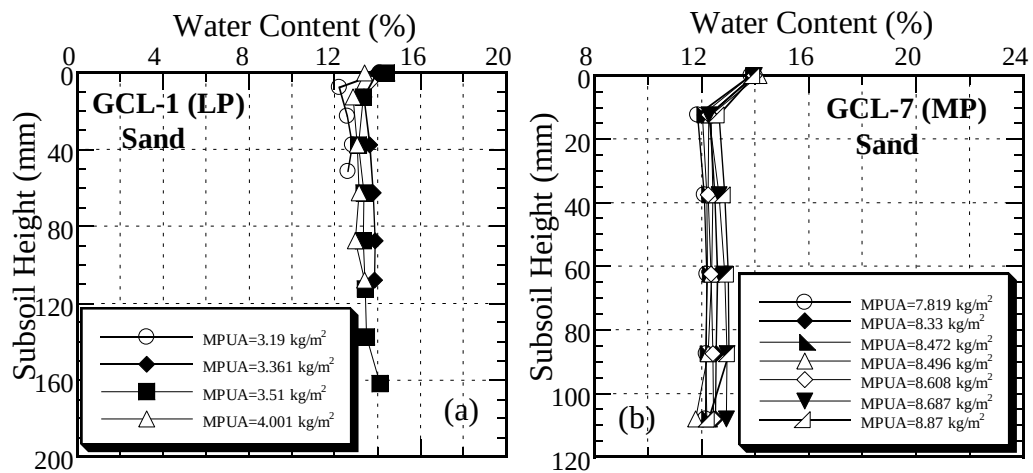


Figure 7.8 Influence of bentonite MPUA on the water content profiles after hydration with: a) GCL-1 (LP) and b) GCL-7 (MP)

As seen in Figure 7.8, the water content profiles of compacted sand after hydration with GCL-1 (LP) and GCL-7 (MP) are quite similar. However, the changes in the

water content levels in the first sublayers show some differences depending on the bentonite MPUA (Figure 7.8). Except two samples (i.e. GCL-1 (LP) with MPUA of 3.51 kg/m^3 and GCL-7 (MP) with MPUA of 8.33 kg/m^3), the reduction in the water contents of the first sublayers becomes remarkable with the increase in the bentonite MPUA (Figure 7.8a and Figure 7.8b). For example, when GCL-1 (LP) with MPUAs of 3.19 kg/m^3 and MPUA of 4.00 kg/m^3 were hydrated over compacted sand, the water contents of the first sublayer decreased by 2% and 0.5%, respectively (Figure 7. 8a). Similarly, the reduction in the water contents of the first sublayers after hydration with GCL-7 (MP) with MPUA of 7.82 kg/m^3 and 8.87 kg/m^3 were 2% and 1.3%, respectively. In contrast, GCL-1 (LP) with MPUA of 3.51 kg/m^3 and GCL-7 (MP) with MPUA of 8.33 kg/m^3 were out of this tendency. The reason for these slightly changes in the water contents are possibly because of the greater initial compaction water contents of the subsoils.

7.5 Hydraulic Conductivity

At the end of the hydration processes, GCLs were conducted to the hydraulic conductivity tests. Deionized water was used as the permeant not to allow any cation exchange between the GCL and the permeant. The long-term hydraulic behaviors of GCLs as a function of PVF which have not been reported so far are presented in Appendix B. Appendix B covers the graphs of hydraulic conductivity behaviors of non-prehydrated (no subsoil) and prehydrated cases of GCLs. As presented in Table 7.2, prehydrated means GCLs were hydrated over compacted zeolite-2 for 30 and 90 days. To investigate the effect of MPUA on the hydraulic conductivity, only final hydraulic conductivities are considered in this chapter. The average of last five readings were taken as the final hydraulic conductivities which are summarized in Table 7.2.

Table 7.2 Summary of the hydraulic conductivity test results

Experiment No	GCL Type	MPUA (kg/m ²)	Subsoil Type	Hydration Duration (days)	PVF	Total Test Time (days)	Hydraulic Conductivity (m/s)
1	LP (GCL-1)	3.65	No subsoil	0	8	145	1.4×10^{-11}
2	LP (GCL-1)	3.41	Sand	7	300	107	3.2×10^{-11}
3	LP (GCL-1)	3.36	Sand	62	261	10	3.6×10^{-7}
4	LP (GCL-1)	4.34	Zeolite-2	7	111	119	2.0×10^{-11}
5	LP (GCL-1)	3.27	Zeolite-2	30	54	136	2.6×10^{-11}
6	LP (GCL-1)	3.22	Zeolite-2	62	262	2	3.2×10^{-7}
7	LP (GCL-1)	3.68	Zeolite-2	90	62	76	3.5×10^{-11}
8	MP (GCL-3)	11.23	No subsoil	0	6	65	4.8×10^{-11}
9	MP (GCL-3)	9.29	Sand	30	37	323	1.6×10^{-11}
10	MP (GCL-3)	9.89	Zeolite-2	30	60	175	2.6×10^{-11}
11	MP (GCL-3)	9.29	Zeolite-2	90	8	202	1.9×10^{-11}
12	MP (GCL-4)	9.56	No subsoil	0	15	352	2.0×10^{-11}
13	MP (GCL-4)	7.52	Sand	30	35	337	3.8×10^{-11}
14	MP (GCL-4)	7.31	Zeolite-2	30	37	242	2.8×10^{-11}
15	MP (GCL-4)	6.75	Zeolite-2	90	11	194	2.0×10^{-11}
16	MP (GCL-6)	8.94	No subsoil	0	42	345	9.8×10^{-11}
17	MP (GCL-6)	7.22	Sand	30	42	323	3.1×10^{-11}
18	MP (GCL-6)	8.24	Zeolite-2	30	46	209	6.8×10^{-11}
19	MP (GCL-6)	7.80	Zeolite-2	90	24	195	4.5×10^{-11}
20	MP (GCL-7)	10.59	No subsoil	0	5	205	1.8×10^{-11}
21	MP (GCL-7)	8.49	Sand	30	13	337	1.4×10^{-11}
22	MP (GCL-7)*	9.29	Sand	90	21	90	8.6×10^{-11}
23	MP (GCL-7)	9.17	Zeolite-2	30	11	344	1.4×10^{-11}
24	MP (GCL-7)*	9.87	Zeolite-2	90	9	505	9.6×10^{-12}
25	HP (GCL-8)	2.86	No subsoil	0	4	190	8.2×10^{-12}
26	HP (GCL-8)	2.76	Sand	7	10	131	1.9×10^{-11}
27	HP (GCL-8)	2.84	Sand	30	14	199	2.3×10^{-11}
28	HP (GCL-8)	2.68	Sand	90	9	125	1.6×10^{-11}
29	HP (GCL-8)	2.98	Zeolite-2	7	10	101	1.8×10^{-11}
30	HP (GCL-8)	2.82	Zeolite-2	30	10	120	1.6×10^{-11}
31	HP (GCL-8)	2.83	Zeolite-2	90	9	112	2.1×10^{-11}

*Tests are continuing. The final hydraulic conductivities may change.

As seen in Table 7.2, the final hydraulic conductivities were around 1.0×10^{-11} m/s and 2.0×10^{-11} m/s when the GCLs were hydrated over compacted sand and zeolite-2, respectively (except for LP-GCLs hydrated for 62 days). It should be noted that the final hydraulic conductivities of GCLs were significantly lower than 1.0×10^{-9} m/s which is the allowable limit for barriers suggested by many environmental regulatory agencies. In contrast, the hydraulic conductivities of GCL-1 (LP) hydrated for 62 days over sand and zeolite-2 subsoils were around 3.0×10^{-7} m/s. The reason of high hydraulic conductivities may be related with the lower bentonite MPUA for GCL-1

(LP). As seen in Table 7.2, GCL-1 (LP) samples had lower bentonite MPUA ($\sim 3.50 \text{ kg/m}^2$). This GCL had also no polymer treatment. Thus, the lower bentonite MPUA for this GCL resulted in bentonite erosion because of higher hydraulic gradients (i.e. 185) applied during the hydraulic conductivity tests.

The influence of bentonite MPUA on the hydraulic conductivity of LP, MP and HP GCLs were also investigated. The final hydraulic conductivities of GCLs hydrated over both compacted sand and zeolite-2 were drawn as a function of bentonite MPUA in Figure 7.9. As seen in Figure 7.9, the bentonite MPUA had no significant effect on the final hydraulic conductivity of GCLs. Except two samples of GCL-1 (LP), the hydraulic conductivities were between $1.0 \times 10^{-10} \text{ m/s}$ and $1.0 \times 10^{-11} \text{ m/s}$ for the GCLs which had $3.00\text{--}11.00 \text{ kg/m}^2$ bentonite MPUA.

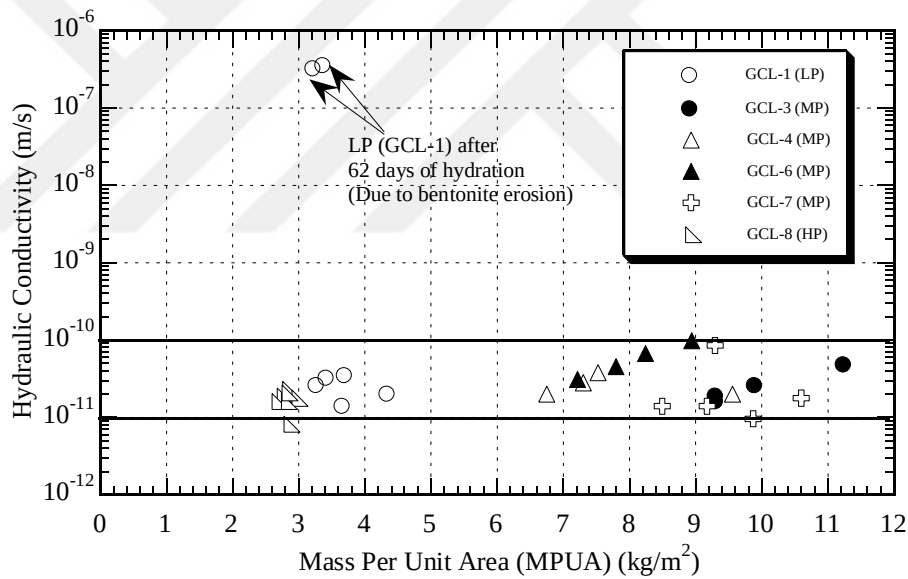


Figure 7.9 Influence of mass per unit area (MPUA) on the hydraulic conductivity of GCLs

In addition, the influence of subsoil type on the hydraulic conductivity was assessed by plotting the hydraulic conductivities of GCLs on a separate axis each of which represents the subsoil used during hydration (sand versus zeolite) (Figure 7.10). The 1:1 line was also drawn with a dashed line on Figure 7.10. It is seen that the hydraulic conductivities of LP, MP and HP GCLs hydrated over compacted sand and zeolite-2 are comparable. Except GCL-6 (MP) hydrated for 30 days and GCL-7 (MP) hydrated for 90 days, the hydraulic conductivities of GCLs are close to each other. However,

the hydraulic conductivity of GCL-6 (MP) hydrated over zeolite-2 for 30 days was 2.2 times greater than that of obtained for the GCL-6 (MP) hydrated over sand. The reason of this difference between the hydraulic conductivities is possibly because of bentonite MPUA. The bentonite MPUAs of GCL-6 (MP) hydrated over zeolite-2 and sand subsoils were 8.24 kg/m^2 and 7.22 kg/m^2 , respectively. The greater bentonite MPUA resulted in slightly lower final water content for the GCL-6 (MP). In contrast, although bentonite MPUA of GCL-7 (MP) hydrated over zeolite-2 for 90 days was slightly greater than that of GCL-7 (MP) hydrated over sand (i.e. 9.87 kg/m^2 versus 9.29 kg/m^2), almost an order of magnitude lower hydraulic conductivity was observed for this GCL. This difference may be due to unevenly distribution of bentonite and polymer along or inside the GCL during the manufacturing process.

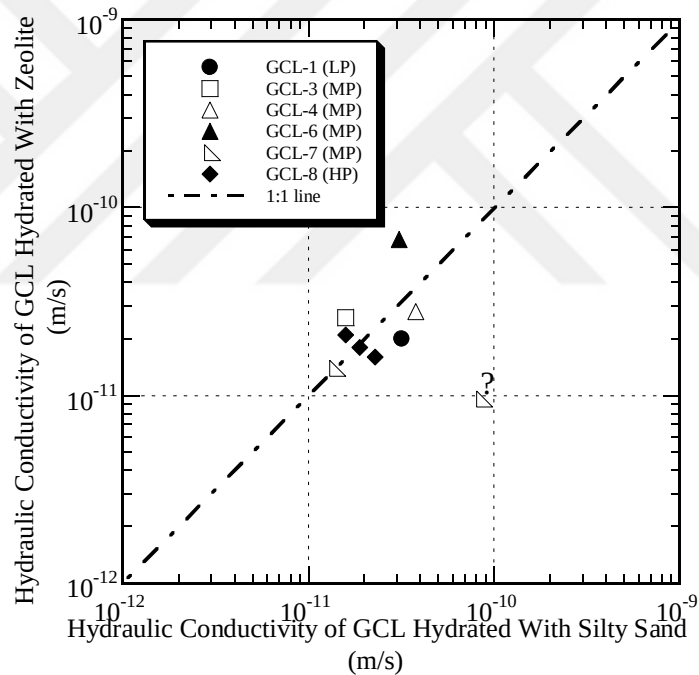


Figure 7.10 Hydraulic conductivity of GCLs hydrated with sand versus zeolite

7.6 Conclusions

The hydration and hydraulic conductivity behaviors of all GCLs (GCL-1 to GCL-8) were investigated based on the subsoil water contents and bentonite mass per unit area (MPUA). To do this, the GCLs were hydrated over compacted sand and zeolite-

2 and then conducted to the hydraulic conductivity tests even after hydration. The conclusions are summarized below:

- Hydration over compacted subsoils (i.e. sand or zeolite) resulted to significant increase in the water contents of GCLs after 30 days. When hydrated over compacted zeolite-2, the water contents of GCLs decreased after 30 days of hydration [GCL-1 (LP), GCL-5 and GCL-6 (MP)]. The reason of this decrease is possibly due to cation exchange during hydration.
- Although both sand and zeolite-2 subsoils were classified as silty sand (SM) in accordance with the Unified Soil Classification System (USCS), the water contents of GCLs after hydration were different within each other. Especially the water contents of GCL-1 (LP) and GCL-8 (HP) affected from the subsoil water content (or subsoil type).
- Up to 2 times greater water contents were observed for GCL-1 (LP) and GCL-8 (HP) when hydrated over compacted zeolite-2 [i.e. 69% versus 147% for GCL-1 (LP) and 120% versus 149% for GCL-8 (HP)]. In contrast, the hydration water contents of MP GCLs were not affected from the subsoil compaction water contents. Regardless of the subsoil water contents, the water contents of MP GCLs after hydration were between 63-88%. It is concluded that the water content levels those reached via hydration is basically controlled by the differences between the suction gradients between GCLs and subsoils.
- The increasing trend previously reported between the final water contents and liquid limits of GCLs were still valid for the hydration with compacted sand. In the case of compacted zeolite-2, however, the final water contents of GCLs decreased up to liquid limit of 300% and increased thereafter. It means the lower final water contents were obtained for MP GCLs when hydrated over compacted zeolite-2. The reason for the lower final water contents of MP GCLs can be attributed to the higher bentonite MPUA in MP GCLs.

- Independent of GCL type, increase in the MPUA up to 6.60 kg/m^2 resulted in a decrease in the final water contents of GCLs. The GCL final water contents were the same when the MPUA was greater than 6.60 kg/m^2 . This finding was also confirmed with additional tests carried out on GCL-1 (LP) and GCL-7 (MP) under wide range of bentonite MPUA. The proposed tendency was also evaluated with the literature data. It was revealed that literature data also compatible with proposed tendency.
- Depending on the GCL properties, the water contents of subsoils decreased up to 7% after hydration. Although changes in the water contents of GCLs were different within each other after hydration over compacted sand and zeolite-2, similar water content profiles were obtained for both subsoils.
- The changes in the water contents of the first sublayers decreased with the increase in the bentonite MPUA of the GCL-1 (LP) and GCL-7 (MP). However, two samples were out of this tendency (i.e. GCL-1 (LP) with MPUA of 3.51 kg/m^3 and GCL-7 (MP) with MPUA of 8.33 kg/m^3).
- Bentonite MPUA had no influence on the final hydraulic conductivities of GCLs. Except GCL-1 (LP) hydrated for 62 days over sand subsoil, the final hydraulic conductivities of all hydrated GCLs were significantly lower than the allowable limit for barriers suggested by may environmental regulatory agencies ($< 1.0 \times 10^{-9} \text{ m/s}$).
- The final hydraulic conductivities of GCLs were independent from the subsoil used for the hydration. The hydraulic conductivity of LP, MP and HP GCLs hydrated over compacted sand and zeolite-2 were comparable.

CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

8.1. Conclusions and Recommendations

The results of an experimental study investigating the water retention and long-term hydraulic conductivity behaviors of GCLs is presented. GCLs were denoted with low performance (LP), medium performance (MP) and high performance (HP) throughout the study by considering their liquid limits. To become an effective barrier GCLs must be sufficiently hydrated. Thus, GCL products were hydrated over compacted silty sand subsoils by simulating the cover applications in the experiments. Natural sand and two different zeolite subsoils (zeolite-1 and zeolite-2) whose optimum water contents (i.e. 42% and 46%) were significantly greater than natural soils (i.e. 12%) were used to show the influence of subsoil type and initial water content on the hydration of GCLs.

The main mechanism governing the hydration properties of GCLs are related with the water retention behaviors of the materials. Therefore, the suction behaviors of GCLs were measured by filter paper method. The hydration tests were performed in flexible wall permeameters with two different methods (i.e. control sample method, CSM and single large sample method, SLSM). The hydration performances were evaluated in terms of water contents, mole fractions of exchangeable cations, swell indices and hydraulic conductivity of GCLs. The results were also evaluated by considering the effect of bentonite mass per unit area in GCLs. The highlighted conclusions through the study and the recommendations for future studies are summarized below:

- It is possible to classify the GCLs depending on their liquid limits or performance. The hydration water contents, swell indices and the hydraulic performances of GCLs varied based on the performance of GCLs. Exchange complex of the GCL and polymer contribution also affected the performances of GCLs. However, it is suggested that the detailed investigations should be

performed especially on the LP-GCL to increase the knowledge about their suction and hydration performance.

- Zeolite plays a critical role on the hydration water contents of LP-GCLs. Hydration over compacted zeolite resulted in almost twice of the water content of the LP-GCL hydrated over sand (i.e. 147% versus 69% after 62 days of hydration). In addition to this, three stages can be suggested for the hydration of GCL over zeolite. Stage I represents the period that rapidly increase the water content and there was no evidence of cation exchange during this stage. Second stage (Stage II) shows the hydration duration between 7 days and 30 days. In this stage, the water content of GCL continued increasing, however, cation replacement also started between the subsoil and the GCL. The hydration period in which the cation replacement was more pronounced is corresponding to the Stage III.
- The suction behaviors of the GCLs and the subsoils had a significant role on the water transfer mechanism during the hydration process. Since GCLs with different bentonite MPUA was used during the filter paper method, it is expected that the suction measurements inevitably affected from the bentonite MPUA. Therefore, the suction measurements should be supported with the filter paper tests on the GCLs which had the same MPUAs or with any direct suction measurement technique.
- The bentonite MPUA had an influence on the hydration performances of GCLs. There is a linear decreasing trend between the final water contents of GCLs and the bentonite MPUA. However, this relationship was not pronounced for the GCLs which had MPUA greater than 6.60 kg/m^2 . Since the hydration performances of GCLs were affected from the bentonite MPUA, it is concluded that the hydration tests on the GCLs should be investigated by using the GCL samples with the same MPUA.

8.2. Paper Published from Dissertation

The outcomes of Chapter Three have already been published in IMO Technical Journal (İMO Teknik Dergi) as a technical paper (Özdamar & Ören, 2018a) and presented in GeoChicago 2016 which was held in Chicago/USA and EuroGeo6 Conference (Ljubljana/Slovenia). Papers submitted to GeoChicago 2016 and EuroGeo6 were published in the CD and USB flash disc, respectively (Özdamar & Ören, 2016a; Özdamar & Ören, 2016b).

The findings of Chapter Four were published in Geotextiles and Geomembranes as technical paper (Özdamar & Ören, 2018b).

The first outcomes of Chapter Five were presented in the Second International Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2) which was held in Leeds/UK. Subsequent findings of the chapter have been published in Geosynthetics International as a technical paper (Özdamar & Ören, 2019) and presented in the 11th International Conference on Geosynthetics which was held in Seoul/South Korea. Papers submitted to both conferences were published in USB flash discs (Özdamar & Ören, 2017; Özdamar & Ören, 2018c)

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APPENDICES

APPENDIX A: Water Re-distributions Between Compacted Subsoils and GCLs

A.1 Water Re-distribution Between Compacted Sand and GCLs

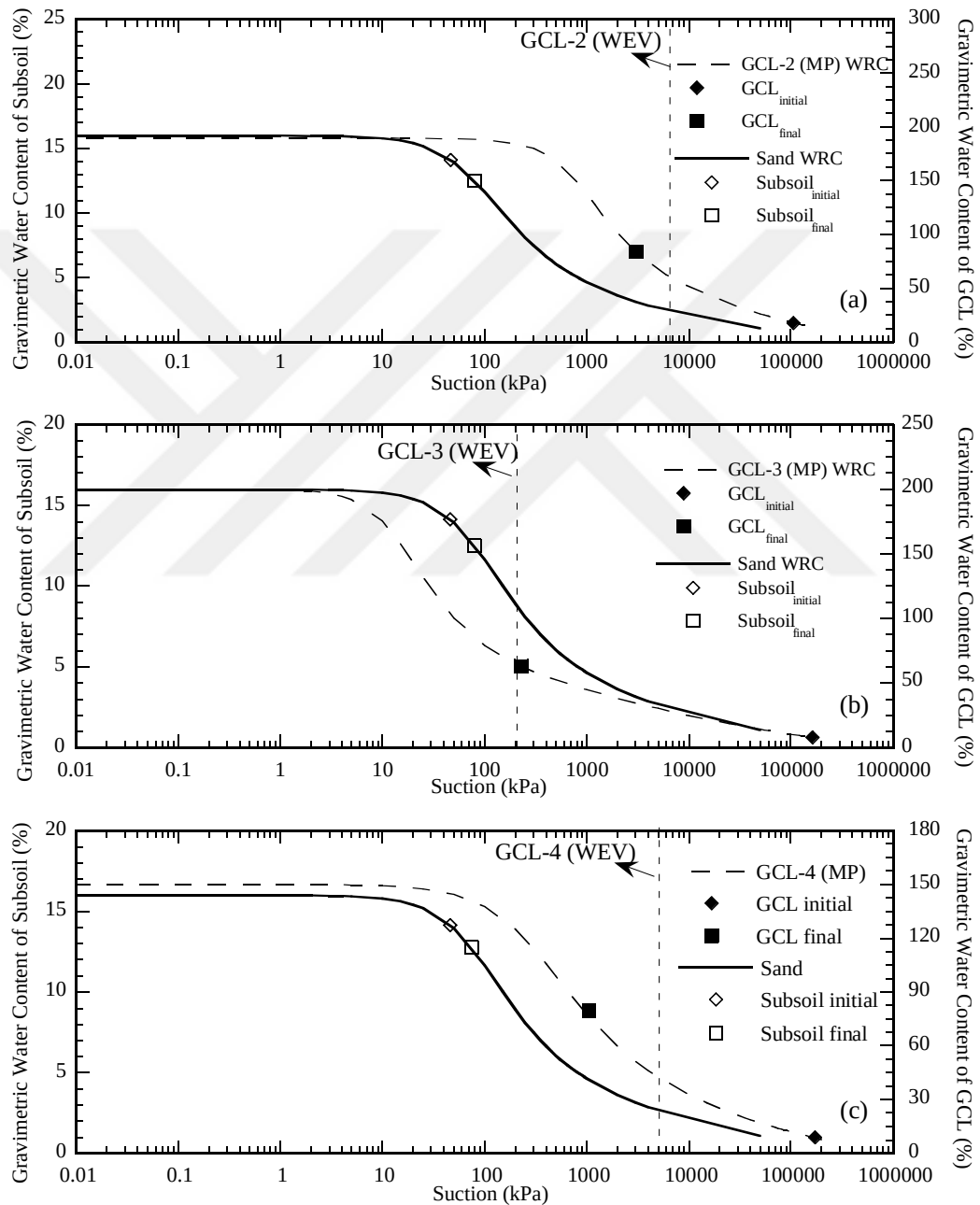


Figure A.1 Water re-distribution between compacted sand and a) GCL-2; b) GCL-3; c) GCL-4; d) GCL-6; e) GCL-7; f) GCL-8

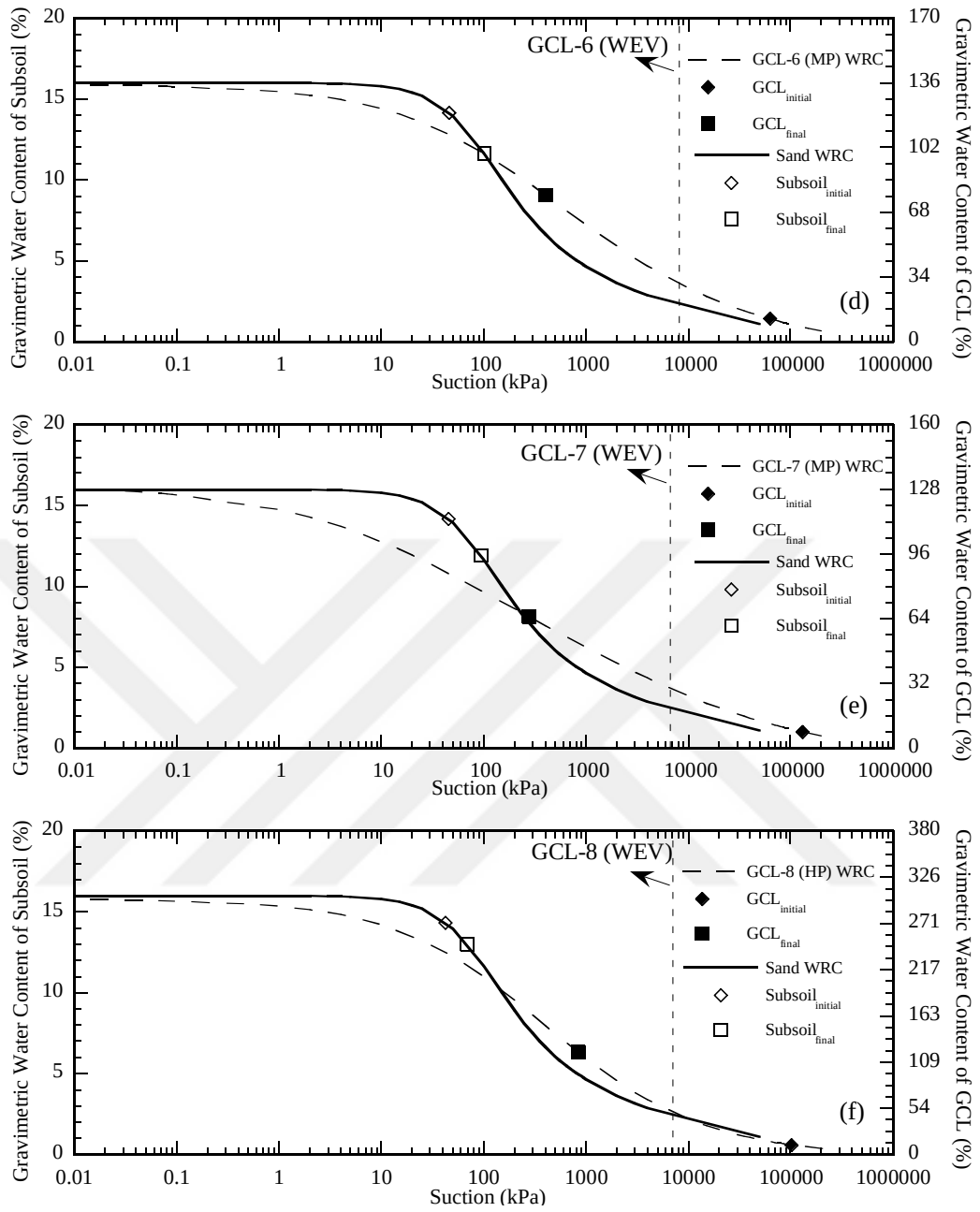


Figure A.1 continues

A.2 Water Re-distribution Between Compacted Zeolite-2 and GCLs

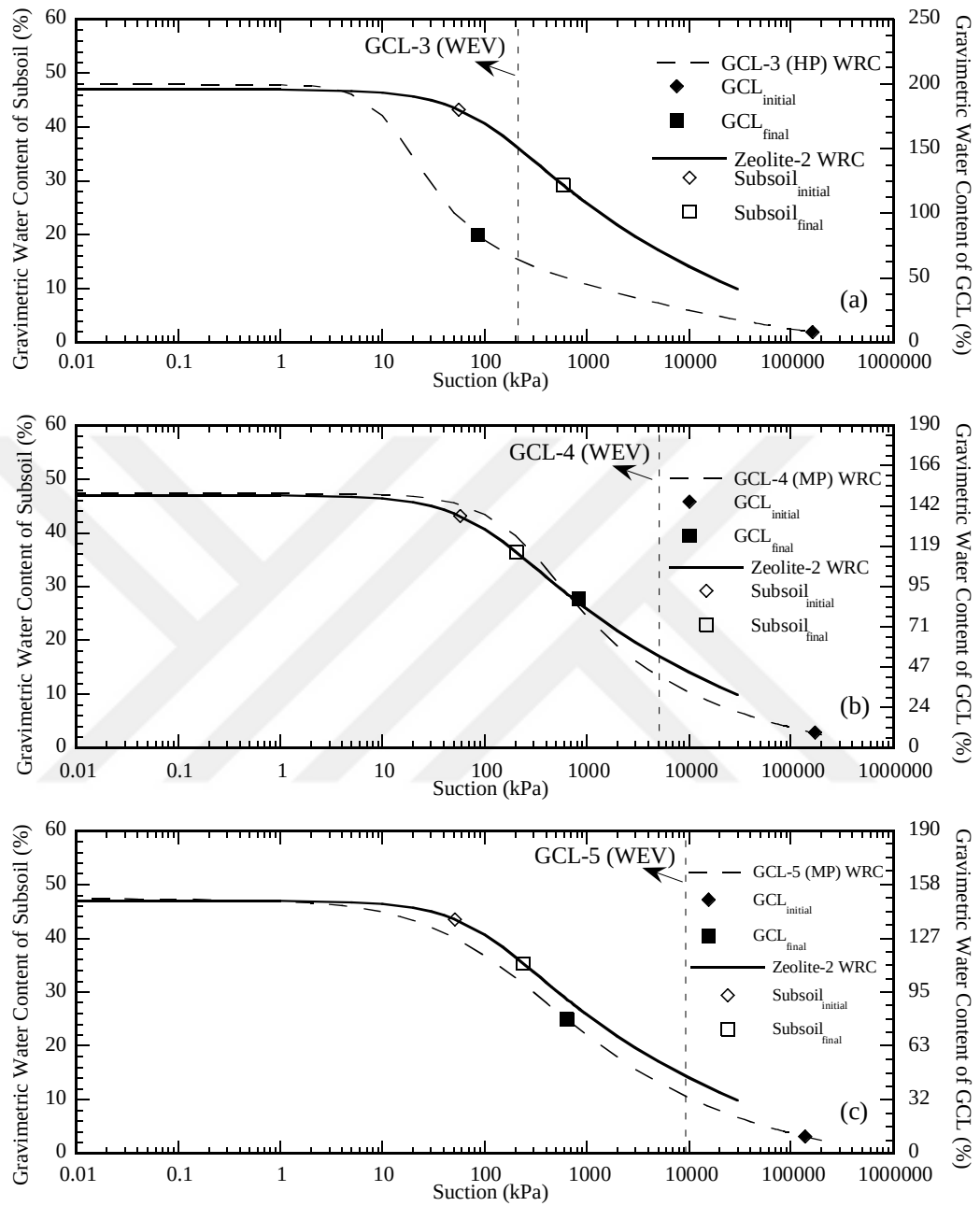


Figure A.2 Water re-distribution between compacted zeolite-2 and a) GCL-3; b) GCL-4; c) GCL-5; d) GCL-6; e) GCL-7; f) GCL-8

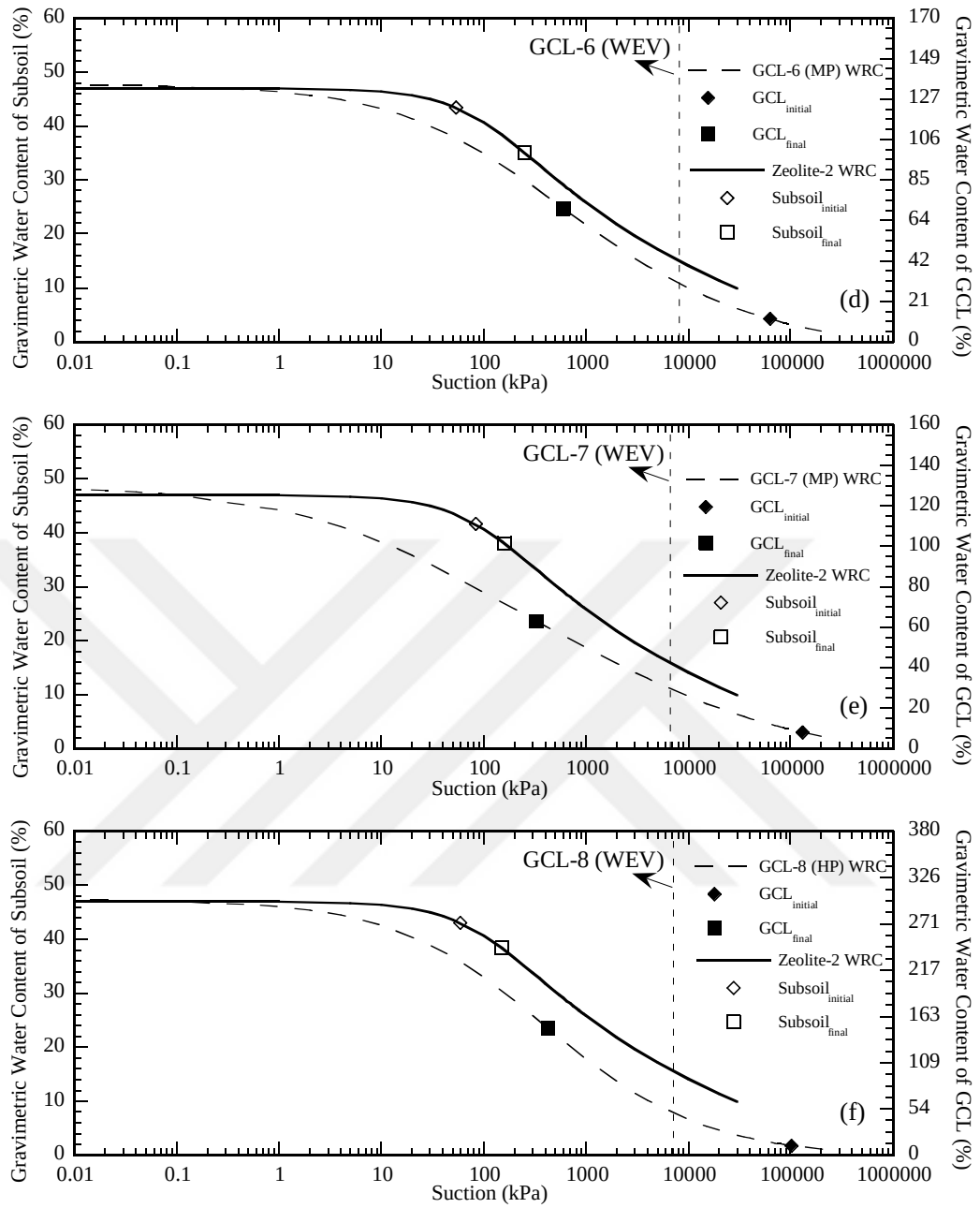


Figure A.2 continues

APPENDIX B: Hydraulic Conductivity Behaviors of Non-prehydrated and Prehydrated Over Compacted Zeolite-2 Cases of GCLs

B.1 Hydraulic Conductivity Test Results

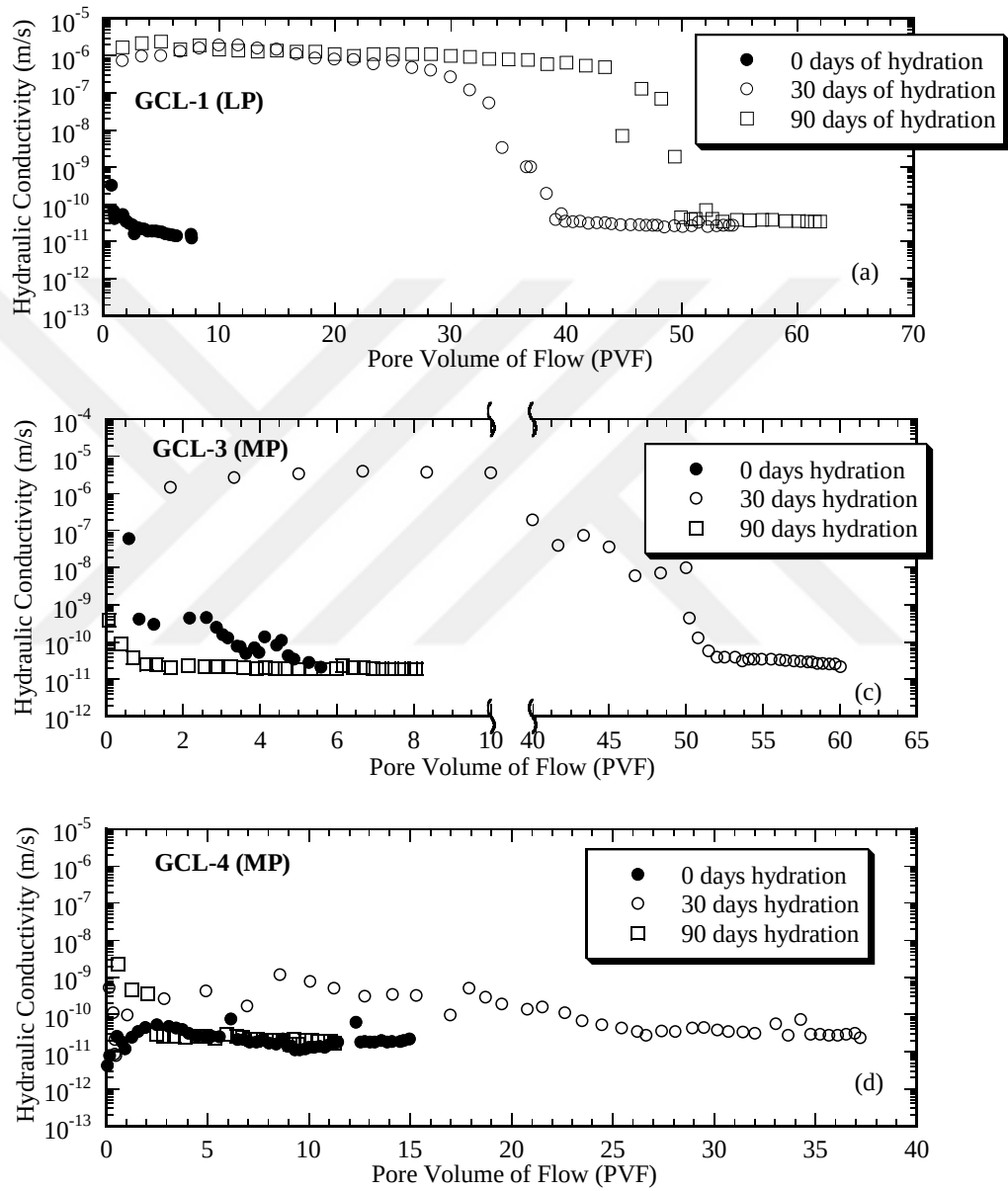


Figure B.1 Hydraulic conductivity test results of: a) GCL-1 (LP), b) GCL-3 (MP), c) GCL-4 (MP), d) GCL-5 (MP), e) GCL-6 (MP), f) GCL-7 (MP) and g) GCL-8 (HP) hydrated over zeolite-2

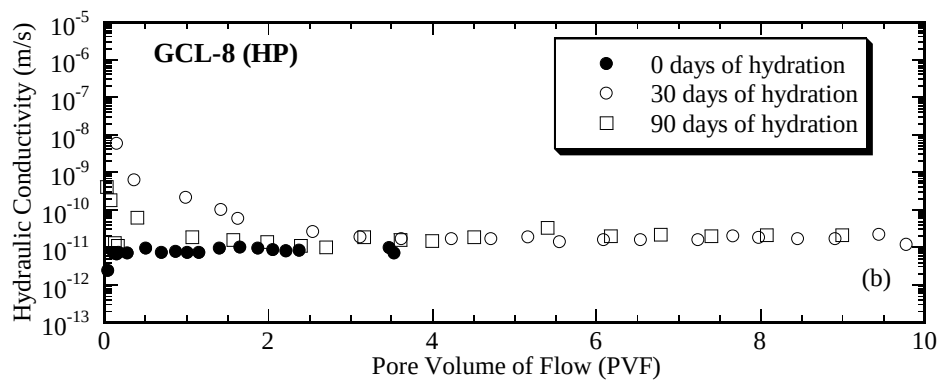
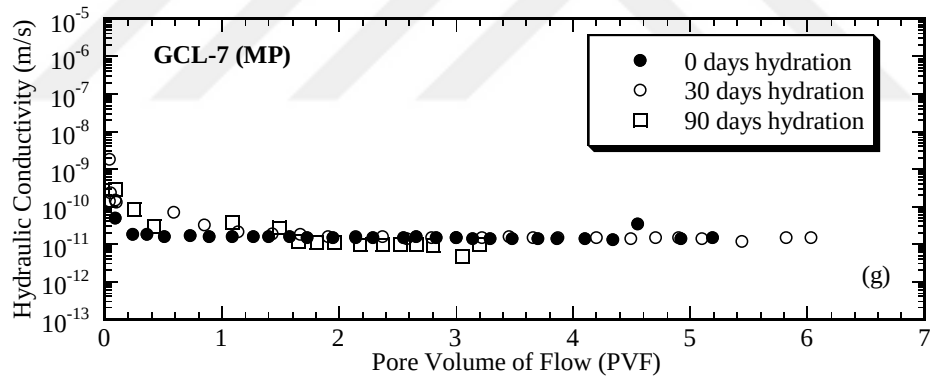
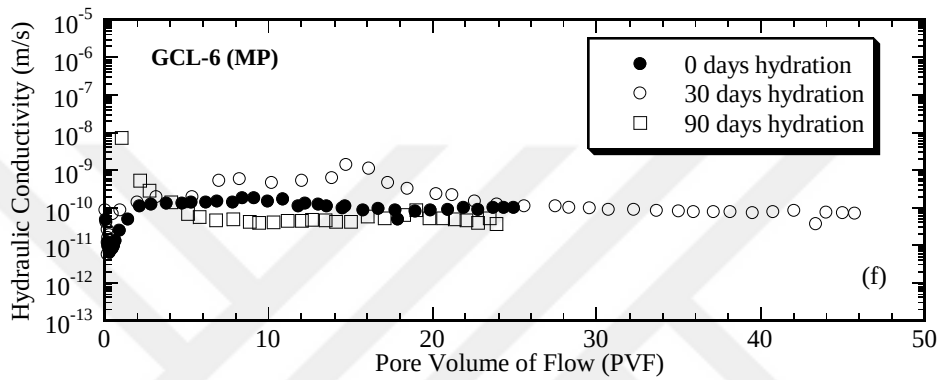
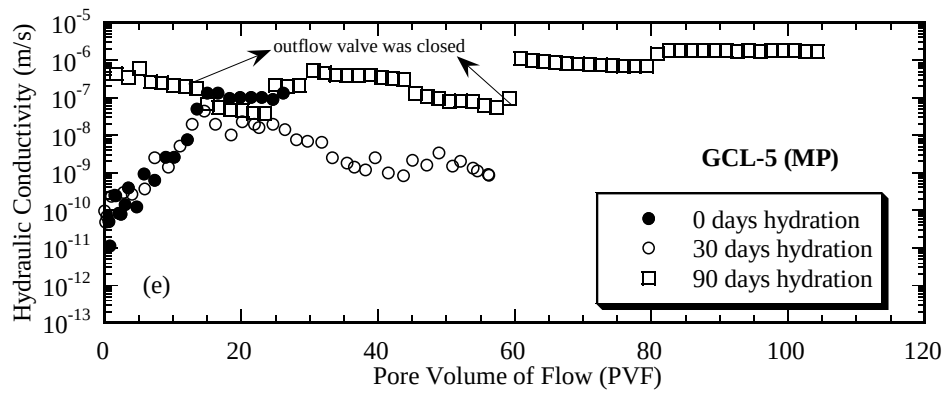


Figure B.1 continues

B.2 Comparison of Hydraulic Conductivity Test Results in Terms of GCL Type

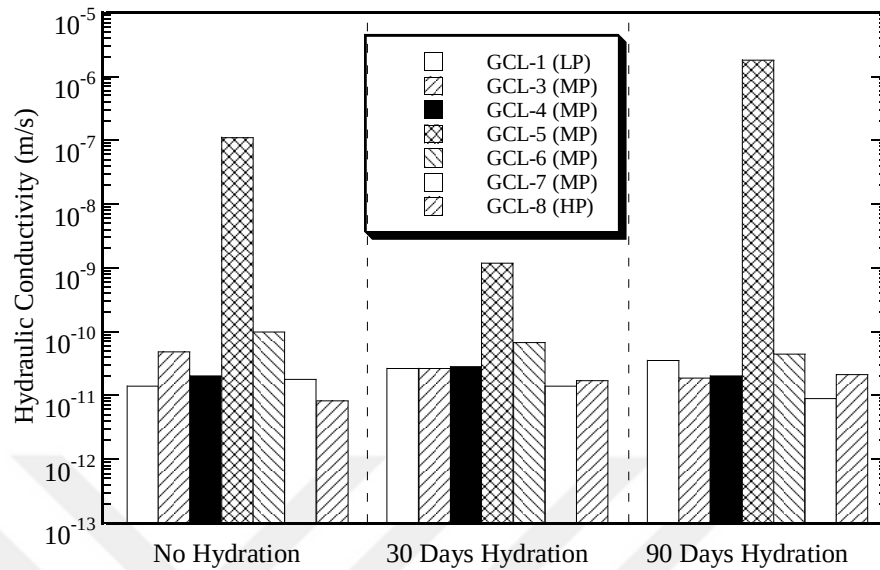


Figure B.2 Comparison of hydraulic conductivity test results in terms of types of GCL

B.3 Change in Hydraulic Conductivity Ratio Throughout the Hydraulic Conductivity Tests

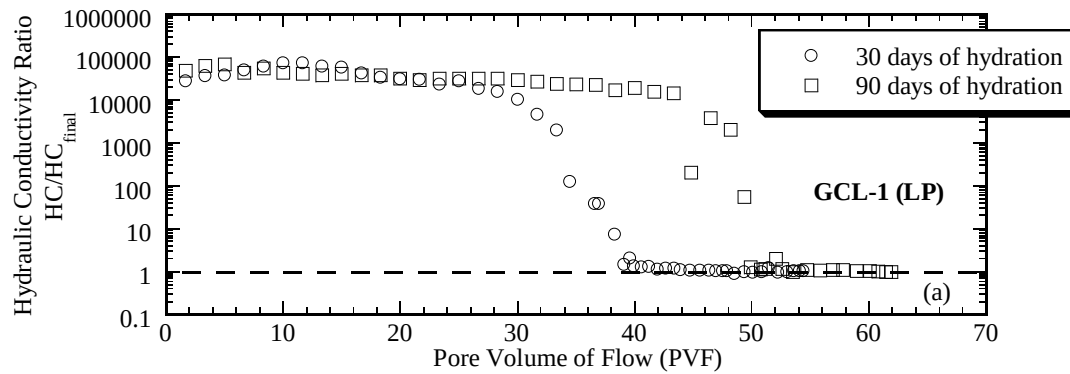


Figure B.3 Changes in the hydraulic conductivity ratio throughout the hydraulic conductivity tests of:
a) GCL-1 (LP), b) GCL-3 (MP), c) GCL-4 (MP), d) GCL-5 (MP), e) GCL-6 (MP), f) GCL-7 (MP)
and g) GCL-8 (HP)

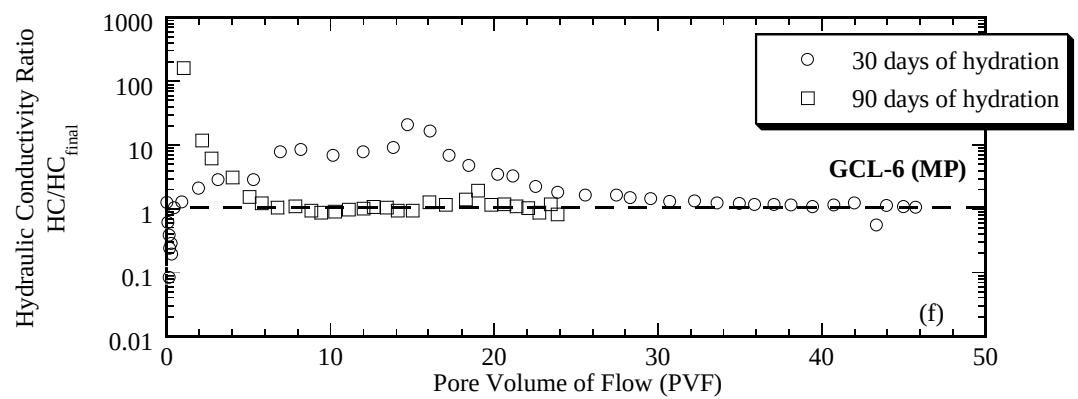
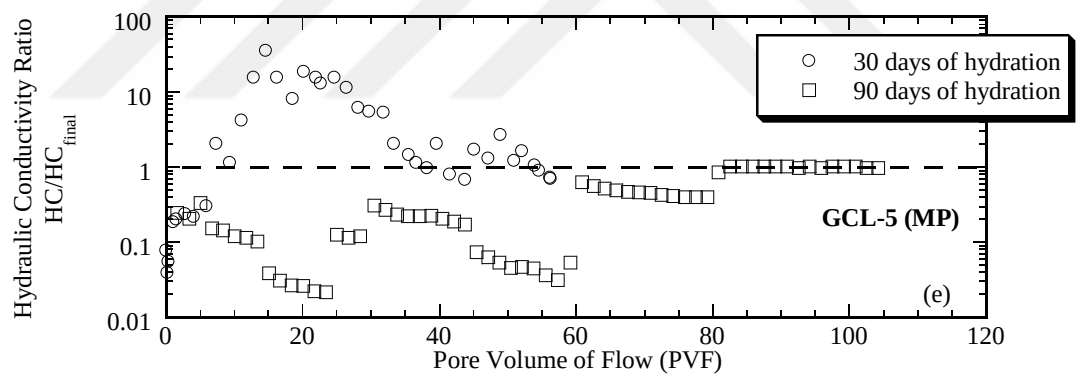
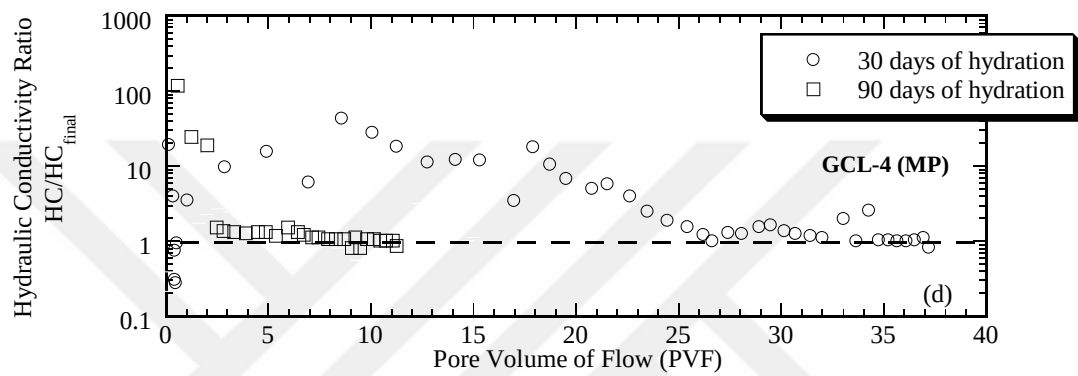
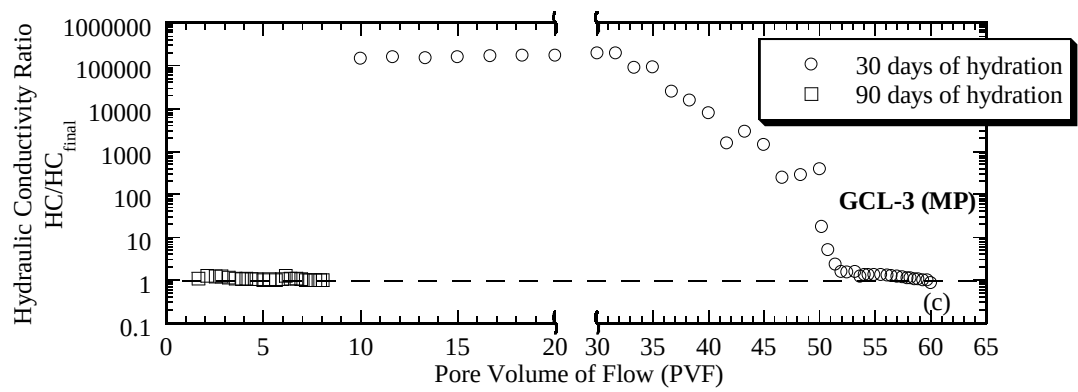


Figure B.3 continues

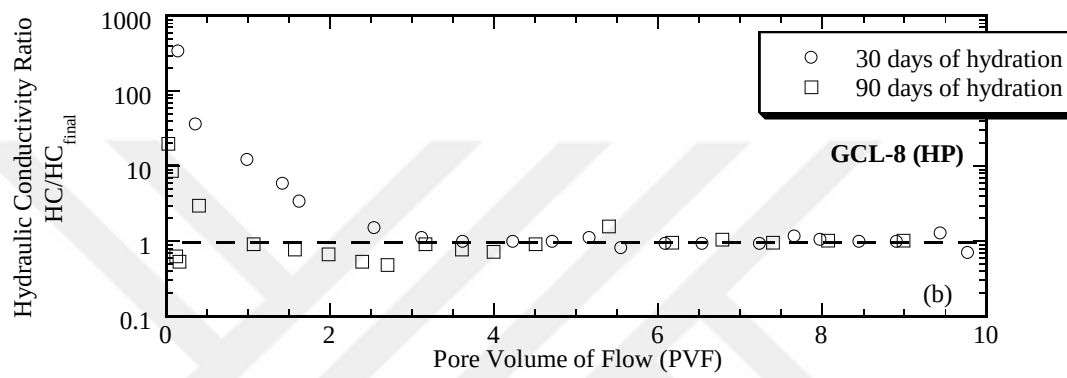
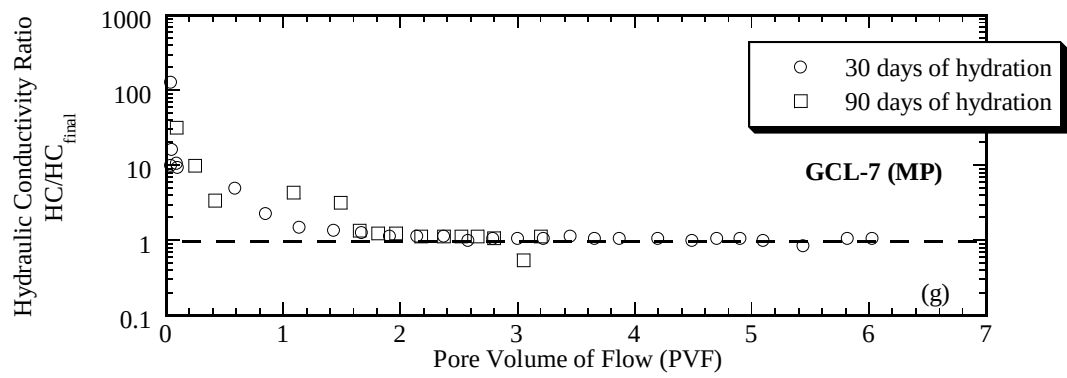


Figure B.3 continues