DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

EFFECT OF MASS PER UNIT AREA OF BENTONITE ON THE HYDRATION AND HYDRAULIC CONDUCTIVITY OF ARTIFICIALLY PREPARED GEOSYNTHETIC CLAY LINERS (A-GCLs)

by
Bilal Enes TAŞKESTİ

July, 2019
İZMİR

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"EFFECT OF MASS PER UNIT AREA OF BENTONITE ON THE HYDRATION AND HYDRAULIC CONDUCTIVITY OF ARTIFICIALLY PREPARED GEOSYNTHETIC CLAY LINERS (A-GCLs)"** completed by **BİLAL ENES TAŞKESTİ** under supervision of **ASSOC. PROF. DR. 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 Master of Science.

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ABSTRACT

This study investigates the effect of mass per unit area (MPUA) of bentonites on the hydration and hydraulic performances of artificially prepared geosynthetic clay liners (A-GCLs). For this purpose, polymer treated GCL (P-GCL) and sodium GCL (Na-GCL) prepared with different MPUAs were used. They were hydrated over compacted silty sand for 7 and 30 days. When the MPUAs of GCLs were increased, final water contents decreased. Longer hydration duration resulted in higher water contents of GCLs. Hydrated GCLs over subsoil were subjected to hydraulic conductivity tests. In the first set, hydraulic conductivity tests were conducted under high hydraulic gradients. In the second set, hydraulic gradients were gradually increased from lower to higher hydraulic gradients. In the tests under higher hydraulic gradients, P-GCL had lower hydraulic conductivity when compared to Na-GCL. The final hydraulic conductivities of GCLs with high MPUAs were around 1.0×10^{-11} m/s. However, GCLs with the MPUA of 3.0 kg/m^2 had greater permeability (i.e. 1.0×10^{-6} m/s) regardless of hydration duration. This can be attributed to the fact that the bentonite cannot fill the gap formed by the bundle of fibers even after swelling and that the bentonite particles might have not been distributed homogeneously in the GCL. As a result of Rhodamine tracer dye test, it was seen that bundle of fibers induced pore in the GCL caused high permeability. On the other hand, in the tests initiated from lower hydraulic gradient, lower hydraulic conductivity values were obtained for Na-GCLs prepared with 3.0, 4.0 and 5.0 kg/m^2 even if hydraulic gradient was further increased. Like Na-GCL, P-GCL with MPUA of 3.0 kg/m^2 had lower hydraulic conductivity under hydraulic gradient of 20.

Keywords: Geosynthetic clay liner, hydration, hydraulic conductivity, hydraulic gradient, mass per unit area of bentonite, water content

BİRİM ALANA GELEN BENTONİT KÜTLE MİKTARININ YAPAY HAZIRLANMIŞ GEOSENTETİK KİL ÖRTÜLERİN (Y-GKÖ) HİDRASYON VE HİDROLİK İLETKENLİKLERİNE ETKİSİ

ÖZ

Bu çalışmada, birim alan başına gelen bentonit kütlesinin (BABBK) yapay olarak hazırlanmış geosentetik kil örtülerin (GKÖ) hidrasyon ve hidrolik performansları üzerine etkisi araştırılmıştır. Bu amaç için, farklı BABBK değerlerine sahip polimer modifiyeli GKÖ (P-GKÖ) ve sodyumca zengin GKÖ'ler (Na-GKÖ) kullanılmıştır. GKÖ'ler sıkıştırılmış siltli kum üzerinde 7 ve 30 gün süreyle hidrate edilmişlerdir. GKÖ'lerin BABBK'leri arttırıldığında, nihai su içerikleri azalmıştır. Uzun hidrasyon süresi GKÖ'lerin daha yüksek su içeriğine sahip olmasına neden olmuştur. Alt zemin üzerinde hidrate edilen GKÖ'ler, hidrolik iletkenlik testlerine tabi tutulmuşlardır. İlk test grubunda, hidrolik iletkenlik deneyleri yüksek hidrolik eğim altında yapılmıştır. İkinci sette ise, deneyler düşük hidrolik eğimden başlatılarak aşamalı olarak arttırılmıştır. Yüksek hidrolik eğim altındaki deneylerde P-GKÖ, Na-GKÖ ile karşılaştırıldığında, daha düşük hidrolik iletkenliğe sahip bir performans sergilemiştir. Yüksek BABBK'li GKÖ'lerin nihai hidrolik iletkenlikleri yaklaşık $1{,}0\times10^{-11}$ m/s'dir. Fakat 3,0 kg/m^2 BABBK'ye sahip GKÖ'ler hidrasyon sürelerine bakılmaksızın yüksek permabiliteye sahiptir. Bunun nedeni bentonitin şiştikten sonra bile iplik demetçiklerinin oluşturduğu boşluğu dolduramamasına ve bentonit partiküllerinin GKÖ içinde homojen olarak dağılmamasına bağlanabilir. Rodamin boya testi sonucunda, GKÖ üzerinde iplik demetçiklerinin yoğun olduğu bölgeden dolayı yüksek permabilite değerine sahip olunduğu görülmüştür. Diğer yandan, düşük hidrolik eğimle başlatılan deneylerde hidrolik eğim arttırılsa bile 3,0, 4,0 ve 5,0 kg/m^2 BABBK değerlerinde hazırlanan Na-GKÖ'lerde düşük hidrolik iletkenlik değerleri elde edilmiştir. Na-GKÖ gibi 3,0 kg/m^2 BABBK'ye sahip P-GKÖ, 20 hidrolik eğimde düşük hidrolik iletkenliğe sahip olmuştur.

Anahtar Kelimeler: Geosentetik kil örtü, hidrasyon, hidrolik iletkenlik, hidrolik eğim, birim alan başına bentonit kütlesi, su içeriği

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Pages

CHAPTER ONE
INTRODUCTION

1.1 Introduction

Turkey has one of the fast growing populations all over the world. This increase in population directly causes an increase in the produce of municipal solid wastes. Excess increase in the solid waste have threatened the environment. Therefore, waste rehabilitations and control mechanisms have been developed to keep waste far from environment.

Solid wastes had been randomly stored on clayey soils until the end of 1990s in Turkey. Then, Compacted Clay Liners (CCL) are started to be used as landfill liner in waste containment facilities. Although it has been preferred in landfill applications, it has some disadvantages. CCLs are negatively influenced by freeze-thaw and wet-dry cycles and cause cracks on the barrier, especially when used as covers. This leads to the increment of the hydraulic conductivity and it is an undesired condition. Besides, thicknesses of CCLs are generally between 0.3 and 1.5 m. This height is quite high and clay material used in this system is one of the most valuable soil materials. Efficient use of this material is important. Therefore, with the development of recent technologies, new solutions were emerged for waste containment systems. Instead of installing CCL in the field, Geosynthetic Clay Liners (GCL) began to employ as landfill liner due to high impermeability property.

GCLs are composite barrier materials containing bentonite sandwiched between woven geotextile and non-woven geotextile (Benson et al., 2010; Jo et al., 2001) as shown in Figure 1.1. Bentonite in GCL is prehydrated during manufacturing process to prevent dust occurrence. Therefore, they have initial water content between 10% and 25%. They have low permeability due to high swelling property of bentonite. As bentonite swells, pore spaces between bentonite particles reduce, resulting in low hydraulic conductivity. Then, GCL gains a barrier property.

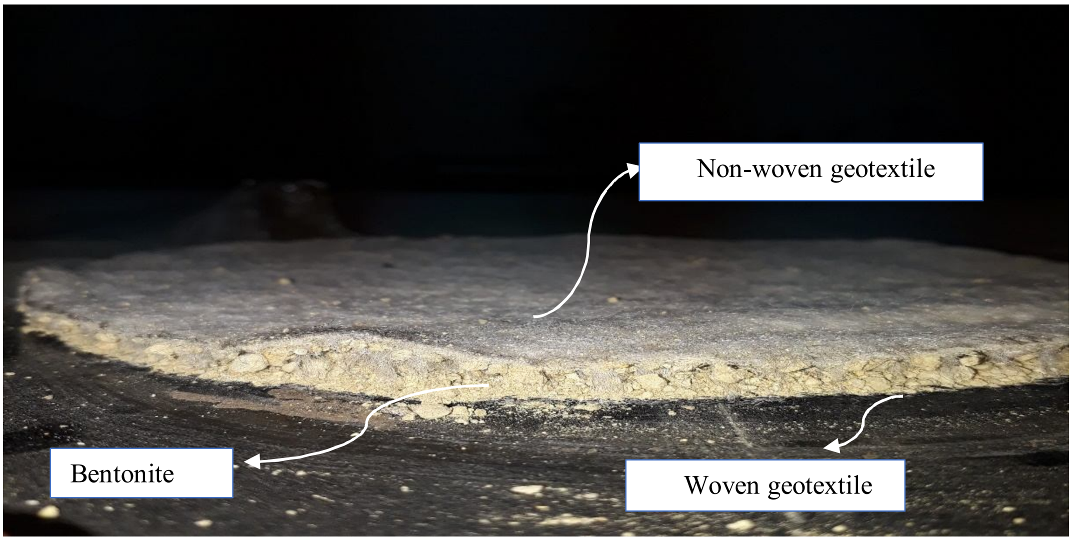


Figure 1.1 Photographic image of Geosynthetic Clay Liner (Personal archive, 2019)

The use of GCL has many advantages. GCL has low cost. It is easy to install in the field and its application is done by overlying GCL on the soil. Since GCL has thickness of ~1.0 cm, it covers less space. During contact between GCL and subsoil, water transfer occurs between GCL and soil. This is called hydration which is the water uptake process of GCL from underlying soil during the post construction stage. As a result, the water content of GCL increases. This contributes GCL to have low permeability. Hydraulic performance changes depending on the bentonite type, mineralogical composition of bentonite, pore fluid chemistry and manufacturing differences (mass per unit area, needle-punching density, geotextile type etc.). In this study, the influence of mass per unit area has been investigated and discussed.

1.2 Scope of the Study

The main purpose of this study is to investigate the effect of mass per unit area (MPUA) on the hydration and hydraulic conductivity of artificially prepared GCLs (A-GCLs).

GCLs are generally manufactured at MPUA of 5.0 kg/m^2 and there is no information why this level of MPUA is selected for the production. It is believed that the MPUA of GCL should be decided depending on the site specific conditions. For example, if GCL are used as covers in landfills or as base in fire-lagoons, then there is no need to use 5.0 kg/m^2 in GCLs. In other words, less bentonite in GCL may be sufficient to limit the flow when water is the permeant. Unlikely, if GCLs are used as bottom or side barriers in landfills or mine tailings, then MPUA of 5.0 kg/m^2 may not be enough to stop the leachate flow. Hence, more bentonite is needed to provide lower hydraulic conductivity. Based on above consideration, site specific use of GCL is directly related to the sustainable use of material, bentonite.

A research program has been conducted to understand the MPUA based change on hydration (water content) and hydraulic conductivity of two types of GCLs (i.e. sodium GCL and polymer treated GCL). For this purpose, both GCLs were hydrated over compacted silty sand for 7 and 30 days. After hydrations, the GCLs were separated into two parts. The first part was used to determine the water content, whereas second part was used to measure the hydraulic conductivity. The hydraulic conductivities were measured using flexible wall permeameters.

CHAPTER TWO
MATERIALS AND METHODS

2.1 Materials

2.1.1 Geosynthetic Clay Liners (GCLs)

Two types of GCLs one of which includes polymer modified (P-GCL) and the other contains conventional sodium (Na-GCL) bentonite were used in this study. GCLs were supplied from a local GCL manufacturing company in Turkey. Pictures of Na-GCL and P-GCL panels are shown in Figure 2.1a-b. The spaces appeared over the panels are due to sampling of GCLs for the tests.

Figure 2.1 Pictures of tested GCLs: a) Sodium GCL (Na-GCL) and b) Polymer GCL (P-GCL) (Personal archive, 2019)

Visual inspection of bentonites in both GCLs showed that bentonites were in aggregated form. This is possibly due to use of water during manufacturing process.

Water is generally sprayed over bentonite immediately after placing bentonite over woven geotextile (i.e. carrier geotextile) to protect dust occurrence during manufacturing. This allows partial swelling of bentonite within the GCL. After a while, however, bentonite starts to desiccate and forms aggregates. Needle punched fibers also help to dislocate the bentonite aggregates within each other, resulting a granular form of bentonite. The pictures showing the observational gradation of bentonites are given in Figure 2.2a-b.

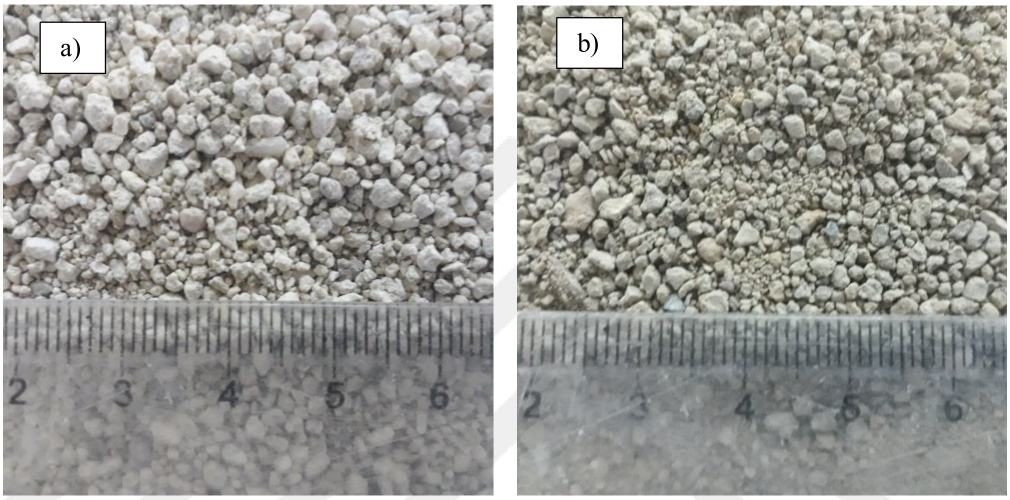


Figure 2.2 Visual appearance of bentonites: a) Sodium bentonite and b) Polymer treated bentonite (P-GCL) (Personal archive, 2019)

The particle size distribution curves of bentonites were previously determined by Özdamar Kul (2019) and shown in Figure 2.3. Mechanical dry sieving test was also performed herein to determine granule (aggregate) size distribution curves of bentonites. For this purpose, GCLs were detached and bentonites were collected in a pan. After drying in an oven at 105ºC, dry sieving analysis was performed. Granule size distribution curves of bentonites are shown in Figure 2.3 along with the particle size distribution curves. It can be seen that D_{50} of granule sodium and polymer bentonites are 1.1 and 0.85 mm, respectively. When subjected to wet sieving, however, the fines contents of sodium and polymer bentonites were found 86 and 90% (Table 2.1), whereas clay contents were found 72 and 68%, respectively.

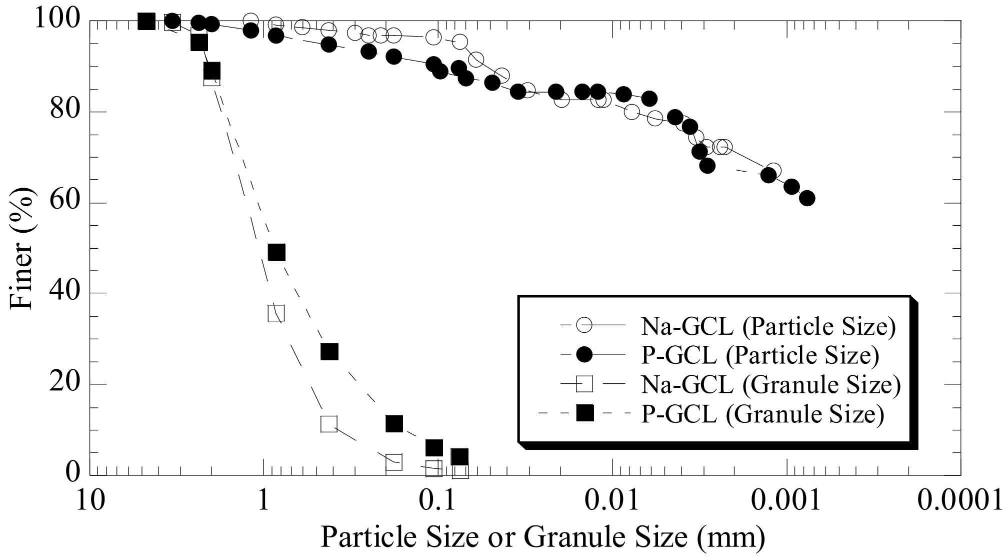


Figure 2.3 Particle and granule size distributions of the bentonite particles in GCLs

Table 2.1 The physical characteristics and index properties of geosynthetic clay liners (Özdamar Kul, 2019)

GCL Type	Specific Gravity	Initial Water Content (%)	Fines Content (%)	Liquid limit (%)		Plasticity Index (%)	
				Casagrande	Fall Cone	Casagrande	Fall Cone
Na-GCL	2.64	10	86	240	215	187	162
P-GCL	2.7	11	90	400	282	340	222

The exchangeable cations of both GCLs are presented in Table 2.2. The chemical analyses conducted on both GCLs indicate that the major cation in GCLs is sodium (Na^+). Based on the information given by the manufacturer, the source of sodium in P-GCL is due to polymerization of bentonite with polyacrylate anionic polymer. In contrast, Na-GCL naturally contains sodium, but there is also appreciable amount of calcium (Ca^{2+}) (Table 2.2).

Table 2.2 Exchangeable cations of Na-GCL and P-GCL (Özdamar Kul, 2019)

GCL Type	**Exchangeable Cations Mole Fractions**			
	Na^+	**K^+**	**Ca^{2+}**	**Mg^{2+}**
Na-GCL	0.7	0.04	0.23	0.03
P-GCL	0.69	0.01	0.16	0.13

2.1.2 Subsoil

Soil which had been supplied from Aydın Municipal Solid Waste (MSW) Disposal Site was used as the subsoil in hydration tests. The image of subsoil is shown in Figure 2.4a-b, whereas the grain size distribution curve of the subsoil is given in Figure 2.5. As seen from Figure 2.5, the fine content of subsoil is 42%. Based on Unified Soil Classification System (USCS), the soil was classified as silty sand (SM).

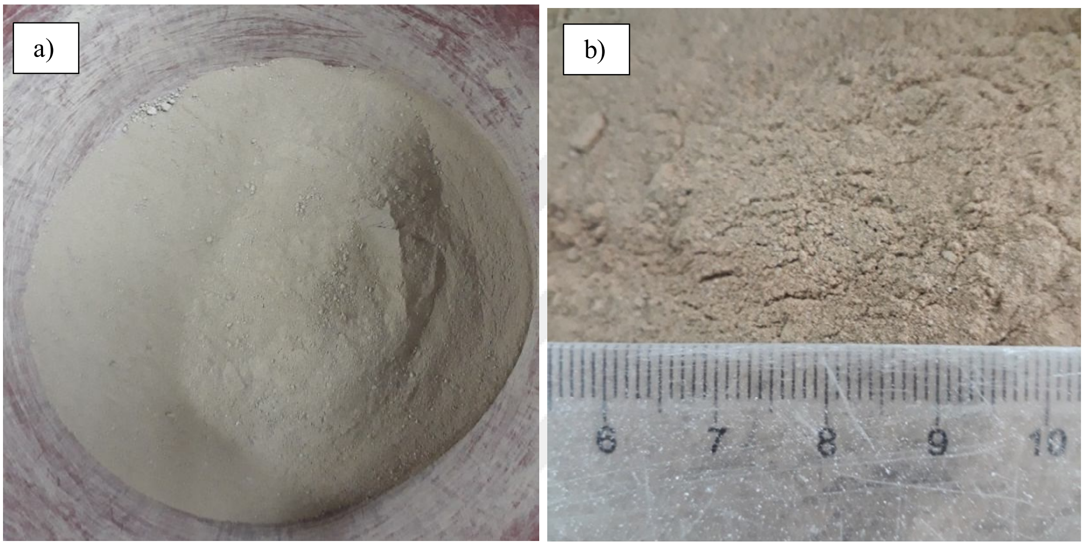


Figure 2.4 Photographs of soil used as the subsoil during hydration test: a) Overall and b) close views of silty sand (Personal archive, 2019)

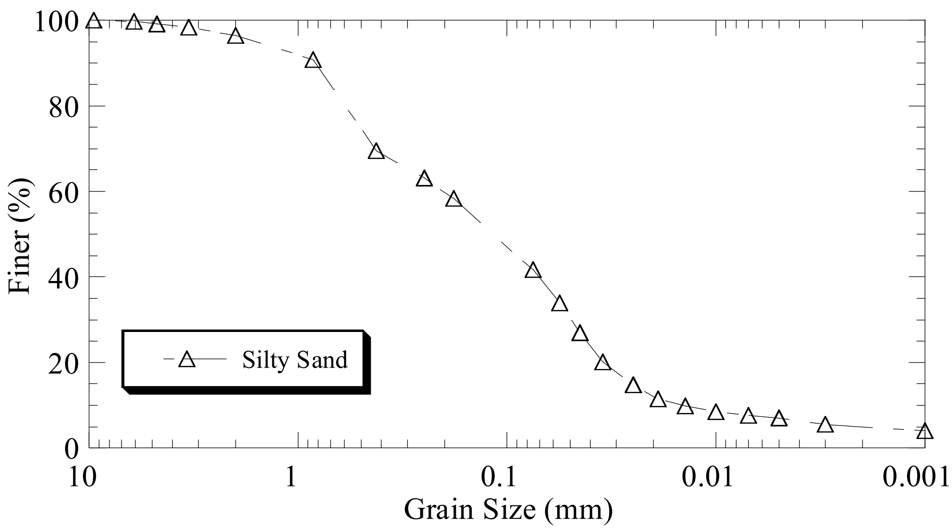


Figure 2.5 Grain size distribution of subsoil (Özdamar Kul, 2019)

2.2 Methods

2.2.1 Index Tests

2.2.1.1 Geosynthetic Clay Liners

To determine some properties of bentonites, fibers that attach non-woven geotextile and woven geotextile were detached and then, bentonites were taken from GCLs. After that, bentonites were dried in an oven at 105ºC. The initial water content, specific gravity, fines content and index properties of bentonites have already been determined and reported by Özdamar Kul (2019). These tests were not repeated herein, but summarized in Table 2.1.

2.2.1.2 Subsoil

The grain size distribution of subsoil had been determined in accordance with ASTM:D422-63 (2007) and reported previously by Özdamar Kul (2019). Wet sieving method and hydrometer test was conducted on subsoil. Based on Unified Soil Classification System (USCS), the subsoil was classified as silty sand (SM). Other basic parameters of subsoil is summarized in Table 2.3.

Table 2.3 The physical characteristics and index properties of subsoil (Özdamar Kul, 2019)

Subsoil properties	**Amount**
Gravel (%)	1
Sand (%)	57
Silt (%)	37
Clay (%)	5
Specific Gravity, G_s	2.67
Liquid Limit w_L (%)	30.7
Plastic Limit w_P (%)	NP

The compaction behavior of silty sand was obtained according to ASTM:D698-12 (2012) and previously reported by Özdamar Kul (2019). Since the same soil was used, compaction test was not repeated to determine the compaction curve. The reported optimum water content (ω_{opt}) and maximum dry unit weight ($\gamma_{d,max}$) for the subsoil were 12% and 18.3 kN/m^3, respectively. Compaction curve of silty sand subsoil is shown in Figure 2.6.

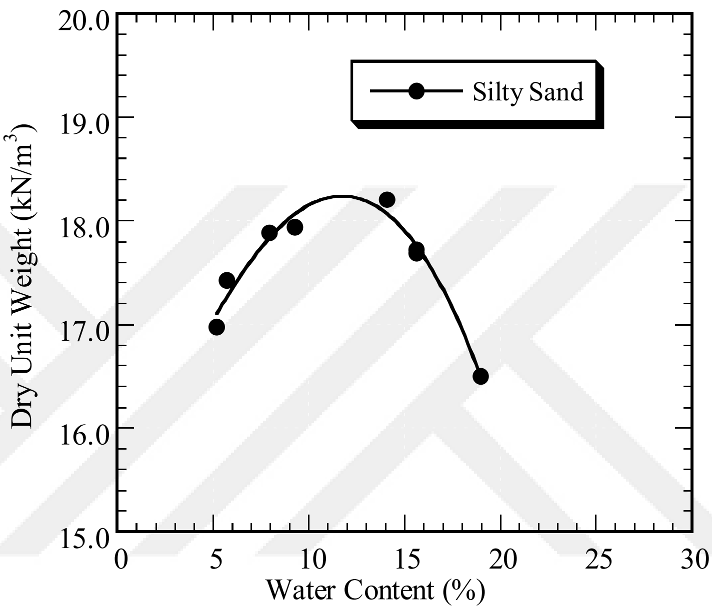


Figure 2.6 Compaction curve of the silty sand (Özdamar Kul, 2019)

2.2.2 Preparation of GCL Sample

Mass per unit area (MPUA) of GCLs were determined as described in ASTM:D5993-99 (2010). Original MPUA of GCLs were measured initially. The original MPUA of P-GCL was between 7.8 kg/m^2 and 10 kg/m^2 and that of Na-GCL was within the range of 9 kg/m^2 and 10 kg/m^2. Then, artificial GCLs (A-GCLs) were prepared in the laboratory by step wise decreasing the mass by rolling.

Initially, GCL sample with diameter of 150 mm was cut from the roll and was weighted on a balance with 0.01 g accuracy. Then, a slight force was applied on the GCL using a stainless steel roller. Rolling process is shown in Figure 2.7. This allowed bentonite to pour from the circumference of the GCL. Then, GCL was weighted. The rolling process was continued until the target MPUA was achieved. Then, edges of GCL were wetted with little droplets of deionized (DI) water to keep MPUA value constant. In other words, bentonite loss was prevented by hydrating circumference of GCL. The target MPUA was set a value as low as 2.92 kg/m^2 in this study. Finally, the thickness of artificially prepared GCL was measured from four different locations on GCL by using Vernier caliper. Since MPUA of GCL was changed with a manmade action, such GCL was named as artificially prepared GCLs and denoted with "A-GCLs".

Figure 2.7 Arranging the mass per unit area (MPUA) of bentonite in GCL (Personal archive, 2019)

2.2.3 Compaction of the Subsoil for Hydration Studies

Silty sand subsoil was compacted under Standard Proctor compaction energy (ASTM:D698-12 2012). The soil was put in plastic bag in its air-dry state. Then, tap water was added to the soil with a spray bottle in a manner to stay on 2% wet side of optimum water content (i.e. 14%). Wet soil was hydrated in plastic bag for 24 hours in order to make sure a uniform water distribution throughout the sample. After hydration, soil was compacted in a mold that has a diameter of 150 mm and height of 116 mm in accordance with ASTM:D698-12 (2012). Pictures of mold, automatic compactor, which was used during compaction, and hydraulic jack are shown in Figure 2.8a-c, respectively.

Figure 2.8 Photographs of compaction mold and compaction process: a) Compaction mold, b) compaction of subsoil by using automatic compactor and c) extrusion of compacted subsoil from mold (Personal archive, 2019)

2.2.4 Hydration of Geosynthetic Clay Liners

The field conditions of GCL hydration was simulated in the laboratory using flexible-wall permeameters. First, a heavy non-woven geotextile was placed on the plexiglass basement of permeameter as shown in Figure 2.9a. Then, compacted soil was placed over it and subsequently A-GCL, HDPE geomembrane and heavy non-woven geotextile were placed over the subsoil (Figure 2.9a). Note that the non-woven face of A-GCL was in contact with the subsoil. Finally, plexiglass top pedestal was mounted on the heavy non-woven geotextile. The principal role of HDPE geomembrane in landfill is containment and its secondary role is to prevent evaporation of water from the subsoil. In this study, only its secondary role was used during hydration. Similarly, placing heavy non-woven geotextile over HDPE geomembrane has no effect on GCL during hydration herein. Although this geotextile is used to protect HDPE geomembrane from puncturing which may be induced by the overlying soil, there was no such kind of risk in this study. Neither gravel nor any kind of geomaterial with sharp edges were placed over non-woven geotextile during hydration (Figure 2.9a). Then, subsoil-geosynthetics system was surrounded by latex membrane and three O-rings were attached on each pedestal (Figure 2.9b). After permeameter cell installations were done, permeameter cell was filled with tap water. Then, the permeameter was connected to the pressure line which provides 10 kPa effective stress during the hydration (Figure 2.9c). This low level of effective stress simulates 0.5-1.0 m of cover soil above GCL in field conditions. The influent and effluent valves of the permeameter were closed and thus, no flow was allowed throughout the hydration duration.

Figure 2.9 Sample preparation for the hydration of GCL: a) components, b) placement of latex membrane and O-rings, c) general view of permeameters during hydration (Personal archive, 2019)

The A-GCLs were subjected to 7 and 30 days of hydration. At the end of hydration, all permeameters were dismantled and A-GCLs were carefully removed from the permeameters. The weights and thicknesses of the GCLs were measured. An inner part of hydrated A-GCL with 100 mm in diameter was cut to run for the hydraulic conductivity test, while the rest part was used to determine the water content (Figure 2.10a). When inner part was cut, it was directly transferred to another permeameter cell to perform hydraulic conductivity test. For the rest of A-GCL, the fibers that connect the non-woven and woven geotextiles were cut with a sharp razor knife. Special care was taken not to disturb the swollen bentonite. After that, bentonite condition after 7 and 30 days of hydration was monitored by taking pictures. As an example, the pictures of the rest of A-GCL and hydrated bentonite are shown in Figure 2.10b and 2.10c, respectively. After taking pictures, the bentonite was taken with a spatula and dried in an oven at 105 °C. Then, the water content of bentonite was determined.

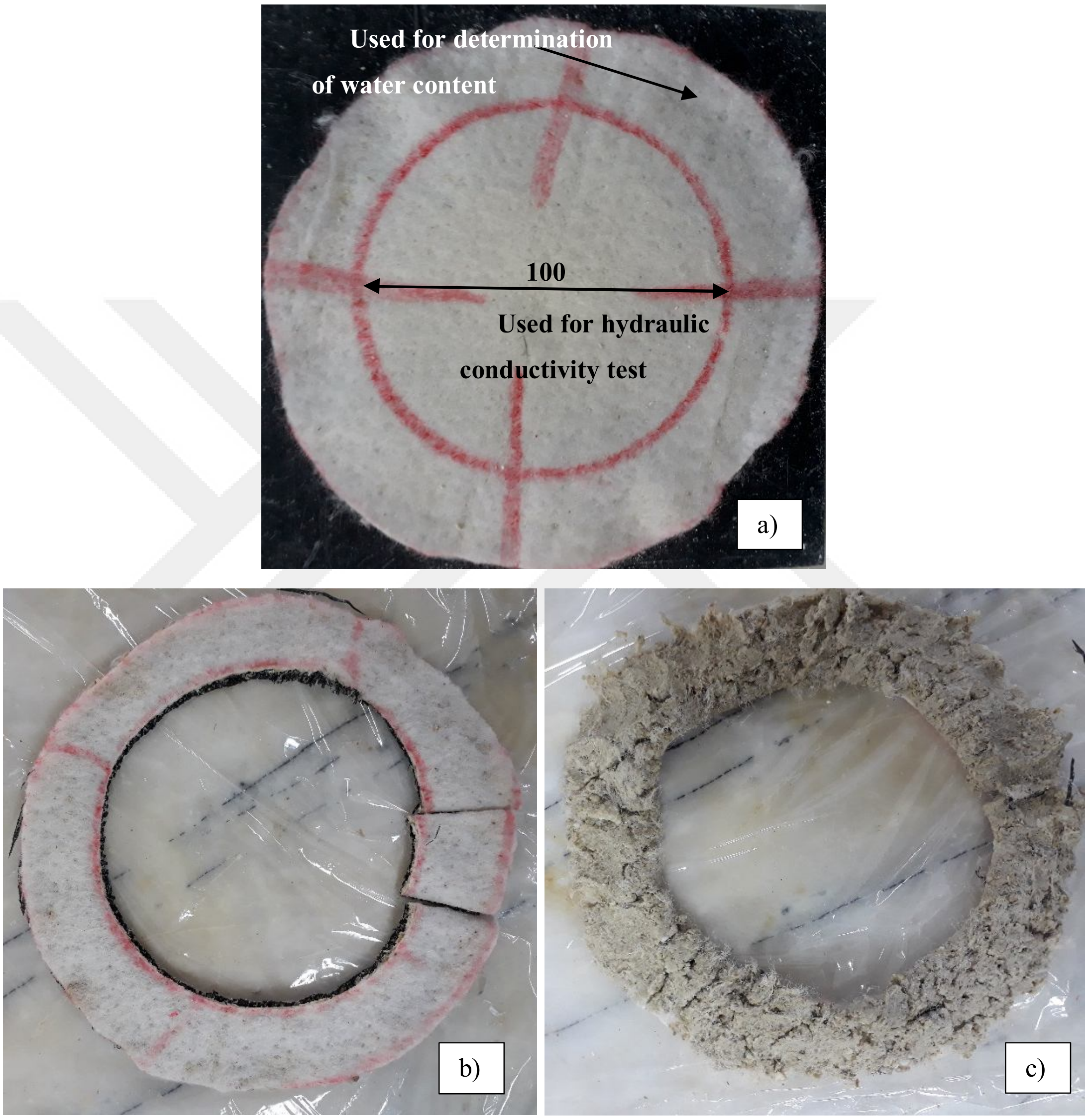


Figure 2.10 Pictures of: a) an A-GCL sample used for hydration and hydraulic conductivity test, b) the rest of A-GCL which was used to determine water content and c) swollen bentonite after hydration (Personal archive, 2019)

2.2.5 Hydraulic Conductivity Tests

After hydration, a sample was cut with a diameter of 100 mm from the center of A-GCL and it was used for the hydraulic conductivity test. A-GCL sample was sandwiched between two heavy non-woven geotextiles and they were placed over the plexiglass base plate of flexible wall permeameter cell as shown in Figure 2.12. The heavy non-woven geotextiles were used instead of porous stones in all hydraulic conductivity tests. Then, top plate was mounted on the heavy non-woven geotextile. Bentonite paste were used to seal the perimeter of spaces present between top and bottom plates to prevent side wall leakage (Figure 2.12). After that, the latex membrane and O-rings were installed.

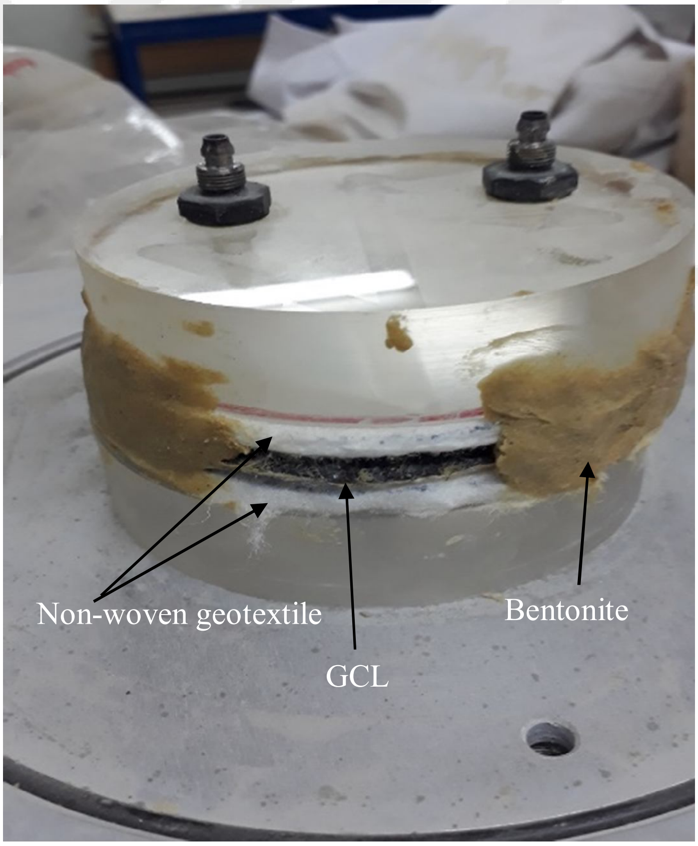


Figure 2.11 GCL sample prepared for the hydraulic conductivity test (Personel archive, 2019)

Hydraulic conductivity tests were conducted in accordance with procedure described in ASTM:D6766-12 (2014). The falling head water and constant tail water method was applied during the hydraulic conductivity tests. The schematic representation of flexible wall permeameter cell is shown in Figure 2.12. Hydraulic conductivity tests were carried out under high and low level of hydraulic gradients. In the first part tests (i.e. high level), an average hydraulic gradient of 110 was applied and the hydraulic conductivities were measured under this level. However, decreasing the MPUA facilitate the escape of bentonite from A-GCL (especially for A-Na-GCL) which can be named as "bentonite erosion". Therefore, some hydraulic conductivity tests performed on A-GCLs with low MPUA (3.0, 4.0 and 5.0 kg/m^2) were started from low level of hydraulic gradient (i.e. 20). After a while, the hydraulic gradients were doubled (i.e. 40, 80, 160) and hydraulic conductivities were measured at each hydraulic gradient. Cell pressure was supplied from pressure panel (Figure 2.13) and average cell pressure was approximately 35 kPa. No backpressure was applied throughout the hydraulic conductivity tests to represent field conditions. The influence of MPUA on the hydraulic conductivity was determined only using deionized water. In other words, A-GCLs were permeated with deionized water. Flow direction was from top to bottom through the specimen. The influent flow (inflow) was supplied by 50 ml burettes, whereas effluent flow (outflow) was collected in 100 ml graduated cylinder (Figure 2.13). Note that top of graduated cylinder was closed by parafilm to obstruct water evaporation. Hydraulic conductivity experiments were ended when the last 4 consecutive hydraulic conductivity values were within the interval of 1.0±0.25. Hydraulic conductivity of A-GCLs is calculated using Equation (2.1) as given below:

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

In this equation; k is the hydraulic conductivity (m/s), A is perpendicular cross section area across flow direction (m^2), a is cross section area of burette (m^2), L is thickness of specimen (m), h_1 (m) and h_2 (m) are initial and final water level in the burettes, respectively and Δt (s) is the elapsed time between two readings.

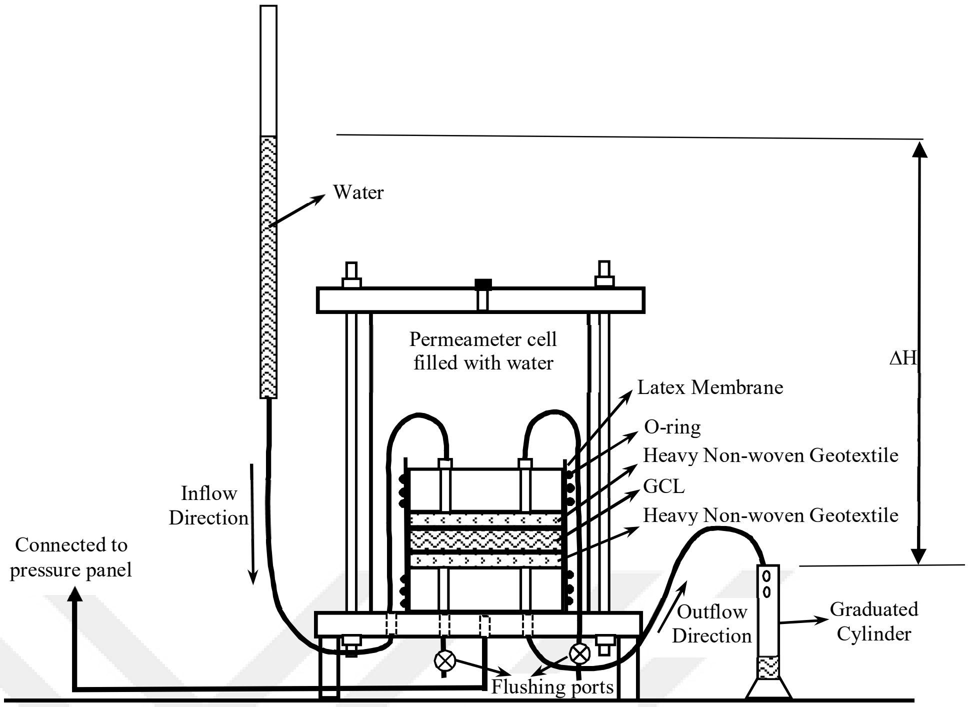


Figure 2.12 Schematic representation of flexible wall permeameter cell.

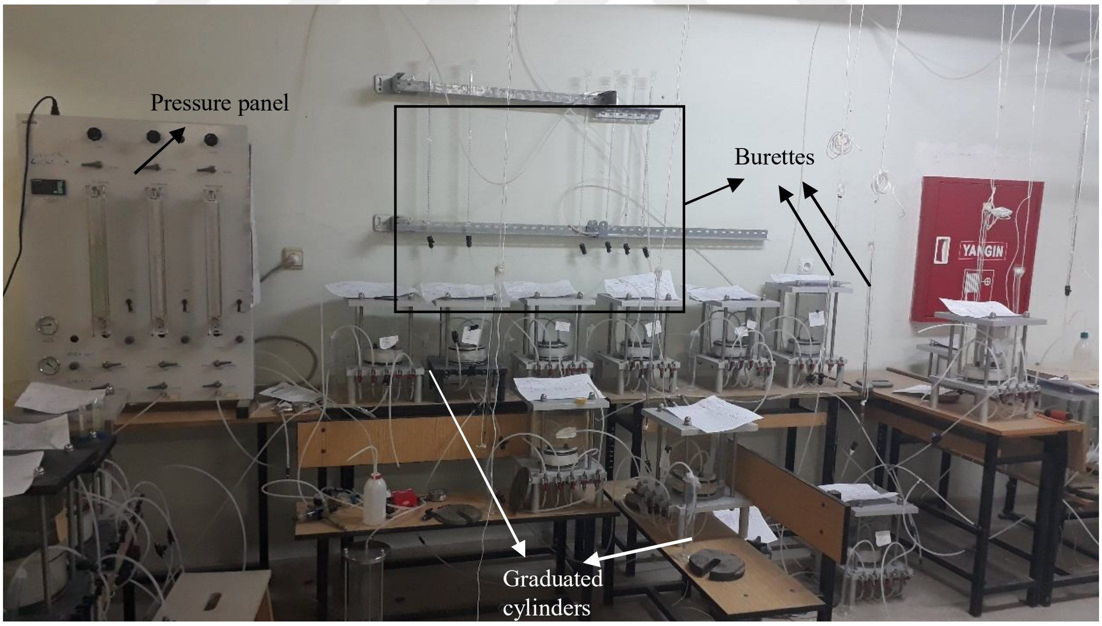


Figure 2.13 Overall view of hydraulic conductivity testing room (Personal archive, 2019)

Hydraulic conductivities are expressed as a function of pore volumes of flow (PVF). For instance, if GCL specimen have 30 cm^3 voids, this amount of flow across the sample corresponds to 1 PVF. Volume of voids in the A-GCL was calculated based on Equation 2.2 which had been proposed by Petrov et al. (1997) as follows:

$$e_b = \frac{V_{vb}+V_{vg}}{V_s} = \frac{V_t - V_s}{V_s} = \frac{H_{GCL} - H_s}{H_s} \tag{2.2}$$

In this equation; V_{vb} is volume of voids in bentonite; V_{vg} is volume of voids in the upper and lower geotextiles; V_s is total volume solids (geotextiles and bentonite); V_t is total volume of the GCL, H_{GCL} is GCL height, H_s is height of solids in the GCL. H_s can be calculated using Equation 2.3:

$$H_s = H_b + H_g = \frac{M_{bent}}{\rho_b(1+w_0)} + \frac{M_{geo}}{\rho_{geo}} \tag{2.3}$$

where, H_g is height of geotextile, M_{bent} is mass per unit area of bentonite in GCL, ρ_{bent} is density of bentonite solids. w_0 is initial bentonite moisture content, M_{geo} is mass per unit area of geotextiles in the GCL and ρ_{geo} is density of geotextile (0.91 Mg/m^3).

CHAPTER THREE
HYDRATION OF GEOSYNTHETIC CLAY LINERS DEPENDING ON THE MASS PER UNIT AREA

3.1 Background

Geosynthetic Clay Liners (GCLs) take water after installation on compacted soil in the field. This is called as hydration of GCL. GCL – subsoil interaction has a significant role on the hydraulic performance of GCL and thus, has been of interest by many researchers for the last decade (Meer & Benson, 2007, Bradshaw et al., 2012, Rowe & Abdelatty, 2012, Bouazza et al., 2017, Özdamar Kul & Ören, 2018, 2019).

GCL starts to be hydrated when it is placed over the subsoil. Water migrates from subsoil to GCL because of suction difference between these two materials. Hence, the water content of GCL increases with time. The water migration lasts until water contents of either subsoil or GCL are balanced (Acikel et al., 2018).

There are some factors that influence the hydration performance of GCLs when placed over subsoil. Basically, the hydration duration, subsoil and GCL types and environmental conditions such as temperature and pore fluid chemistry have all deep impact on the hydration of GCLs (Meer & Benson, 2007, Benson & Meer, 2009, Anderson et al., 2012, Rowe & Abdelatty, 2012, Barclay & Rayhani, 2013, Rowe & Hosney, 2013, Hosney & Rowe, 2014, Bouazza et al., 2017, Özdamar Kul & Ören, 2018, 2019).

Among others, researchers have mainly focused on understanding the subsoil induced performance change on GCLs. It is reported that increase in the subsoil water contents also increase the water contents of GCLs. Moreover, subsoil type lead to change the hydration pattern of GCLs. In other words, if GCLs are hydrated over sand, silty sand or clayey subsoil, the hydration rate and the water content may possibly be different (Meer & Benson, 2007, Katsumi et al., 2008, Rayhani et al., 2011, Anderson et al., 2012, Bradshaw et al., 2012, Rowe & Abdelatty, 2012, Rowe & Hosney, 2013, Hosney & Rowe, 2014).

There are some other studies reporting the influence of GCL type on hydration as well. These studies especially handle the hydration process in terms of cation exchange that take place between subsoil and GCL (Meer & Benson 2007, Benson & Meer 2009, Rowe & Abdelatty 2012, Hosney & Rowe 2013, Özdamar Kul & Ören 2019), the bentonite type used in GCL (i.e. conventional or polymer treated bentonite) (Bouazza et al., 2017; Hosney & Rowe 2013; Özdamar Kul & Ören 2018, 2019) and manufacturing differences in the GCL (Anderson et al., 2012; Rayhani et al., 2011; Sarabian & Rayhani 2013). Regarding to the manufacturing differences, type of geotextile used in GCL, MPUA of bentonite and type of bonding can be counted. But only MPUA of bentonite will be considered herein. Rayhani et al. (2011) stated that MPUA of GCL had some effect on the final hydration water content of GCLs. They reported that lower water content (88% versus 99%) were obtained for GCL with high MPUA (4.88 kg/m^2) than for GCL with low MPUA (3.49 kg/m^2) after 30 weeks of hydration. However, MPUA was within limited range in their study. Since little attention has been on MPUA of bentonite so far, the influence of MPUA on the hydration of GCL will be investigated in this chapter.

3.2 Influence of Mass Per Unit Area on the Water Contents of GCLs

3.2.1 Influence of Hydration Duration on Water Contents of GCLs

The water contents of GCLs were determined by hydrating the GCLs over compacted subsoil for 7 days (short term) and 30 days (long term). Since most of the GCLs have MPUA of 5.0 kg/m^2, the final water contents of GCLs depending on the hydration duration is given for this MPUA herein (Figure 3.1). As can be seen in Figure 3.1, the final water contents increased remarkably in the first 7 days of hydration. This conclusion is in agreement with the previous studies reported in the literature (Bradshaw et al., 2012, Rowe & Abdelatty, 2012, Özdamar Kul & Ören, 2019).

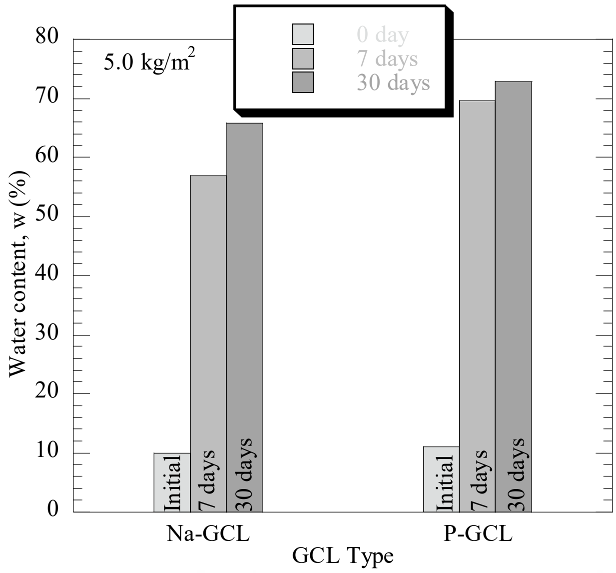


Figure 3.1 Water contents of GCLs with MPUA of 5.0 kg/m^2 before and after 7 and 30 days of hydration

The target MPUAs were arranged roughly between 3.0 kg/m^2 and 7.0 kg/m^2 for Na-GCL and between 3.0 kg/m^2 and 10.0 kg/m^2 for P-GCL. Like Figure 3.1, many graphs can be produced for other GCLs that have different MPUAs. Instead of this, the rate of change in water content with hydration duration (i.e. $\Delta w/\Delta t$) is drawn as a function of MPUA as shown in Figure 3.2. The rate of change in water content was calculated by considering the time intervals in the first 7 days and between 7 and 30 days. Increase in the MPUA remarkably decreased the rate of change in water content in the first 7 days of hydration (from 7.9 to 5.1 %/day for P-GCL and from 7.0 to 5.0 %/day for Na-GCL). Regardless of MPUA, GCLs adsorbed water from the underlying soil rapidly in the first 7 days of hydration. In contrast, the rate of change in water content considerably decreased between 7 and 30 days of hydration, indicating the water contents of GCLs slightly changed after 7 days of hydration (from 2.8 to 2.1 %/day for both GCLs). Moreover, the rate of change in water content were greater for P-GCL than for Na-GCL at 7 days of hydration. However, the rate of change at 30 days of hydration was independent of GCL type.

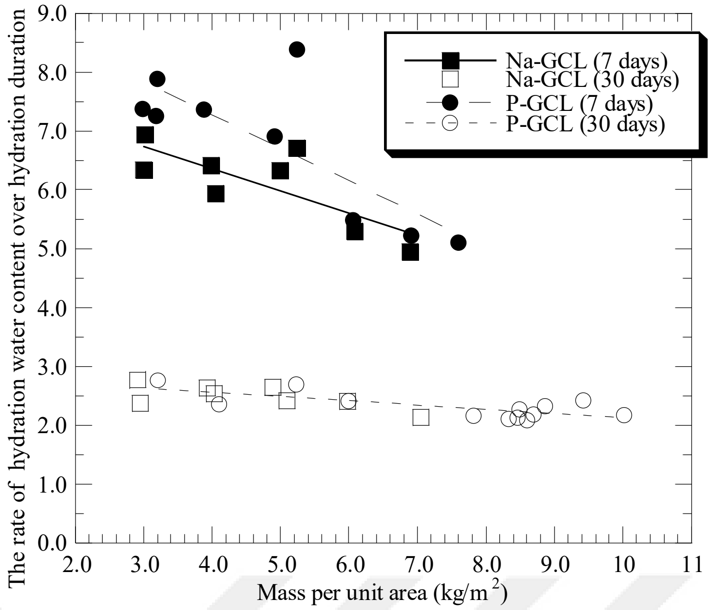
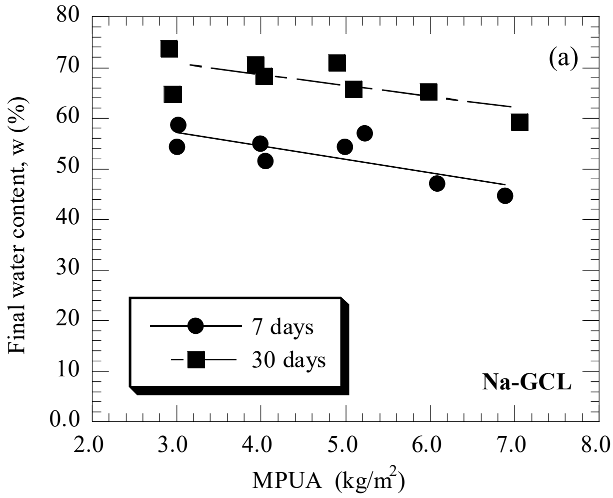


Figure 3.2 Change of rate of hydration water content over hydration duration as a function of mass per unit area (kg/m^2)

The influence of MPUA on the hydration of GCL is interpreted in terms of GCL final water content as well and shown in Figure 3.3a-b. As indicated in Figure 3.3a-b, increase in the MPUA linearly decreased the final water contents of GCLs for both hydration durations. When MPUA increased from 3.0 to 10.0 kg/m^2, the final water contents of P-GCLs decreased from 70% to 47% after 7 days of hydration and from 74% to 59% after 30 days of hydration. In the considered MPUA range for Na-GCL, the final water contents reduced from 59% to 45% and from 74% to 59% after 7 and 30 days of hydration, respectively. The slope of the decrement with MPUA for Na-GCL were almost the same for 7 days and 30 days of hydration. In the case of P-GCL, however, the slope for 7 days of hydration was steeper than that for 30 days of hydration (Figure 3a-b).



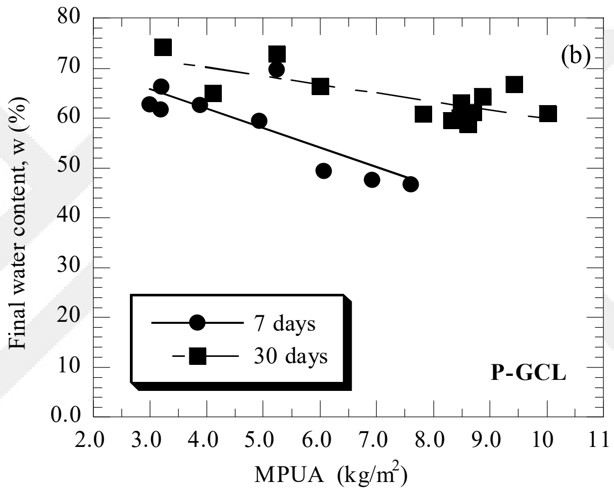


Figure 3.3 Change of water content as a function of mass per unit area (MPUA): a) Na-GCL, b) P-GCL

To reach the same water contents of GCLs, more MPUA is needed for 30 days of hydration when compared to the 7 days of hydration. For example, as shown in Figure 3.3a, it was required to use 3.0 kg/m^2 MPUA to achieve 59% water content when Na-GCL was hydrated for 7 days. In contrast, 7.1 kg/m^2 MPUA is enough to reach the same water content for the same GCL when hydrated for 30 days. The same conclusion can also be drawn for P-GCL (Figure 3.3b). This finding is important since GCLs with lower MPUA have higher final water contents than GCLs with higher MPUAs.

Conversely, at any MPUA, the greater the hydration duration, the greater is the final water contents for both GCLs (Figure 3.3a-b). However, it does not make any sense because the water content of GCL will increase with time.

The final water contents of both GCLs are tabulated and GCL heights before and after hydration are summarized in Table 3.1. The variation in the water contents of GCLs ranged between 46% and 74%. The initial height of GCLs increased as the MPUA increased (Figure 3.4a). To determine the change in GCL heights are evaluated in terms of normalized heights ($H_{final}/H_{initial}$). The normalized heights are plotted as a function of initial GCL heights shown in Figure 3.4b. Slight changes occurred in the Na-GCL heights during 7 days of hydration ($H_{final}/H_{initial} \approx 1.0$). Only 1.2-fold change was measured when Na-GCL was hydrated for 30 days. In contrast, the P-GCL heights changed considerably during the hydration. The maximum normalized height for P-GCL is 1.8 and 1.5 times for 7 days and 30 days of hydration, respectively (Figure 3.4b).

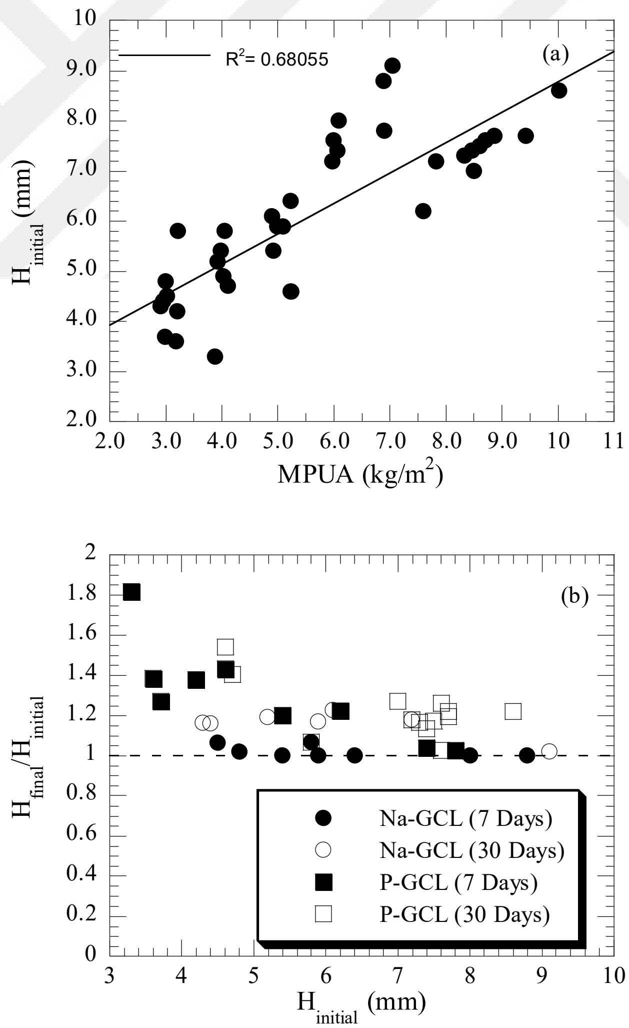


Figure 3.4 Change of: a) Initial height as a function of mass per unit area (MPUA) and, b) normalized heights of GCLs versus initial height

Table 3.1 Initial and post-test height and final water contents of GCLs

Test No	GCL Type	MPUA (kg/m^2)	Hydration Duration (Days)	GCL Final Water Content (%)	GCL Height (cm)	
					$H_{initial}$	H_{final}
1	Na-GCL	3.02	7	59	0.45	0.48
2	Na-GCL	3.00	7	54	0.48	0.49
3	Na-GCL	3.99	7	55	0.54	0.54
4	Na-GCL	4.05	7	52	0.58	0.62
5	Na-GCL	5.23	7	57	0.64	0.64
6	Na-GCL	4.99	7	54	0.59	0.59
7	Na-GCL	6.08	7	47	0.8	0.8
8	Na-GCL	6.89	7	45	0.88	0.88
9	Na-GCL	2.95	30	65	0.44	0.51
10	Na-GCL	2.91	30	74	0.43	0.50
11	Na-GCL	4.03	30	68	0.49	x
12	Na-GCL	3.93	30	71	0.52	0.62
13	Na-GCL	5.09	30	66	0.59	0.69
14	Na-GCL	4.89	30	71	0.61	0.75
15	Na-GCL	5.98	30	65	0.72	0.85
16	Na-GCL	7.05	30	59	0.91	0.93
17	P-GCL	3.20	7	66	0.42	0.58
18	P-GCL	3.18	7	62	0.36	0.5
19	P-GCL	2.99	7	63	0.37	0.47
20	P-GCL	3.88	7	63	0.33	0.6
21	P-GCL	5.24	7	70	0.46	0.66
22	P-GCL	4.92	7	59	0.54	0.65
23	P-GCL	6.06	7	49	0.74	0.77
24	P-GCL	6.91	7	48	0.78	0.8
25	P-GCL	7.60	7	47	0.62	0.76
26	P-GCL	3.21	30	74	0.58	0.62
27	P-GCL	4.11	30	65	0.47	0.66
28	P-GCL	5.23	30	73	0.46	0.71
29	P-GCL	6.00	30	66	0.76	0.78
30	P-GCL	8.50	30	63	0.7	0.89
31	P-GCL	10.02	30	61	0.86	1.05
32	P-GCL	9.43	30	67	0.77	0.94
33	P-GCL	8.87	30	64	0.77	0.92
34	P-GCL	8.47	30	60	0.74	0.84
35	P-GCL	8.61	30	59	0.75	0.88
36	P-GCL	8.70	30	61	0.76	0.96
37	P-GCL	8.33	30	60	0.73	0.85
38	P-GCL	7.82	30	61	0.72	0.85

3.2.2 Influence of GCL Type on the Water Contents of GCLs

The final water contents of GCLs are evaluated as a function of MPUA to compare the hydration performance of GCLs in terms of GCL type (shown Figure 3.5a-b). P-GCLs had higher final water contents than Na-GCLs in both hydration durations. However, difference between the final water contents of P-GCLs and Na-GCLs for 30 days of hydration were lower than difference between that of P-GCLs and Na-GCLs hydrated for 7 days. This shows that P-GCL had better hydration performance in comparison with Na-GCL in the short-term (i.e. 7 days). In contrast, in the long-term hydration duration (i.e. 30 days), water contents of both GCLs approached each other and they exhibited almost similar performance. In other words, further hydration duration (i.e. 30 days of hydration) decreased the difference between final water contents of Na and P-GCLs.

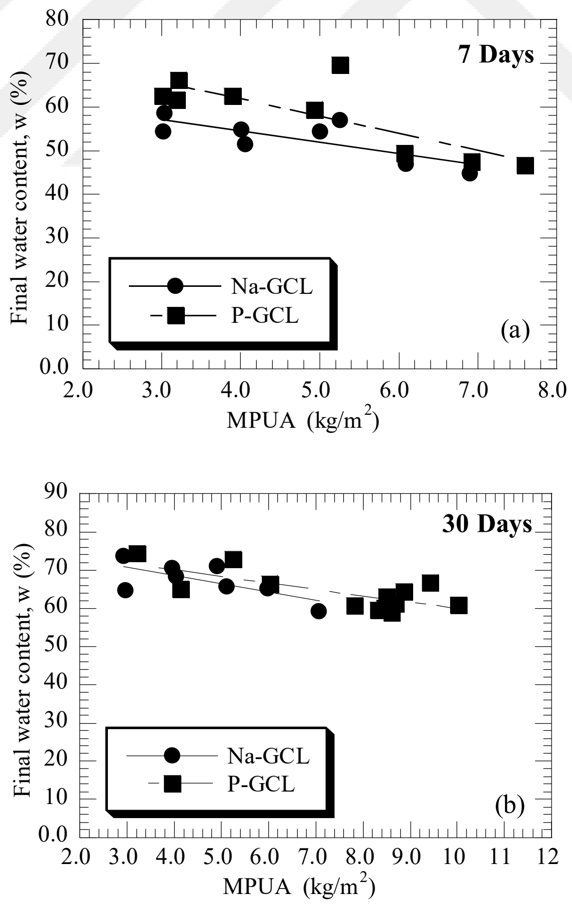


Figure 3.5 Change of water content as a function of mass per unit area (MPUA): a) 7 days, b) 30 days

3.3 Discussion

The decrement in the final water contents of GCLs with increasing the MPUA is mainly due to the restricted swelling of bentonite on account of needle-punching of GCLs. The fibers connecting the woven and non-woven geotextiles limit the vertical expansion of GCL during hydration and therefore, the volume between the geotextiles can increase to a certain value. The swelling of bentonite particles within GCLs before and after hydration is demonstrated in Figure 3.6. Needle-punched fibers are not shown on GCLs in Figure 3.6 not to allow any confusion on the schematic representation.

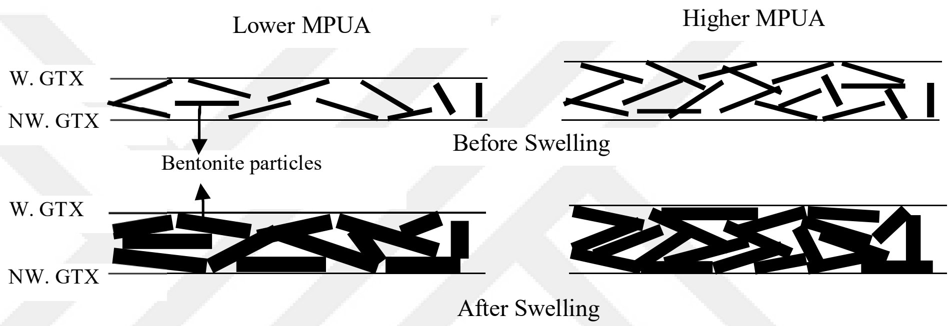


Figure 3.6 Schematic representation of bentonite swelling before and after hydration

The initial height of GCL (i.e. before hydration) with lower MPUA is generally lower than the GCL with higher MPUA (Table 3.1). That is, higher MPUA makes GCLs rather thicker as shown in Figure 3.4a. When GCLs are subjected to hydration, it is expected that the GCLs with lower MPUA swell more than the GCLs with higher MPUA. Because there is more place for the bentonite particles to swell at lower MPUA. However, particles could swell in the lateral and vertical direction within the GCL at lower MPUA, whereas they swell mostly in the vertical direction at higher MPUA. Thus, the final GCL heights for higher MPUA are still greater than those for lower MPUA. Indeed, such kind of tendency were observed herein during the hydration process (Figure 3.7a-b). The final GCL height increased as the MPUA increased for both hydration durations.

Figure 3.7a-b also shows that the hydration duration has an influence on the final GCL heights. For all considered MPUA range, lower GCL heights were obtained after

7 days of hydration, indicating the role of hydration duration on the final GCL height. It is expected because longer hydration results in greater swelling of the bentonite and consequently an increase in the final water content and height of the GCL.

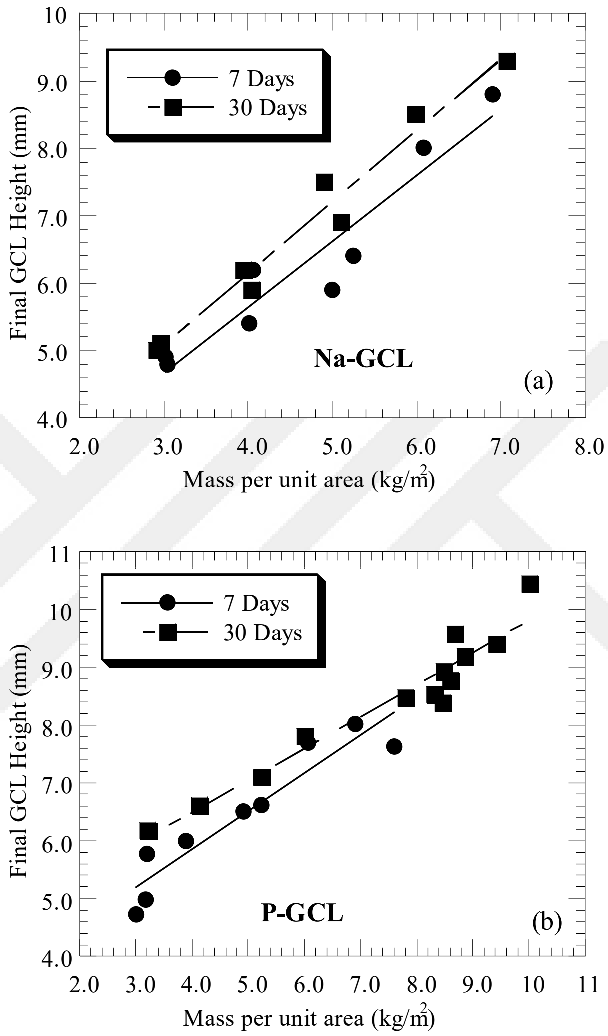


Figure 3.7 Final GCL height after hydration as a function of mass per unit area (MPUA): a) Na-GCL, b) P-GCL

Out of 14 data most of which belong P-GCL stacked between 8.0-10.0 mm (Figure 3.7b). This shows that the swelling of GCLs can increase to a certain level. Higher MPUA means stacking of more bentonite particles between non-woven and woven geotextiles. Hence, initial and final void ratios should be expected lower for the GCL with higher MPUA than for the GCL with lower MPUA as demonstrated in Figure

3.8. To show this tendency as a function of MPUA, the final GCL void ratios were calculated in a similar manner to the equation proposed by Petrov et al. (1997).

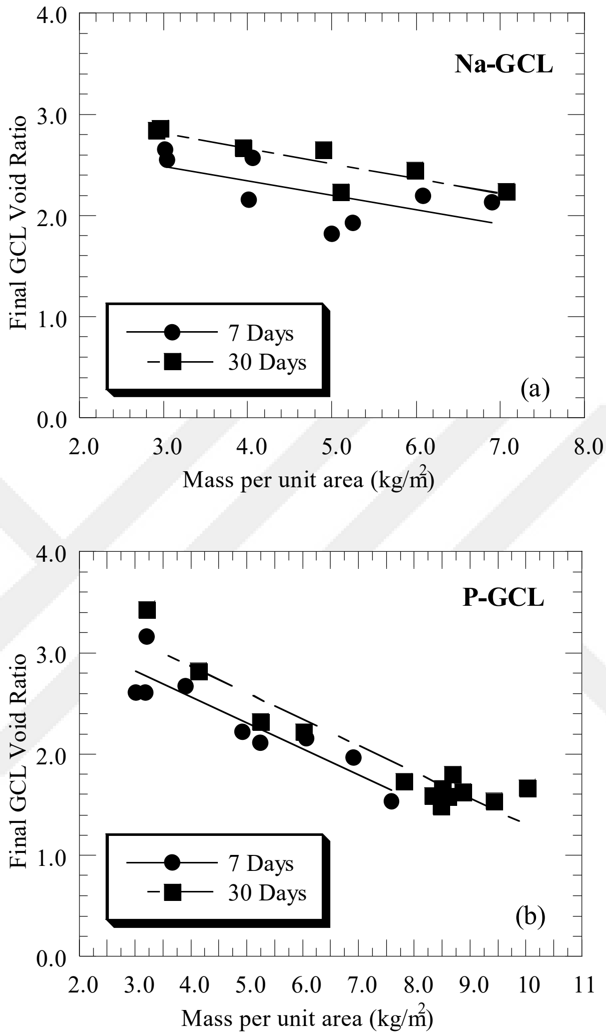


Figure 3.8 Change of final GCL void ratio after hydration as a function of mass per unit area (MPUA): a) Na-GCL, b) P-GCL

Figure 3.8a-b shows that the final GCL void ratio decreased as the MPUA of the GCL increased. The measured final GCL heights are also consistent with the calculated final void ratios. That is, similar to final GCL height, final GCL void ratios were lower for 7 days of hydration than for 30 days of hydration. Moreover, it is obvious that the lower the final GCL height, the higher is the final GCL void ratio.

Change in GCL void ratio as a function of MPUA is in the same decreasing trend with change in water content depending on MPUA for both GCL types. Increase in the water content resulted in higher void ratio and vice versa.

3.4 Conclusion

The hydration performance of two types of GCLs (i.e. Na-GCL and P-GCL) depending on the MPUA was investigated and discussed herein for two hydration durations.

The water contents of both GCL types increased as the hydration duration increased. However, this increment was rapid in the first 7 days of hydration. In addition, at any MPUA, the higher final water contents were obtained for both GCLs subjected to 30 days of hydration than GCLs subjected to 7 days of hydration. In contrast, higher MPUA was needed for the 30 days of hydration to reach the same water content as with the 7 days of hydration.

Regardless of GCL type, initial GCL heights linearly increased as the MPUA increased. Since it is polymer treated, remarkable changes in GCL heights were obtained for P-GCLs with respect to Na-GCLs for both hydration durations. There was significant difference between the height of P-GCL when hydrated for 7 days and 30 days. In the case of Na-GCL, GCL height negligibly increased from 7 days to 30 days of hydration.

The final water contents of the two types of GCLs were in close relationship with their final GCL heights and final GCL void ratios. Increasing the MPUA means stacking of more bentonite particles inside of the GCL, resulting higher GCL final height and therefore, lower final void ratio.

CHAPTER FOUR
HYDRAULIC CONDUCTIVITY OF GEOSYNTHETIC CLAY LINERS DEPENDING ON THE MASS PER UNIT AREA

4.1 Background

Geosynthetic Clay Liners (GCLs) are composite materials which provide barrier performance in landfills. The effectiveness of GCLs as a barrier are governed by hydraulic conductivity of GCLs. Therefore, it is critical to determine hydraulic conductivity of GCLs.

Hydraulic conductivity is controlled by bentonite in GCL. Bentonite allows GCL to have low permeability (2×10^{-11} m/s). Bentonite particles adsorb water and this causes an increase in the thickness of diffuse double layer when in contact with water. Then, pore spaces between bentonite particles reduces, resulting in low hydraulic conductivity. This mechanism is influenced by many factors. These are bentonite type in GCL, bentonite mineralogy, cation exchange capacity, etc.

Besides, hydraulic conductivity is affected from physical factors. For example, when GCL is installed on compacted subsoil in the field, it starts absorbing water from the underlying soil. As a result, water content of GCL increases. This results in low hydraulic conductivity as well. This phenomenon has been investigated in many studies (Bouazza et al., 2017; Bradshaw et al., 2012; Meer & Benson, 2007; Özdamar Kul & Ören, 2018; Rowe & Abdelatty, 2012).

On the other hand, there are a few studies in the literature that investigate the influence of mass per unit area (MPUA) on the hydraulic conductivity of GCLs. Salemi et al. (2018) reported a decrease in the hydraulic conductivity when MPUA was increased. However, the range of MPUA considered in their study was limited (i.e. 4.0-6.0 kg/m^2).

There is still scarce knowledge about how MPUA affects hydraulic conductivity of GCL. Thus, the aim of the study is to put forward research programme by carrying out hydraulic conductivity tests on GCLs having wide range of MPUAs (3.0-10 kg/m^2). This chapter deals with only hydraulic conductivities of GCLs.

4.2 Influence of Mass per Unit Area on Hydraulic Conductivities of GCLs

4.2.1 Na-GCL

Hydraulic conductivity behavior of Na-GCLs are evaluated in terms of pore volume of flow (PVF) to compare the hydraulic performances of GCLs in different MPUAs. Hydraulic conductivities of Na-GCLs prehydrated for 7 days are shown in Figure 4.1a-e. Na-GCLs with MPUAs of 3.0, 4.0 and 5.2 kg/m^2 had high hydraulic conductivities (i.e. 1.4×10^{-6} m/s) throughout the test duration (Figure 4.1a-c). These tests continued more than one day to check whether further hydration would change the hydraulic conductivity. Thus, the outlet valve was closed at the end of the day and GCLs were subjected to hydration in the permeameter cell during overnight. When flow was initiated on the next day, a sudden decrease was observed in the hydraulic conductivity. This reduction is possibly due to overnight hydration of GCL. After a while, hydraulic conductivities increased with time and reached the same values as measured previously.

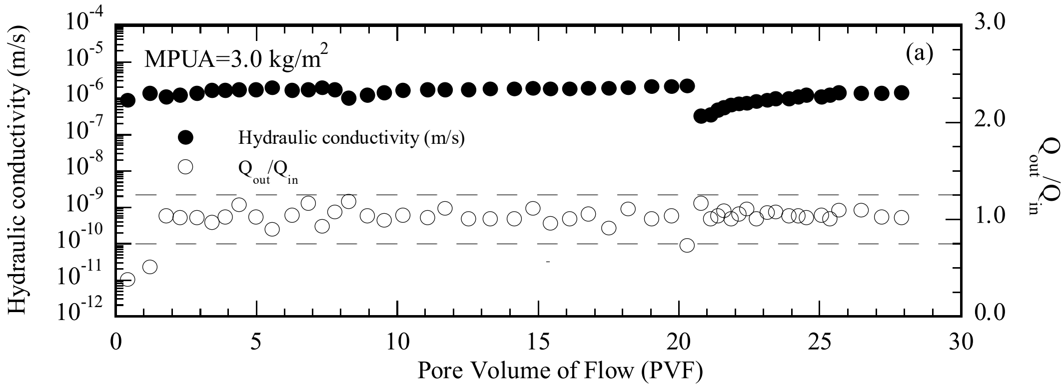


Figure 4.1 Hydraulic conductivities of Na-GCLs after 7 days of hydration: a) MPUA=3.0 kg/m^2, b) MPUA=4.0 kg/m^2, c) MPUA=5.2 kg/m^2, d) MPUA=6.1 kg/m^2, e) MPUA=6.90 kg/m^2

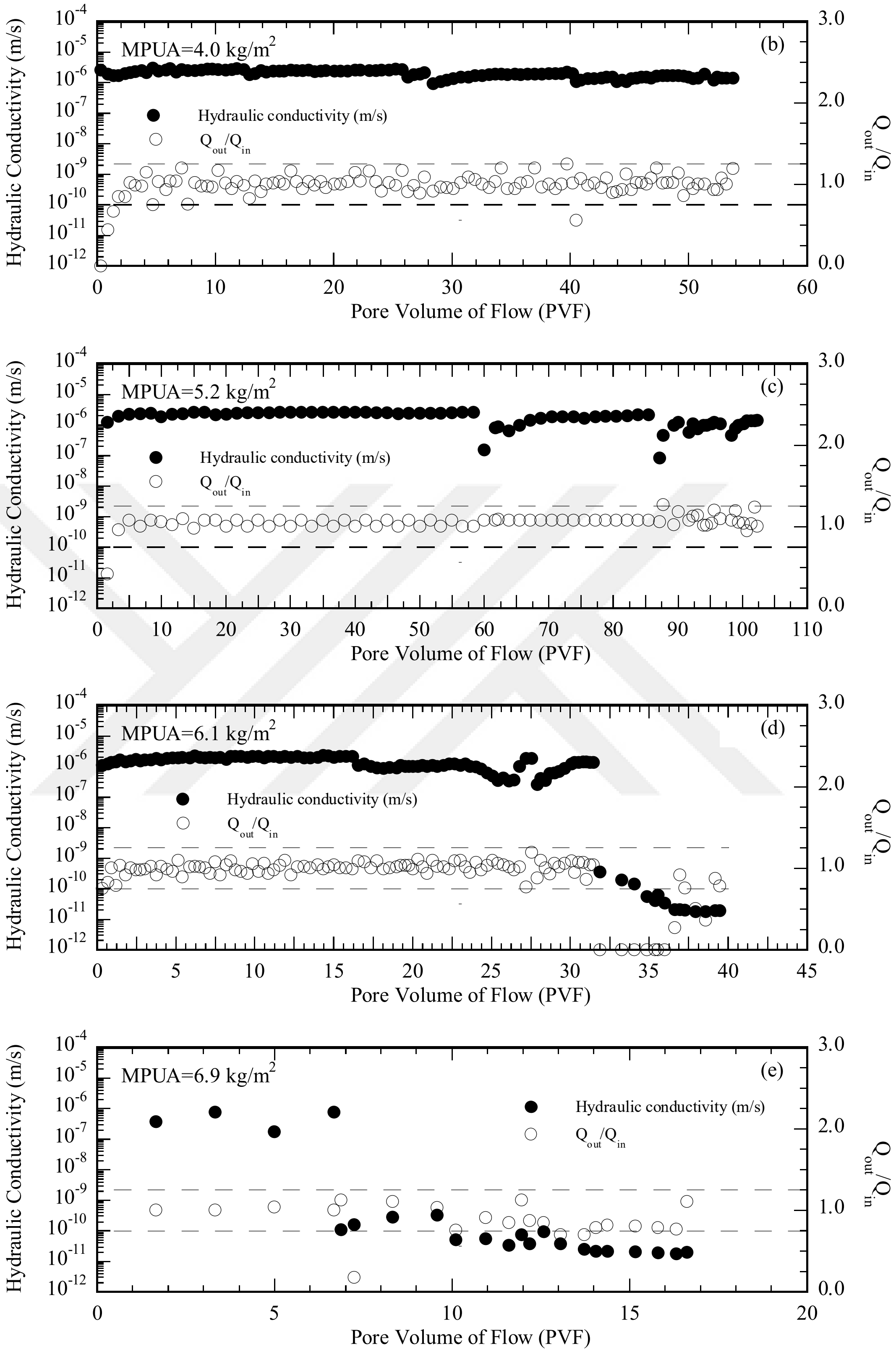


Figure 4.1 continues

In the case of GCL with MPUA of 6.1 and 6.9 kg/m^2, the initial hydraulic conductivities were obtained as 1.1×10^{-6} m/s and 3.8×10^{-7} m/s, respectively (Figure 4.1d-e). Hydraulic conductivities did not change significantly until the end of the day. Then, these GCLs were allowed hydration during overnight and the hydraulic conductivity tests were initiated in the next day again. At this time, the flow was slow where the hydraulic conductivities were measured as ~2.3×10^{-10} m/s. These tests lasted for 4 months and the final hydraulic conductivities were recorded as ~2.0×10^{-11} m/s for both GCLs (Figure 4.1d-e).

Hydraulic conductivities of Na-GCLs prehydrated for 30 days are interpreted in terms of PVF as shown in Figure 4.2a-e. Hydraulic conductivity behavior of 30 days hydrated GCLs were similar with the GCLs hydrated for 7 days.

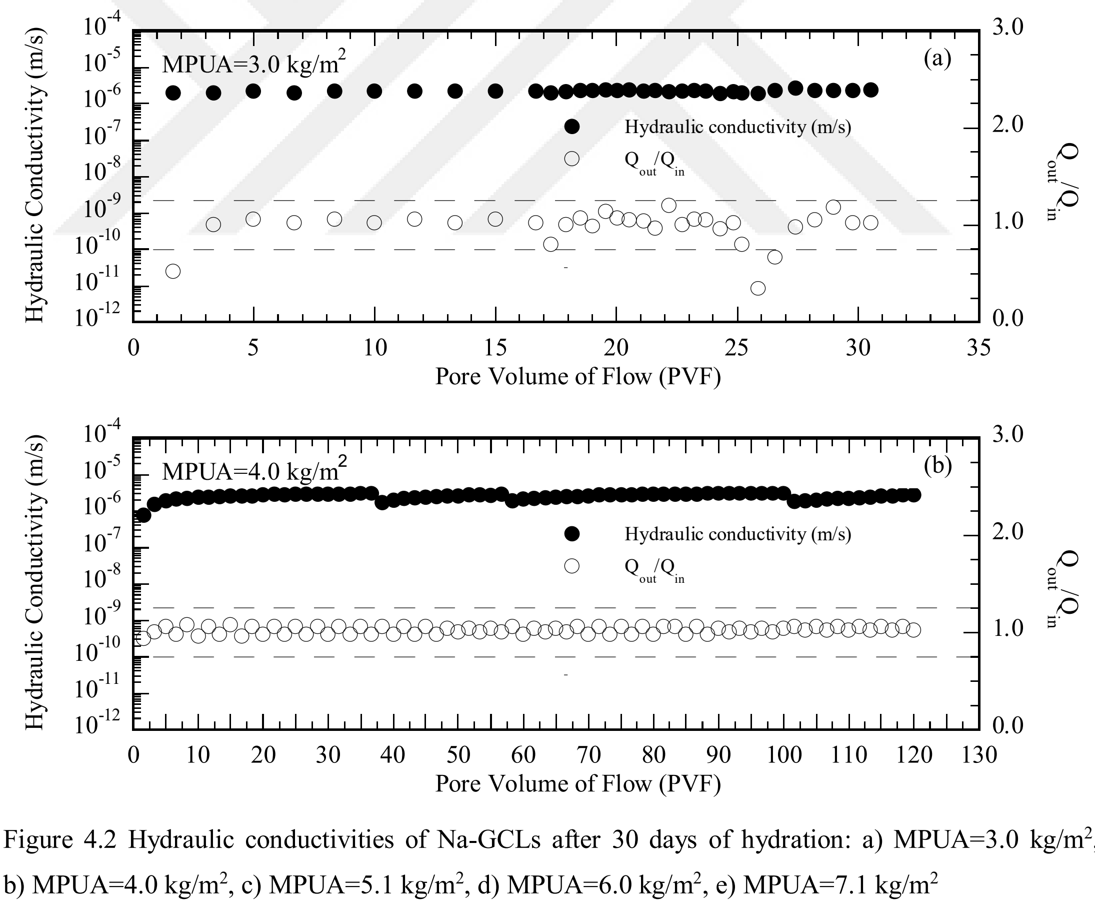


Figure 4.2 Hydraulic conductivities of Na-GCLs after 30 days of hydration: a) MPUA=3.0 kg/m^2, b) MPUA=4.0 kg/m^2, c) MPUA=5.1 kg/m^2, d) MPUA=6.0 kg/m^2, e) MPUA=7.1 kg/m^2

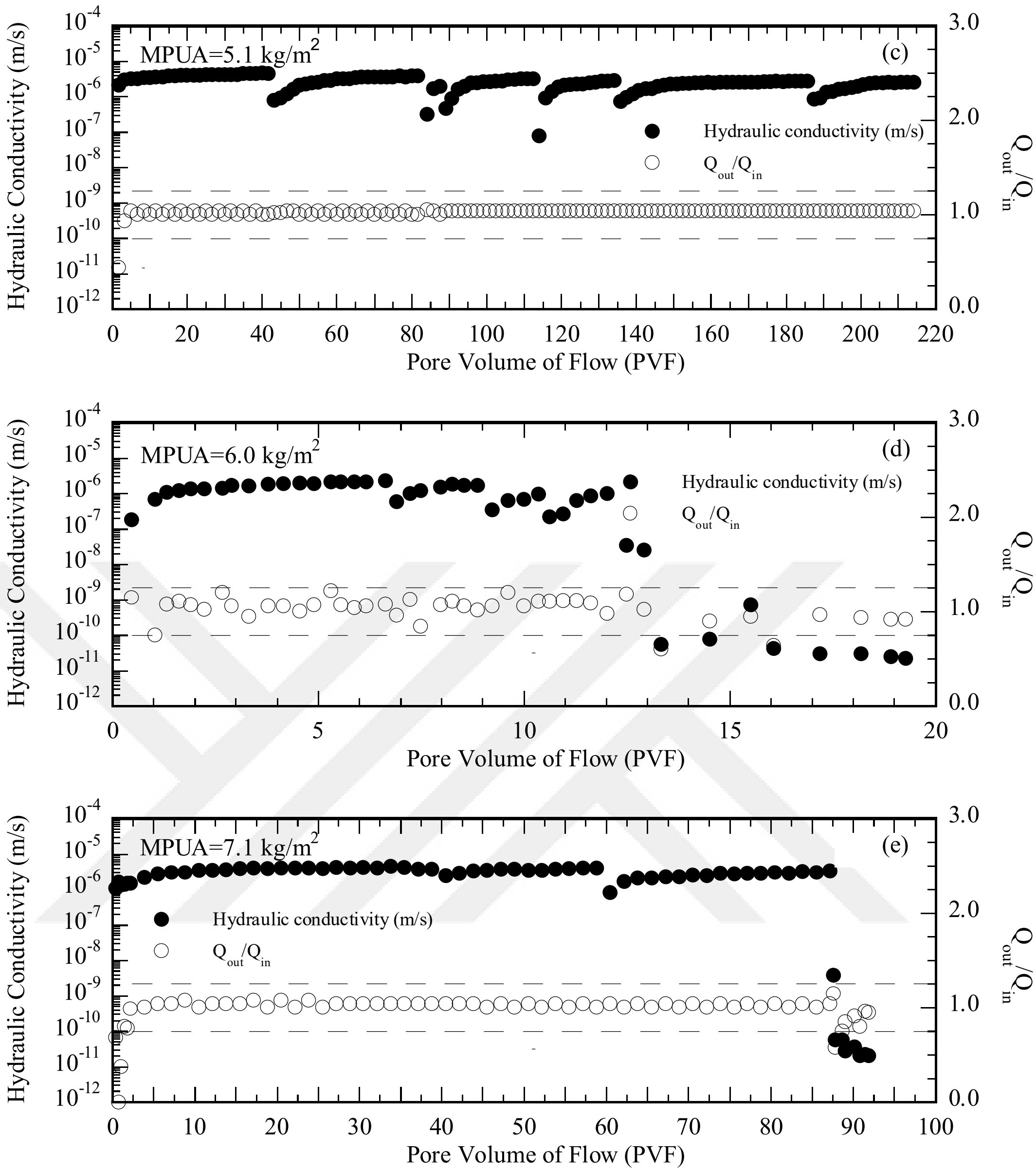


Figure 4.2 continues

The hydraulic behavior of Na-GCLs can be discussed regarding to the initial and final hydraulic conductivities and depending on the MPUA. Regardless of hydration duration, the initial hydraulic conductivities of Na-GCLs prepared with MPUA of 3.0, 4.0 and 5.0 kg/m^2 were around 2.0×10^{-6} m/s (Figure 4.1a-c and 4.2a-c). This hydraulic conductivity value did not change significantly throughout the test duration. The initial hydraulic conductivities were also high for the Na-GCL prepared with MPUA of 6.0 and 7.0 kg/m^2. The difference is that the final hydraulic conductivities decreased to

$\sim 2.0\times10^{-11}$ m/s. This considerable reduction in the hydraulic conductivity is due to hydration of bentonites during permeation stage.

Na-GCLs were subjected to additional hydration stage during permeation. For this purpose, the samples were left overnight for hydration many times and hydraulic conductivities were measured once more. The cumulative hydration durations applied during permeation stage is shown in Figure 4.3a-b. Regardless of hydration duration (for 7 and 30 days), the cumulative hydration durations applied on Na-GCLs prepared with MPUA less than 5.0 kg/m^2 (MPUA $\leq$ 5.0 kg/m^2) were up to 37 days during permeation stage. Even 37 days of hydration, the hydraulic conductivity was still around $\sim 2.0\times10^{-6}$ m/s.

Except Na-GCL prepared with MPUA of 7.1 kg/m^2 which were hydrated over subsoil for 30 days, the cumulative hydration durations applied during permeation stage were less than one day when Na-GCL was prepared with MPUA of 6.0 and 7.0 kg/m^2 (Figure 4.3a-b). This is because, the hydraulic conductivities for these GCLs decreased to $\sim 2.0\times10^{-11}$ m/s in a short time period. However, the cumulative hydration duration was 4 days for Na-GCL prepared with MPUA of 7.1 kg/m^2 which were hydrated for 30 days over subsoil. Generally, it can be said that the required cumulative hydration duration to reduce the hydraulic conductivity decreases as the MPUA increases and this tendency does not depend on the hydration duration applied using a subsoil.

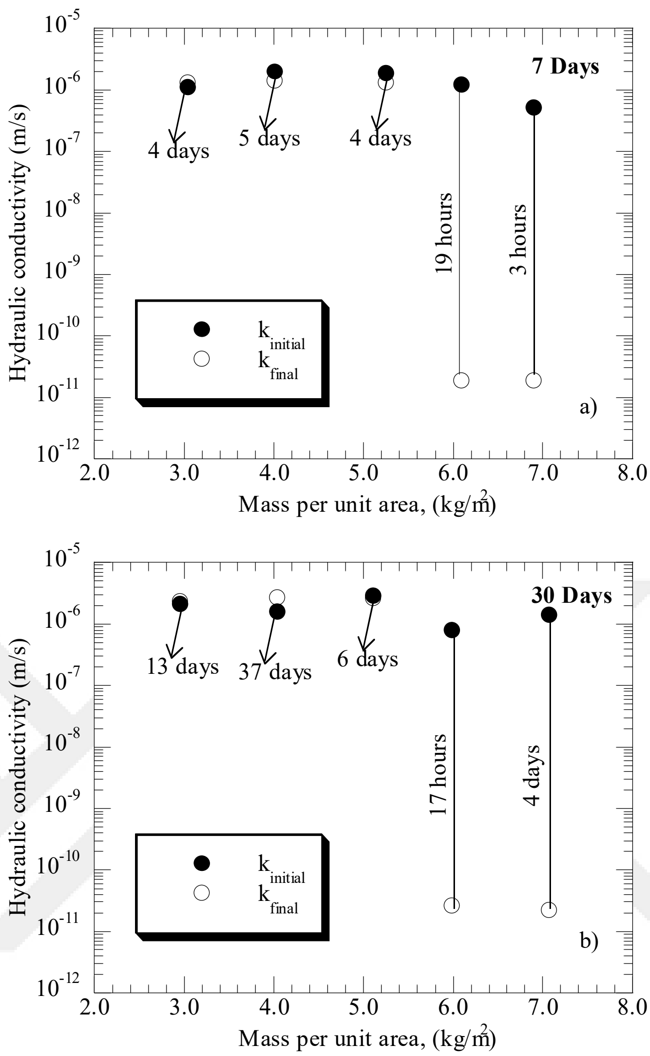


Figure 4.3 Hydration duration applied during permeation stage in the hydraulic conductivity tests for Na-GCL subjected to subsoil hydration: a) 7 days and b) 30 days

4.2.2 P-GCL

Hydraulic conductivity of P-GCLs prehydrated for 7 days are interpreted as a function of PVF and shown in Figure 4.4a-h. Hydraulic conductivity test was replicated on P-GCL prepared with MPUA of 3.2 kg/m^2 (Test 1 and Test 2). Two distinct hydraulic conductivity behaviors were observed for these P-GCLs (Figure 4.4a-b). The hydraulic conductivity is quite high (2.6×10^{-6} m/s) in the first test (Test 1). Outlet valve was closed at the end of the day and this P-GCL were left hydration for cumulative of 17 days. Once the flow was initiated, no reduction in the hydraulic conductivity was observed during permeation. In contrast, low hydraulic conductivity was measured for P-GCL in Test 2 (1.1×10^{-11} m/s) which was not hydrated during permeation. It means the hydraulic conductivity was even low at the beginning of the permeation. The considerable difference between the hydraulic conductivities of these GCLs (MPUA of 3.2 kg/m^2) may be possibly due to uneven distribution of bentonites in GCLs. This means that the MPUA of GCLs may change depending on the efficiency of rolling method. The MPUA may be locally different in GCL. It is accepted herein that the MPUA of GCL cut for the hydraulic conductivity test (i.e. 100 mm) is the same as with the MPUA of GCL prepared for the hydration (i.e. 150 mm).

Initial hydraulic conductivity of P-GCL prepared with MPUA of 3.9 kg/m^2 were roughly 5.7×10^{-7} m/s (Figure 4.4c). Between 58 to 68 PVF, this P-GCL was hydrated for 15 hours during permeation (not cumulative, applied once), resulting in a gradual decrease in the hydraulic conductivity until 1.5×10^{-11} m/s (Figure 4.4c). Then, P-GCL preserved its low hydraulic conductivity until now. This test has not been terminated yet.

For the GCLs prepared with MPUA more than 4.0 kg/m^2 (MPUA $\geq$ 4.0 kg/m^2), lower hydraulic conductivities were obtained from the beginning until the end of the test (no hydration was applied during permeation). Initial hydraulic conductivity of P-GCL prepared with MPUA of 4.9 kg/m^2 was measured as 3.5×10^{-11} m/s (Figure 4.4d). Then, hydraulic conductivity reduced 4.7 times and reached to 7.4×10^{-12} m/s after 5.0 PVF. Another P-GCL prepared at similar MPUA (5.2 kg/m^2) had an initial hydraulic conductivity of 5.5×10^{-11} m/s. Then, the hydraulic conductivity decreased to 1.6×10^{-11} m/s at 5.0 PVF (Figure 4.4e).

P-GCLs prepared with MPUA of 6.0, 7.0, 7.60 kg/m^2 preserved their low hydraulic conductivity from beginning to the end of the test (Figure 4.4f-h). Since hydraulic conductivities are low, the PVF obtained so far is less than 8 and the final hydraulic conductivities for these GCLs were ~1.3×10^{-11} m/s.

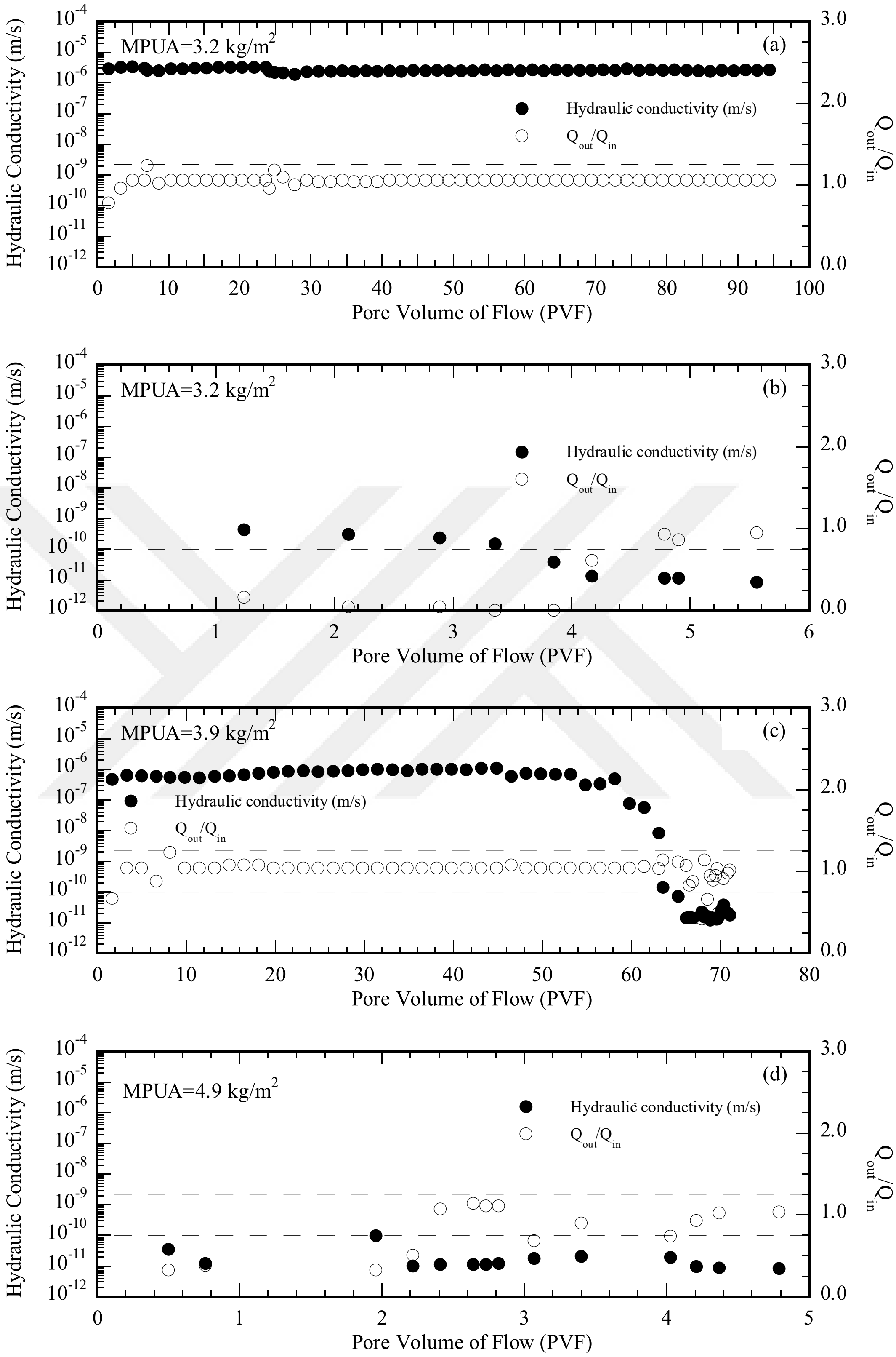


Figure 4.4 Hydraulic conductivities of P-GCLs after 7 days of hydration: a) MPUA=3.2 kg/m^2, b) MPUA=3.2 kg/m^2, c) MPUA=3.9 kg/m^2, d) MPUA=4.9 kg/m^2, e) MPUA=5.2 kg/m^2, f) MPUA=6.1 kg/m^2, g) MPUA=7.0 kg/m^2 and h) MPUA=7.6 kg/m^2

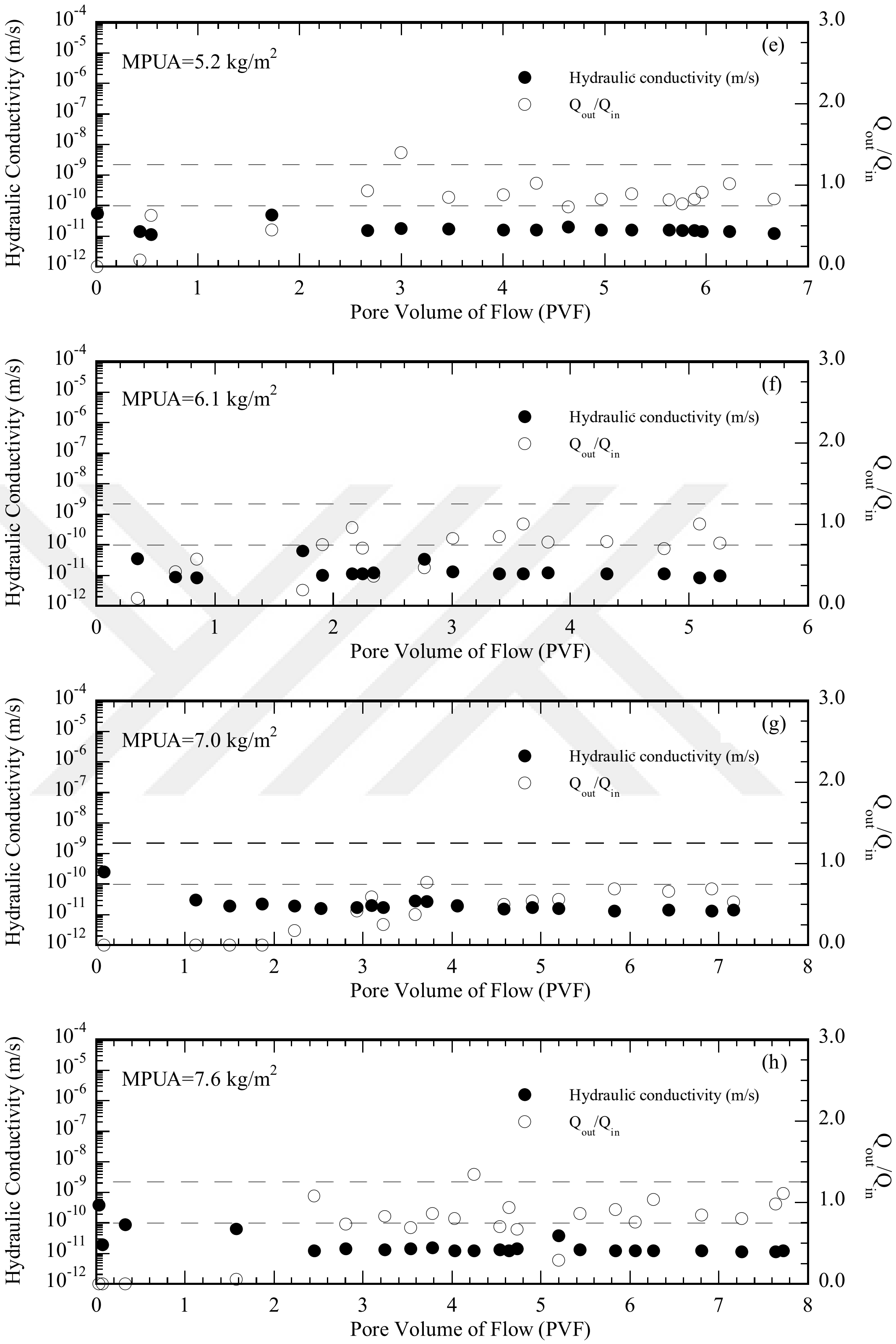
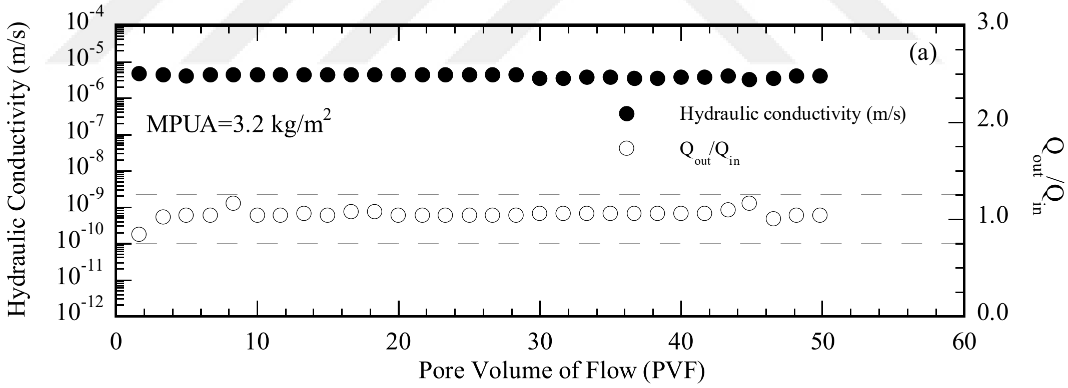


Figure 4.4 continues

The hydraulic conductivities of P-GCLs hydrated for 30 days over compacted subsoil are shown in Figure 4.5a-d. Similar to P-GCLs hydrated for 7 days, GCLs with MPUAs of 3.2 and 4.1 kg/m^2 had high hydraulic conductivity at the beginning of the tests (Figure 4.5a-b). These GCLs were subjected to hydration during permeation for 15 and 6 days, respectively. Note that these hydration durations are cumulative of individual hydration duration applied throughout the testing. With the applied hydrations, the hydraulic conductivity of P-GCL with MPUA of 3.2 kg/m^2 did not change (3.6×10^{-6} m/s), whereas P-GCL with MPUA of 4.1 kg/m^2 reduced to 2.5×10^{-11} m/s throughout the test duration.

In the case of P-GCLs prepared with MPUA of 5.2 and 6.0 kg/m^2, hydraulic conductivity of P-GCLs were stable from the beginning until the end of the test (Figure 4.5c-d). The final hydraulic conductivity of both GCLs was measured as 1.2×10^{-11} m/s. It should be noted that no hydration was applied during the permeation stage for these GCLs.



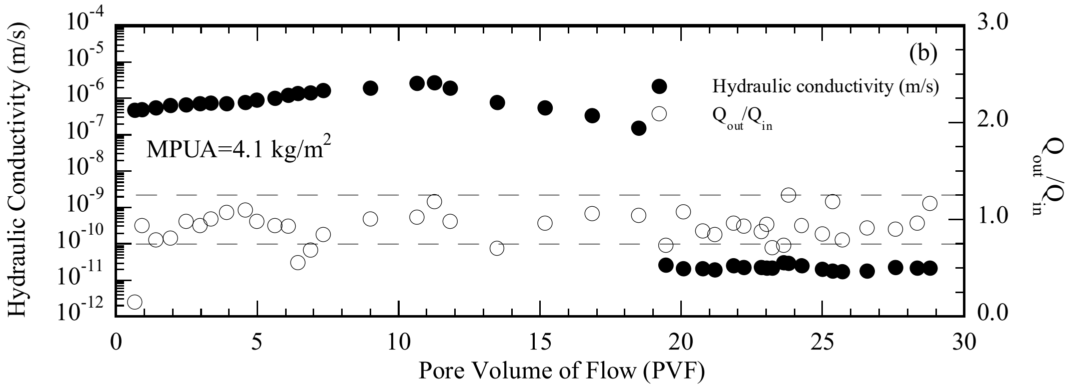


Figure 4.5 Hydraulic conductivities of P-GCLs after 30 days of hydration: a) MPUA=3.2 kg/m^2, b) MPUA=4.1 kg/m^2, c) MPUA=5.2 kg/m^2 and d) MPUA=6.0 kg/m^2

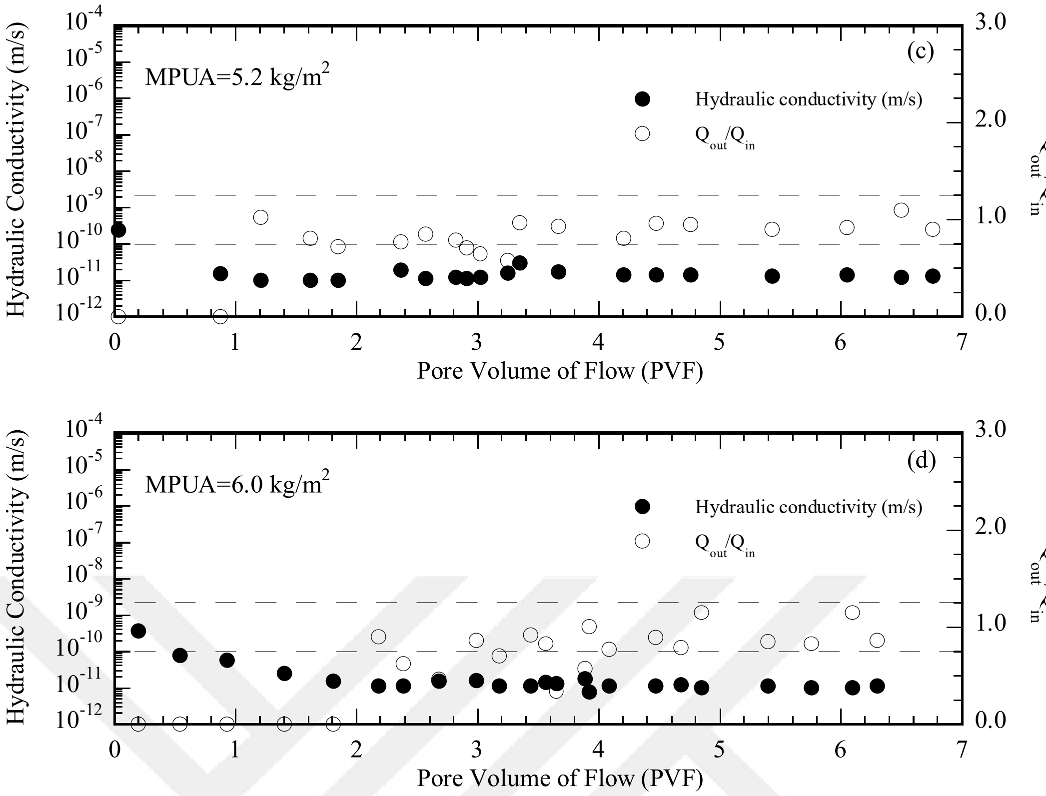


Figure 4.5 continues

4.3 Comparison of Hydraulic Conductivity Test Results in Terms of GCL Type

To investigate the effect of GCL type on the hydraulic conductivity, the final hydraulic conductivities are interpreted as a function of MPUA (Figure 4.6a-b). Regardless of hydration duration, the final hydraulic conductivities of Na- and P-GCLs prepared with 3.0 kg/m^2 are roughly the same (1.7×10^{-6} m/s) (the hydraulic conductivity of P-GCL obtained from Test 2 is ignored). Therefore, it can be said that GCL type had no effect on the hydraulic conductivity of GCLs at lower MPUA (i.e. 3.0 kg/m^2).

The hydraulic conductivity is about five orders of magnitude less for P-GCL than for Na-GCL between MPUA of 3.2 and 6.0 kg/m^2 (i.e. 3.2 kg/m^2 <MPUA<6.0 kg/m^2). In this MPUA range, the hydraulic conductivities of Na-GCL and P-GCL are 1.3×10^{-6} m/s and 1.1×10^{-11} m/s, respectively (Figure 4.6a-b). It shows that the use of polymer treated bentonite in GCL has a significant role in terms of decreasing the hydraulic conductivity within this MPUA range.

When MPUA was further increased (MPUA ≥ 6.0 kg/m^2), however, GCL type had no effect on the hydraulic conductivity. It shows that the hydraulic conductivity of Na-GCL approached to that of P-GCL (Figure 4.6a-b).

As an overall behavior, GCL type has a considerable effect on the hydraulic conductivity of GCL when MPUA ranged between 3.2 and 6.0 kg/m^2. This also indicates the role (or efficiency) of using polymer treated bentonite in GCL. This study also showed that if GCL contains less or conversely more bentonite, the hydraulic performance becomes independent of GCL type.

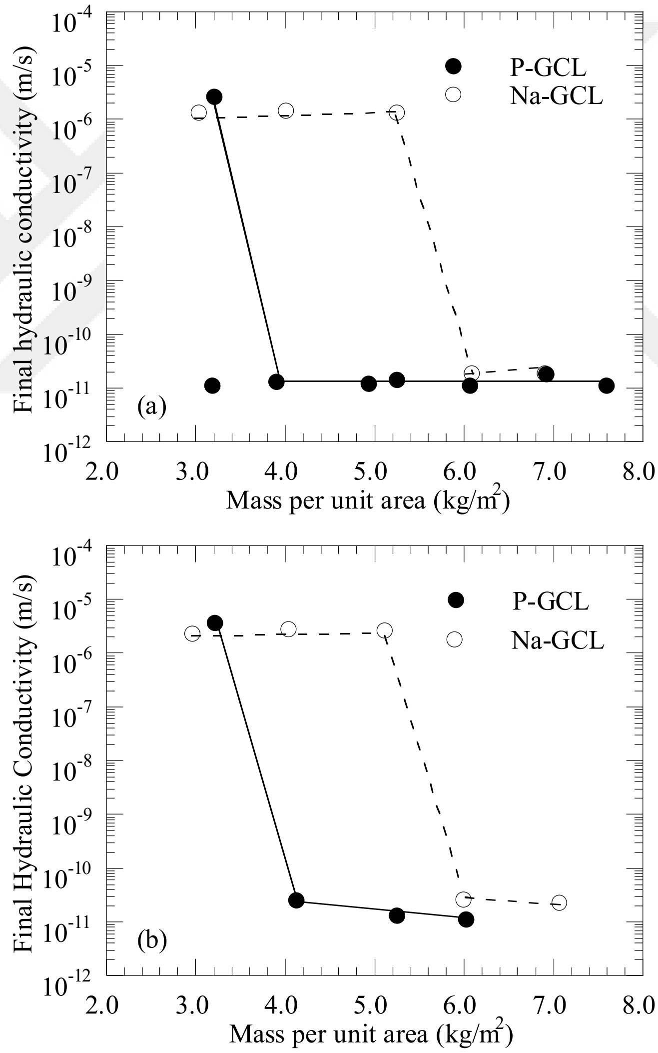


Figure 4.6 Change in the final hydraulic conductivity of GCLs as a function of mass per unit area: a) 7 days of hydration b) 30 days of hydration

4.4 Influence of Hydration Duration on Hydraulic Conductivity

The effect of MPUA on the hydraulic conductivities of GCLs are evaluated in terms of hydration durations in Figure 4.7a-b. For Na-GCLs hydrated for 7 days, the final hydraulic conductivities are similar with Na-GCLs hydrated for 30 days at each MPUA. As for P-GCLs, the final hydraulic conductivities subjected to both hydration durations were roughly the same.

Unlike GCL type and MPUA, prehydrating the GCLs over compacted silty sand had no considerable effect on the final hydraulic conductivities of both GCLs. It means that the hydraulic conductivities of GCLs subjected to 7 and 30 days of hydration had more or less the same hydraulic conductivity.

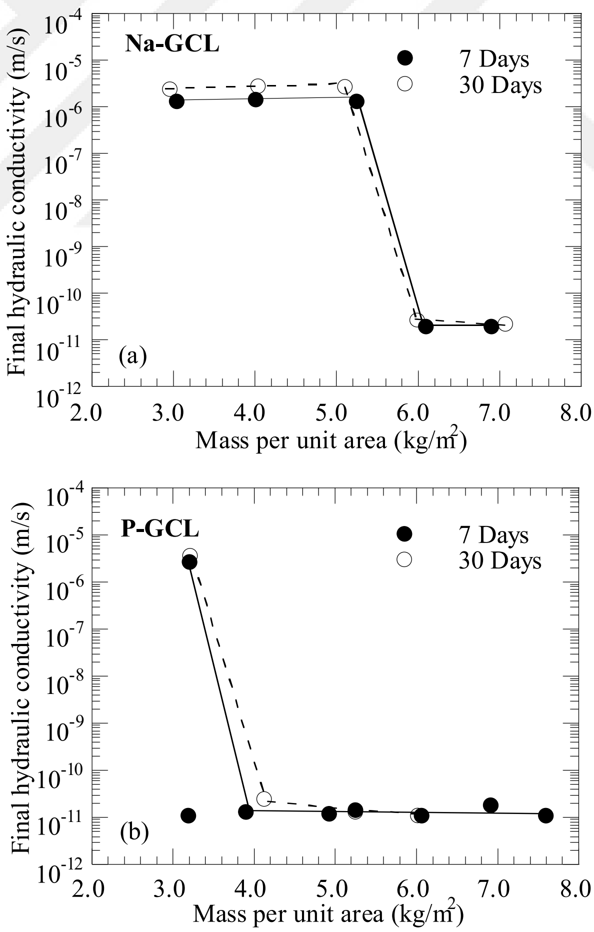


Figure 4.7 Change in final hydraulic conductivities of GCLs as a function of mass per unit area: a) Na-GCL, and b) P-GCL

4.5 Discussion

The hydraulic conductivity tests were carried out with an average of hydraulic gradient of 110. This hydraulic gradient level can be accepted as rather high. Under such kind of hydraulic gradients, seepage forces can be important. Thus, seepage forces acting on the GCLs were high during the permeation phase in this study. This facilitated bentonite erosion from the GCLs at lower MPUAs. The evidence of bentonite erosion was observed in the graduated cylinders which were connected to the outflow lines of permeameters. The appearance of outflow water was cloudy (or blurred) at MPUA of 3.0 kg/m^2 (Figure 4.8a-b). Even though the outflow water was not clear at greater MPUAs, the appearance of them were lighter than those of MPUA of 3.0 kg/m^2. Therefore, the testing conditions applied during the hydraulic conductivity tests (i.e. hydraulic gradient and effective stress) play a significant role when the hydraulic conductivity is measured as a function of MPUA.

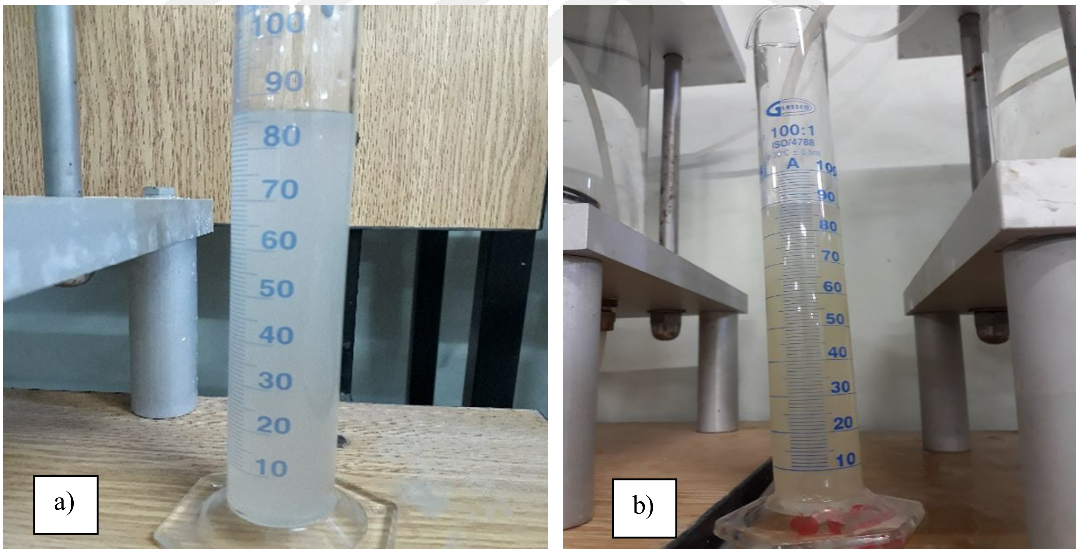


Figure 4.8 Evidence of bentonite erosion during hydraulic conductivity tests: a) Na-GCL, and b) P-GCL (Personal archive, 2019)

Rhodamine tracer dye test was performed on Na-GCL prepared with 3.0 kg/m^2 and hydrated for 30 days to visualize the flow path across the GCL. To do this, Rhodamine was added to deionized water in burette. Then, test was ended as soon as colored liquid passed from the GCL and dropped into the graduated cylinder. At the end of the test, it was seen that there was a colored region on the GCL where preferential flow occurred (Figure 4.9a-b). When fibers that connect non-woven and woven geotextiles were cut, bundle of fibers was seen of which was colored with pink (Figure 4.9c). It is interesting to note that the appearance of bentonite was perfect by means of swollen particles and distributed well in GCL. There was no visible eroded parts on GCL. However, as can be seen in Figure 4.9d-e, a hole existed on GCL which was caused by the bundle of fibers. This may be occurred during needle-punching process. Although bentonite particles swollen during hydration and permeation phases, they were unable to penetrate into the bundle. Thus, the hole was not closed along the test duration, resulting in greater hydraulic conductivity.

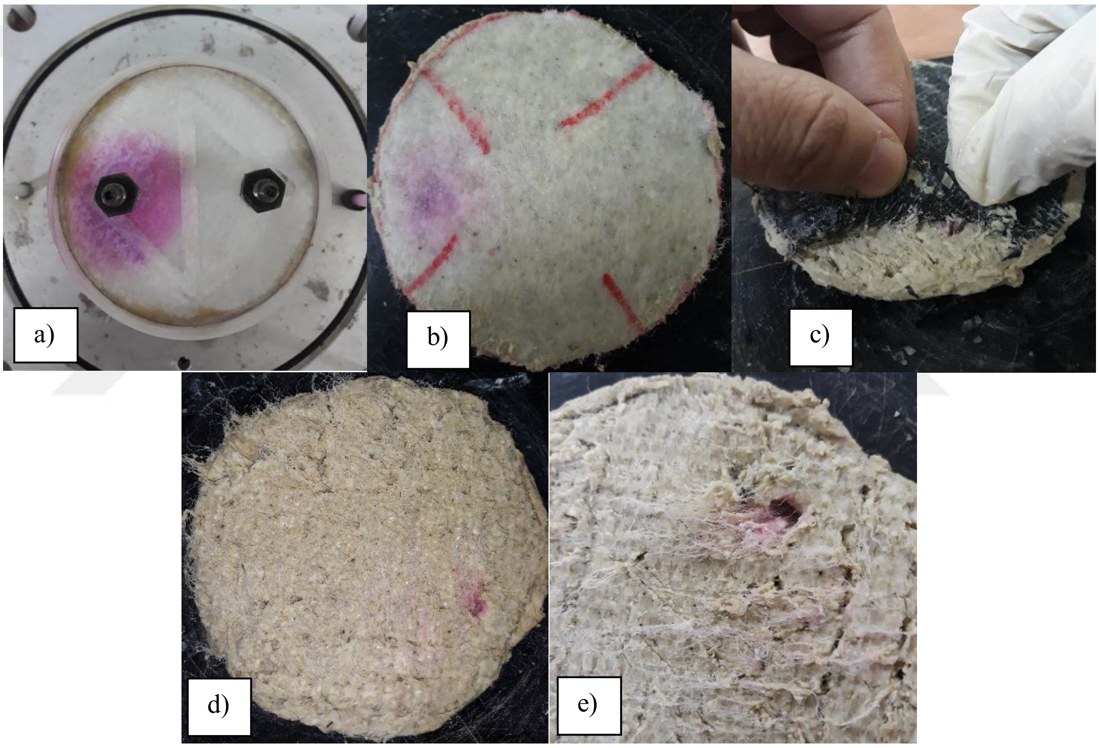


Figure 4.9 Photographs after Rhodamin-B tracer dye test: a) General view of GCL in permeameter cell, b) trace showing preferential flow path, c) view of intense bundle of fibers resulting fast flow, d) color change on bentonite, and e) gap caused by bundle of fibers (Personal archive, 2019)

4.6 Conclusion

The hydraulic conductivities of two GCLs (i.e. Na-GCL and P-GCL) hydrated over compacted subsoil for 7 and 30 days were investigated and discussed as a function of MPUA in this chapter.

The MPUA was accepted as “unchanged” herein when hydrated GCL was cut for the hydraulic conductivity tests. Especially at low MPUAs, the efficiency of rolling method applied during sample preparation is questionable. Because, the movement of particles from center to edge of GCL is resisted by the needle-punched fibers which may result in locally uneven distribution of bentonite in GCL. To check the efficiency of applied methodology for the sample preparation, a new test program has been started which also evaluates the water holding capacity of geotextile components of GCL.

Regardless of hydration duration and MPUA, the initial hydraulic conductivities of Na-GCLs were about 1.0×10^{-6} m/s. However, Na-GCLs prepared with MPUA of 6.0 and 7.0 kg/m^2 decreased to 1.0×10^{-11} m/s along the test duration whereas, others (MPUA $\leq$ 5.0 kg/m^2) remained high until the end of the tests.

P-GCLs prepared with 3.0 kg/m^2 exhibited two different hydraulic performances, one of which had higher, while other had lower hydraulic conductivity (1.7×10^{-6} m/s versus 1.1×10^{-11} m/s). This difference may be related to uneven distribution of bentonite particles in GCLs due to applied methodology. If the lowest hydraulic conductivity is ignored, then, it can be said that the hydraulic conductivity became higher only at MPUA of 3.0 kg/m^2 for P-GCL.

GCL type has significant role on the hydraulic conductivity of GCL as well. Similar hydraulic conductivity behaviors were observed for both GCLs at lower and higher MPUAs. Independent of GCL type, the hydraulic conductivity was about 1.3×10^{-6} m/s at MPUA of 3.2 kg/m^2, whereas it was about 1.1×10^{-11} m/s at MPUA $\geq$ 6.0 kg/m^2. Out of this MPUA range, GCL type was being important (3.2 kg/m^2 < MPUA < 6.2 kg/m^2).

GCLs were initially hydrated over compacted subsoils by considering two hydration durations (i.e. 7 and 30 days). Although water contents of GCLs changes depending on the hydration duration, it has no significant effect on the hydraulic conductivity. This conclusion was found similar at all MPUAs.

The reason why hydraulic conductivity was high at MPUA of 3.0 kg/m^2 is possibly because of bundle of fibers existed in either Na- and P-GCLs. Although Rhodamine dye test was applied just on Na-GCL, the visual inspection after hydraulic conductivity test also showed the existence of bundle induced hole on P-GCL.

CHAPTER FIVE
EFFECT OF HYDRAULIC GRADIENT ON THE HYDRAULIC CONDUCTIVITY OF GEOSYNTHETIC CLAY LINERS

5.1 Background

Hydraulic behaviors of GCLs can change depending on the testing conditions. The most significant testing conditions can be summarized as effective stress and hydraulic gradient. Increase in the effective stress led to decrease the inter-particle pore space of bentonite, resulting in lower hydraulic conductivity. This can also be achieved by changing the hydraulic gradient. Decrease in the hydraulic gradient causes a reduction in the seepage forces acting on the GCL, resulting in an increase in the effective stress. On the other hand, bentonite erosion may take place under higher hydraulic gradient which causes formations of open pores or channels across the GCL. This allows increasing the hydraulic conductivity of GCL.

In the field, the maximum hydraulic head over the GCL can be 0.3 m. If the thickness of GCL is accepted to be 5 cm (0.05 m), then the hydraulic gradient can be 60 (0.3/0.05=60). Note that increasing the GCL thickness will decrease the hydraulic gradient. Therefore, it is desirable to conduct hydraulic conductivity tests under the hydraulic gradient that may be encountered in the field.

Hydraulic gradients are applied rather higher at laboratory conditions. There are two reasons, one of which is to simulate the worst-case scenario and the other is to shorten the test duration. There are many studies in literature that investigates the effect of hydraulic gradient and effective stress on the hydraulic conductivity of GCLs (Bradshaw & Benson, 2014; Chen et al., 2018; Shackelford et al., 2000; Wang et al., 2019). In these studies, hydraulic conductivity tests were performed under higher hydraulic gradients and effective stresses. They reported that hydraulic gradient has negligible effect on the hydraulic conductivity of GCLs. Although these studies addressed the effect of hydraulic gradient, MPUA based evaluation of hydraulic conductivity investigating the influence of hydraulic gradient is still limited. This research program was conducted to investigate hydraulic gradient sensitivity of GCLs on different MPUAs.

5.2 Hydraulic Conductivities of GCLs under Elevated Hydraulic Gradients

Hydraulic conductivity tests were conducted under high level of hydraulic gradient in the first set of experiments as reported in Chapter 4. In the second set, the effect of hydraulic gradient on the hydraulic conductivity was investigated initially on Na-GCLs prepared at MPUA of 3.0, 4.0 and 5.0 kg/m^2 and hydrated for both hydration durations (i.e. 7 and 30 days). Hydraulic conductivity of P-GCL under different hydraulic gradient was determined only at MPUA of 3.0 kg/m^2 and hydrated for 7 days. Overall view of hydraulic conductivity tests conducted undder low hydraulic gradient is shown in Figure 5.1.

Figure 5.1 Overall view of the hydraulic conductivity tests under elevated hydraulic gradient (Personal archive, 2019)

5.2.1 Na-GCL

Hydraulic conductivity behaviors of GCLs under elevated hydraulic gradients were assessed in terms of pore volume of flow (PVF) to compare their hydraulic performances under elevated hydraulic gradients. Hydraulic conductivities of Na-GCLs prehydrated for 7 days are shown in Figure 5.2a-c. Initial hydraulic conductivity of GCL with MPUA of 3.0 kg/m^2 was 5.6×10^{-9} m/s (Figure 5.2a). Then, one order of magnitude increase in the hydraulic conductivity of Na-GCL was seen in the second reading and hydraulic conductivity values slightly fluctuated around 5.7×10^{-8} m/s until 2.0 PVF. Decreasing trend in the hydraulic conductivity was observed after 2.0 PVF and hydraulic stability was achieved at 3.5 PVF where the hydraulic conductivity was 2.6×10^{-11} m/s. Although hydraulic gradient was gradually increased to 40, 80 and 160, respectively, no significant change in the hydraulic conductivity occurred throughout the test duration. Final hydraulic conductivity of Na-GCL at MPUA of 3.0 kg/m^2 was reported as 2.4×10^{-11} m/s (Figure 5.2a).

Hydraulic conductivity of Na-GCL prepared with 4.1 kg/m^2 is shown in Figure 5.2b. The initial hydraulic conductivity (9.8×10^{-7} m/s) is higher for this GCL than for the same GCL prepared with MPUA of 3.0 kg/m^2 (5.6×10^{-9} m/s). When flow was continued, hydraulic conductivity decreased. Equilibrium was achieved at 16.5 PVF and hydraulic conductivity was 3.7×10^{-11} m/s when hydraulic gradient was 20. Like Na-GCL with MPUA of 3.0 kg/m^2, no considerable change in the hydraulic conductivity was observed after doubling the hydraulic gradients (40, 80 and 160). The final hydraulic conductivity was obtained as 1.9×10^{-11} m/s at hydraulic gradient of 160 which was about two times less than that obtained under hydraulic gradient of 20 (1.9×10^{-11} m/s vs. 3.7×10^{-11} m/s).

In the case of Na-GCL with MPUA of 5.0 kg/m^2, the initial hydraulic conductivity was lower (2.6×10^{-7} m/s) than the Na-GCLs prepared with MPUA of 3.0 and 4.1 kg/m^2 (Figure 5.2c). There was an increase in the second reading of hydraulic conductivity and then, a decreasing trend was observed throughout the test duration. Hydraulic stability was achieved at 2.2 PVF and the hydraulic conductivity was measured as 3.1×10^{-11} m/s under hydraulic gradient of 20. When applied hydraulic gradients were gradually elevated to 40, 80 and 160, the hydraulic conductivity decreased about two times and the final hydraulic conductivity was obtained as 1.7×10^{-11} m/s.

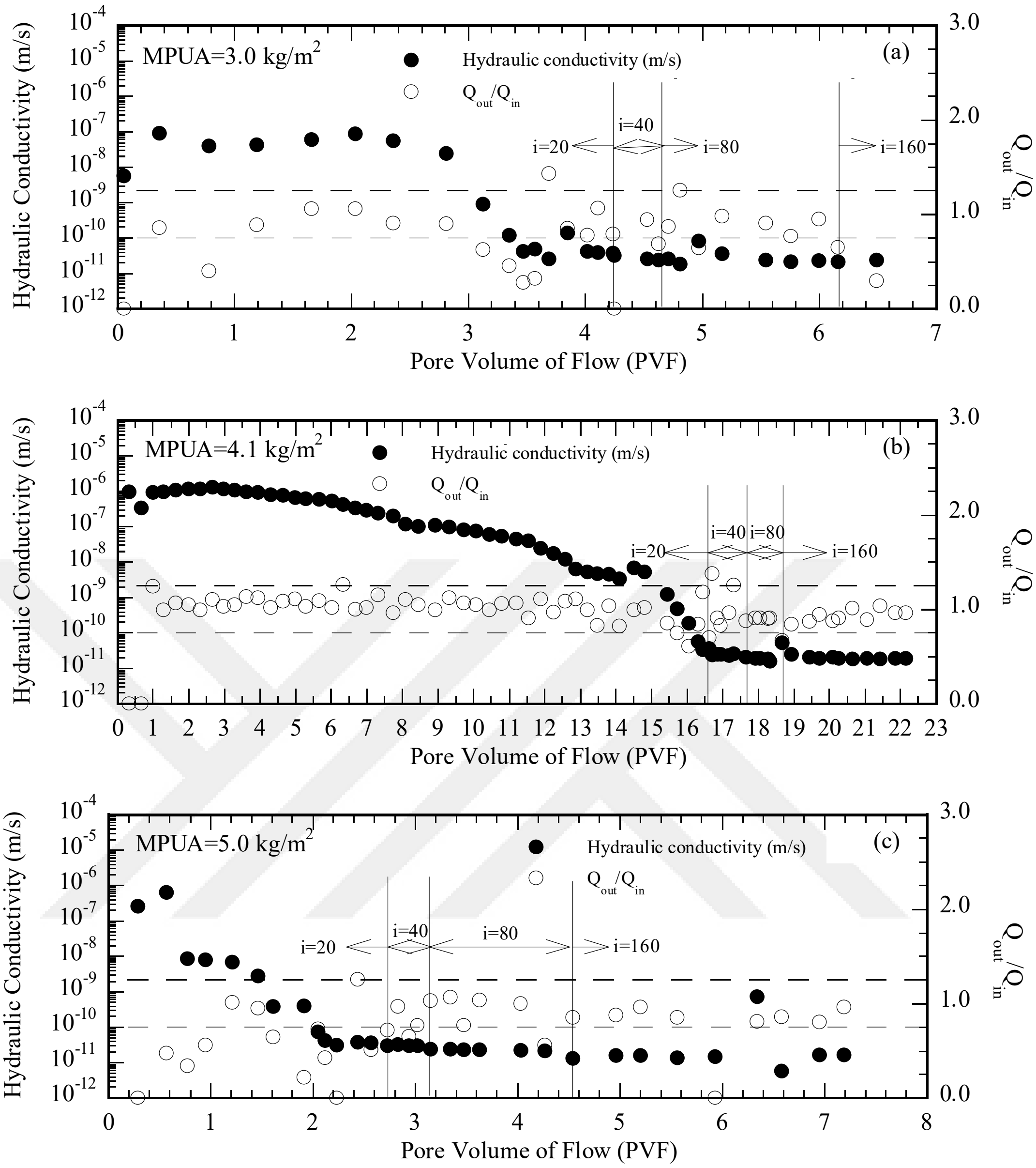


Figure 5.2 Hydraulic conductivities of Na-GCLs hydrated for 7 days at elevated hydraulic gradient: a) MPUA= 3.0 kg/m^2, b) MPUA= 4.1 kg/m^2, c) MPUA= 5.0 kg/m^2

Hydraulic conductivities of Na-GCLs subjected to 30 days of hydration are evaluated in terms of PVF to see the difference between their hydraulic performances under elevated hydraulic gradients and are shown in Figure 5.3a-c. The initial hydraulic conductivity of Na-GCL prepared with MPUA of 2.9 kg/m^2 was 2.1×10^{-7} m/s under hydraulic gradient of 20 (Figure 5.3a). Although flow was continued until 16 PVF, the hydraulic conductivity did not decrease and the final hydraulic conductivity was measured as 3.9×10^{-7} m/s.

In the case of 30 days hydrated Na-GCL with MPUA of 4.0 kg/m^2, the initial hydraulic conductivity was around 1.4×10^{-7} m/s and hydraulic conductivity reduced to 3.5×10^{-11} m/s at 2.4 PVF under hydraulic gradient of 20 (Figure 5.3b). Then, hydraulic gradient was increased to 40, 80 and 160. No considerable change was seen in the hydraulic conductivity of GCL. The final hydraulic conductivity was obtained as 1.8×10^{-11} m/s.

Hydraulic conductivity behavior of Na-GCL prepared with 4.9 kg/m^2 is shown in Figure 5.3c. The initial hydraulic conductivity of GCL was measured as 6.0×10^{-10} m/s. Then, slight reduction in the hydraulic conductivity was observed and it was obtained as 3.3×10^{-11} m/s at 0.9 PVF. The hydraulic conductivity is low at hydraulic gradient of 20. Once the hydraulic gradient was elevated to level of 40, hydraulic conductivity did not change significantly until 1.5 PVF. Then, slight increase in the hydraulic conductivity was observed and it was decreased again. The final hydraulic conductivity was measured as 5.2×10^{-11} m/s. The cumulative PVF is still less than 2 PVF. Therefore, this test has been continued for 3 months under elevated hydraulic gradient and has not been terminated yet. Since increasing the gradient lead to increase the hydraulic conductivity, the gradient will be increased in the future and hydraulic conductivity will be recorded at hydraulic gradients of 80, 160.

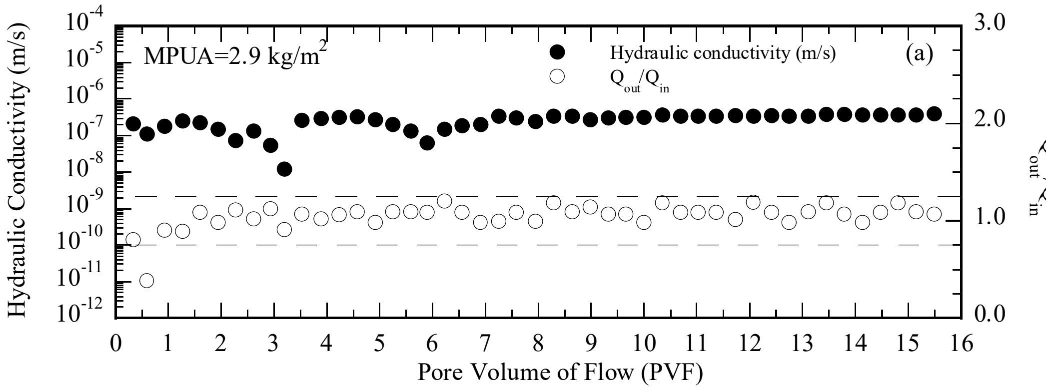


Figure 5.3 Hydraulic conductivities of Na-GCLs hydrated for 30 days at elevated hydraulic gradient: a) MPUA= 2.9 kg/m^2, b) MPUA= 4.0 kg/m^2, c) MPUA= 4.9 kg/m^2

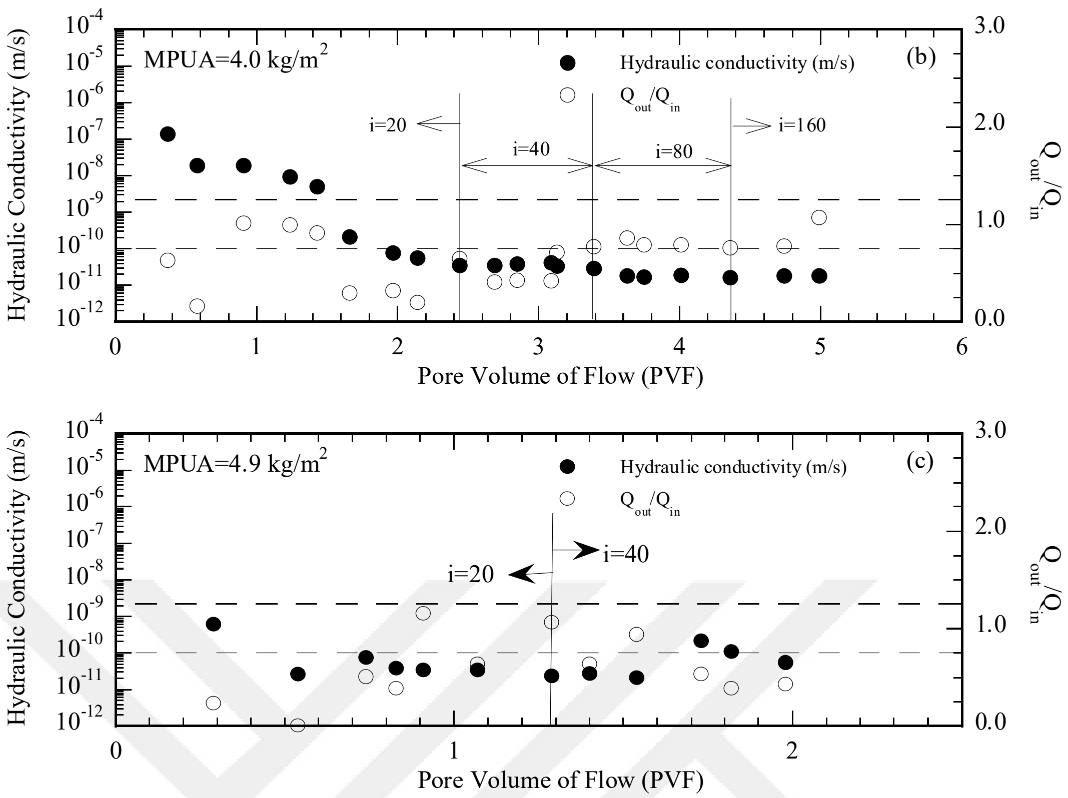


Figure 5.3 continues

5.2.2 P-GCL

The hydraulic conductivity of P-GCL hydrated over subsoil for 7 days was evaluated in terms of PVF to investigate hydraulic performance under elevated hydraulic gradient. However, the test has been started with hydraulic gradient of 20 and has not been terminated yet. Because of time restriction, the hydraulic conductivity readings at i= 80 and 160 could not have been taken. The test is still kept going and the hydraulic conductivities at elevated hydraulic gradients will be recorded in the following period.

Hydraulic conductivity of P-GCL prepared with 3.0 kg/m^2 is shown in Figure 5.4. Once flow was initiated, the initial hydraulic conductivity was as low as 1.3×10^{-10} m/s under hydraulic gradient of 20. Hydraulic stability was achieved at 0.5 PVF and the final hydraulic conductivity was obtained as 7.0×10^{-11} m/s. When hydraulic gradient was increased to 40, the hydraulic conductivity decreased to 7.5×10^{-12} m/s. Note that this value may change until the end of test. Since the hydraulic conductivity of P-GCL with MPUA of 3.0 kg/m^2 hydrated for 7 days was so low, it was not needed to conduct hydraulic conductivity test for the same MPUA hydrated for 30 days.

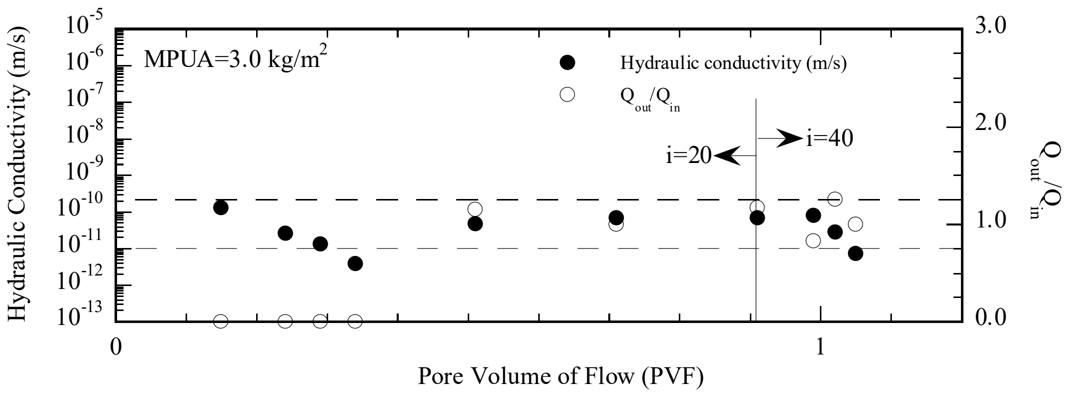


Figure 5.4 Hydraulic conductivity of P-GCL hydrated for 7 days at elevated hydraulic gradient

5.3 Comparison of the Hydraulic Conductivities of GCLs in terms of GCL type

To investigate the effect of GCL type on the hydraulic conductivity, the final hydraulic conductivities were interpreted as a function of hydraulic gradient (Figure 5.5). Since only one hydraulic conductivity test under elevated hydraulic gradient was conducted on P-GCL, comparison of the final hydraulic conductivities was made between Na-GCL and P-GCL prepared with 3.0 kg/m^2 and hydrated for 7 days. Roughly the same final hydraulic conductivities were obtained for both GCLs under hydraulic gradient of 20 (3.5×10^{-11} m/s). Once the hydraulic gradient was increased up to 160, a slight decreasing trend in the hydraulic conductivity was recorded for Na-GCL. There is almost no difference between the hydraulic conductivities of Na- and P-GCLs at i=20. However, the difference between hydraulic conductivities became 3.3 times when the hydraulic gradient was 40. Therefore, it can be said that GCL type had negligible effect on the final hydraulic conductivity of GCL at these gradient levels.

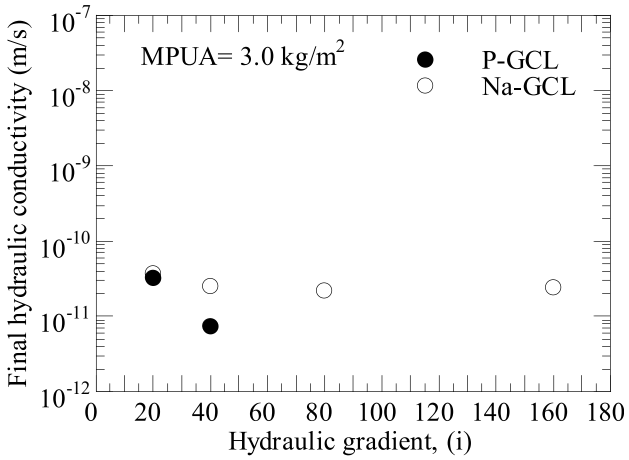


Figure 5.5 Change in the final hydraulic conductivity of GCLs as a function of hydraulic gradient

5.4 Comparison of the Hydraulic Conductivities in terms of Hydration Duration

The influence of hydration duration on the hydraulic conductivities of Na-GCLs are evaluated as a function of MPUA (Figure 5.6). Na-GCLs with MPUA of 4.0 and 5.0 kg/m^2 hydrated over subsoil for both hydration durations (i.e. 7 and 30 days) had roughly the same hydraulic conductivity under elevated hydraulic gradients. Na-GCL prepared with 3.0 kg/m^2 and subjected to 7 days of hydration had low hydraulic conductivity, whereas hydraulic conductivity of GCL with the same MPUA subjected to hydration for 30 days was high (2.4×10^{-11} m/s vs. 3.9×10^{-7} m/s).

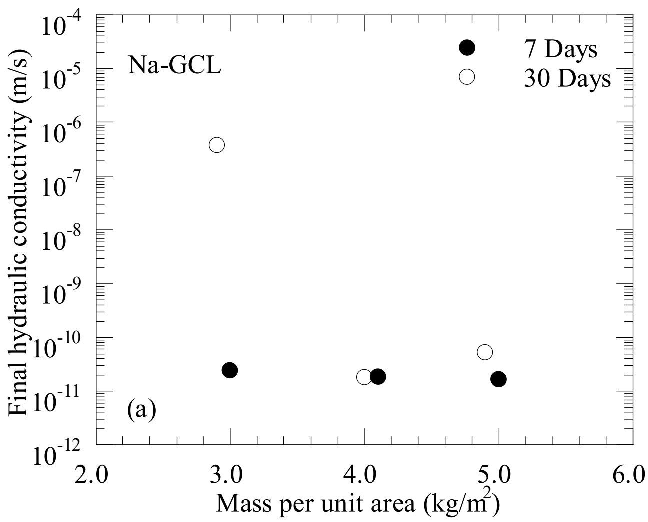


Figure 5.6 Change in the final hydraulic conductivities of Na-GCLs as a function of MPUA

5.5 Discussion

To compare the hydraulic performances of Na-GCLs obtained from two testing conditions (i.e. high hydraulic gradient and elevated hydraulic gradient), the final hydraulic conductivities are evaluated in terms of hydraulic gradient for each MPUA (~3.0, 4.0 and 5.0 kg/m^2). The final hydraulic conductivities of Na-GCLs hydrated for 7 days are shown in Figure 5.7a-c. Test 1 in Figure 5.7 represents the hydraulic conductivity test conducted under high hydraulic gradient (i=85-160) and Test 2 represents the test performed under elevated hydraulic gradients (i=20, 40, 80, 160). Na-GCLs with MPUA of 3.0, 4.0 and 5.0 kg/m^2 had high and roughly the same hydraulic conductivities within each other when the tests were conducted directly under greater hydraulic gradient (i.e. 85-160). However, when the hydraulic gradient was applied as 20 at the beginning of the test, relatively low final hydraulic conductivities were measured at each MPUA. Then, increase in hydraulic gradient (i.e. 40, 80, 160) did not considerably affect the hydraulic conductivity and close hydraulic conductivity values were measured within each hydraulic gradient level. The difference in the hydraulic conductivities for two testing conditions is more than 4 orders of magnitude.

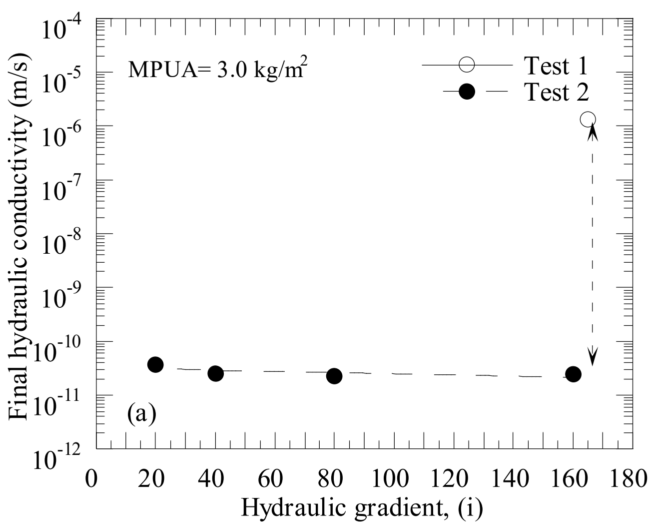
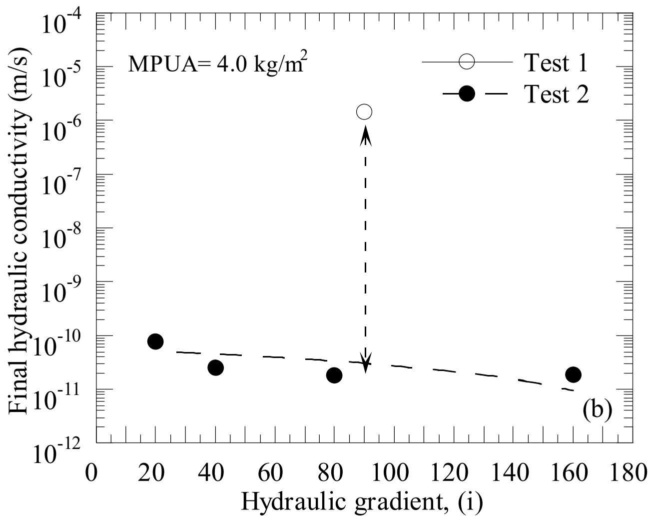


Figure 5.7 Comparison of the final hydraulic conductivities of Na-GCLs obtained from two test conditions (7 days of hydration): MPUA of a) ~3.0 kg/m^2, b) ~4.0 kg/m^2, and c) ~5.0 kg/m^2



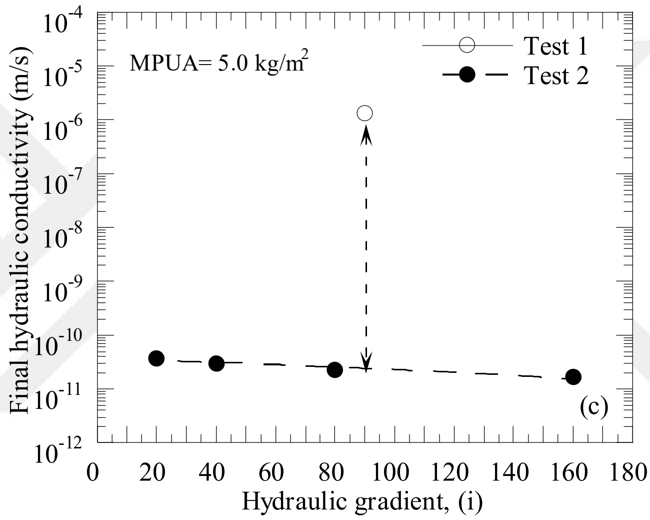
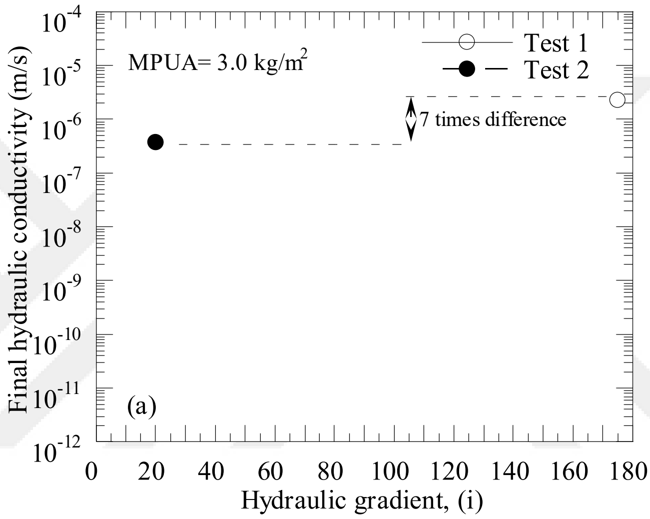


Figure 5.7 continues

Similarly, the final hydraulic conductivities of Na-GCLs prehydrated for 30 days are evaluated as a function of hydraulic gradient in Figure 5.8a-c. Test 1 and Test 2 refer to testing conditions as previously described. The final hydraulic conductivities of Na-GCL prepared with MPUA of 3.0 kg/m^2 were high and the difference between two testing conditions was only 7 times (Figure 5.8a).

In the case of Na-GCL with MPUA of 4.0 kg/m^2, the final hydraulic conductivity was obtained as 2.3×10^{-6} m/s when hydraulic conductivity test was conducted under hydraulic gradient of 175 (Test 1). In contrast, when applied hydraulic gradient was initially 20 and gradually increased to 160, lower final hydraulic conductivity values were obtained. The difference between Test 1 and Test 2 is more than 4 orders of magnitude as shown in Figure 5.8b.

Similar tendency was also observed for Na-GCL prepared with MPUA of 5.0 kg/m^2 (Figure 5.8c). Hydraulic conductivity was high (2.6×10^{-6} m/s) when the test was performed at hydraulic gradient of 80 (Test 1). However, the hydraulic conductivity was measured as 3.5×10^{-11} m/s when the test was conducted under elevated hydraulic gradients (Test 2).



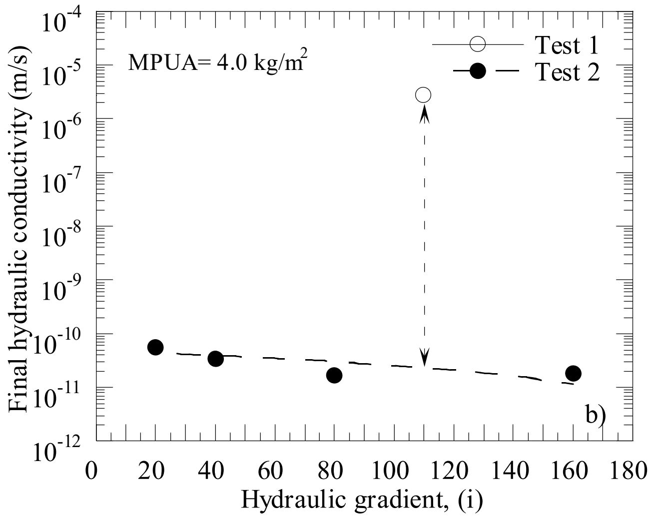


Figure 5.8 Comparison of the final hydraulic conductivities of Na-GCLs obtained from two test conditions (30 days of hydration): MPUA of a) ~3.0 kg/m^2, b) ~4.0 kg/m^2, and c) ~5.0 kg/m^2

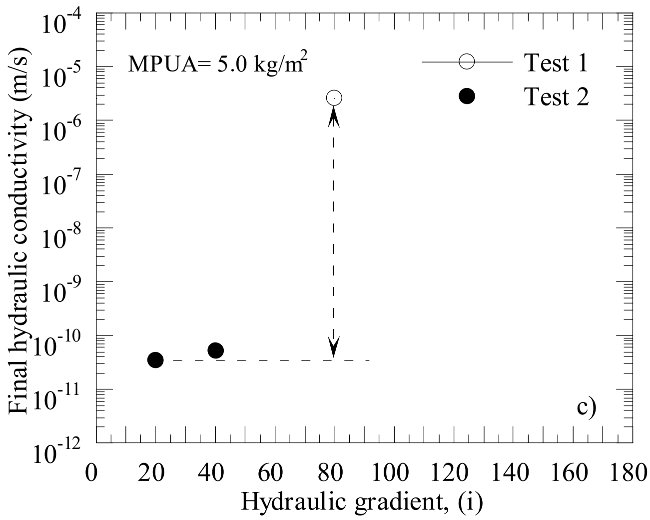


Figure 5.8 continues

To investigate the effect of hydraulic gradient on the hydraulic conductivities of P-GCLs prehydrated for 7 days, three testing conditions namely Test 1, Test 2 and Test 3 were compared (Figure 5.9). Test 1 and Test 2 are the tests conducted under high level of hydraulic gradient (i.e. 110 and 140, respectively) and Test 3 is a test performed under hydraulic gradient of 20 and 40. As for Test 1 and Test 2, two distinct hydraulic behaviors were observed when these tests were conducted at hydraulic gradients of 110 and 140. The final hydraulic conductivity of Test 1 was high (2.6×10^{-6} m/s), whereas it was low for Test 2 (1.1×10^{-11} m/s). In contrast, hydraulic conductivity of Test 3 was obtained low when hydraulic gradient was 20 and 40.

The difference in the hydraulic conductivities of Test 1 and Test 2 may be attributed to: i) uneven distribution of bentonite in GCL because of rolling method and ii) bundle induced hole present in the GCL.

When rolling process was applied on GCL, fibers might have resisted movement of some dry bentonite aggregates. This may result in stacking of more bentonite at one location in the GCL, resulting locally different MPUAs in GCL. This may lead to cause different hydraulic conductivity behavior even at the same MPUA.

In addition to the rolling process, needle-punching density may have an influence on the hydraulic conductivity. As reported in Chapter 4, Rhodamine tracer dye test showed that GCL had high permeability due to bundle of fibers. Similar to this, GCL sample used in Test 2 might have bundle of fibers, resulting in high permeability. Thus, the difference between the hydraulic conductivity of Test 1 and Test 2 can be attributed to uneven distribution of bentonite particles and availability of bundles of fibers in the GCL.

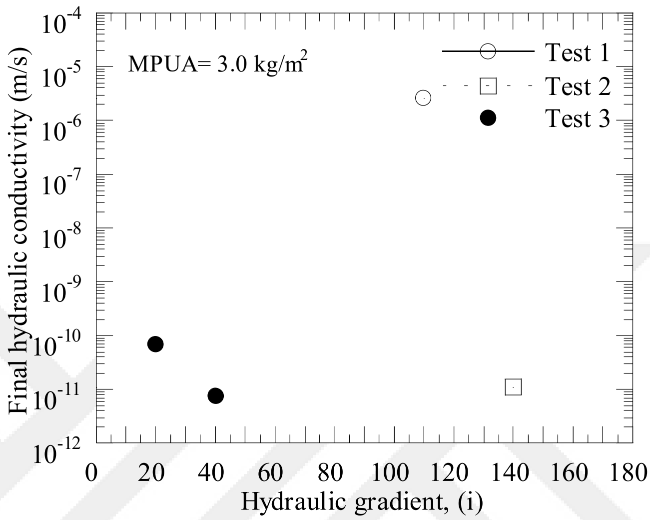


Figure 5.9 Comparison of the final hydraulic conductivities of P-GCLs obtained from three test conditions (7 days of hydration)

As an overall behavior, there is a significant effect of hydraulic gradient on the hydraulic conductivity of Na-GCLs hydrated for 7 and 30 days at MPUA of 4.0 and 5.0 kg/m^2. As reported in discussion part of Chapter 4, seepage forces on GCL under larger hydraulic gradient were high during permeation stage. This led to bentonite erosion, resulting in high permeability. However, once applied hydraulic gradient was initially low (i.e. 20), reduction in the seepage forces on GCL provides closing of pore spaces between bentonite particles, resulting in a low hydraulic conductivity. Although hydraulic gradient increased until 160, hydraulic conductivities did not change considerably.

Similar behavior was also valid for Na-GCL prepared with 3.0 kg/m^2 and prehydrated for 7 days. In contrast, the final hydraulic conductivity of Na-GCL with MPUA of 3.0 kg/m^2 and prehydrated for 30 days was obtained high under two different testing conditions (Figure 5.8a). This difference may be possibly due to uneven distribution of bentonite particles after sample preparation or availability of bundle of fibers in GCL. As for P-GCLs with MPUA of 3.0 kg/m^2, two different behaviors were seen under greater hydraulic gradients. This difference can be related to two factors described above (i.e. bentonite distribution or occurrence of bundle of fibers in GCL).

5.6 Conclusions

The influence of hydraulic gradient on the hydraulic conductivity of Na-GCLs and P-GCLs were investigated and discussed in this chapter.

Except GCL with MPUA of 3.0 kg/m^2 and hydrated for 30 days, the difference between the hydraulic conductivities of Test 1 and Test 2 for Na-GCL with MPUA of 3.0, 4.0 and 5.0 kg/m^2 was more than four orders of magnitude. However, the difference between the testing conditions was only 7 times for Na-GCL with MPUA of 3.0 kg/m^2 and hydrated for 30 days.

P-GCL prepared with MPUA of 3.0 kg/m^2 exhibited better hydraulic performance under low hydraulic gradient in comparison to the performance under high hydraulic gradient. However, two tests conducted under high hydraulic gradient showed different tendency: One of them had high hydraulic conductivity and the other one had low hydraulic conductivity.

The differences between the hydraulic conductivities at the same MPUAs may be attributed to the applied method during sample preparation. Rolling method might have caused uneven distribution of bentonite particles in GCLs, resulting locally different MPUAs on GCL. Moreover, a test conducted on Na-GCL with 3.0 kg/m^2 showed that availability of bundle of fibers in GCLs was also responsible for the higher hydraulic conductivity.

CHAPTER SIX
SUMMARY AND CONCLUSIONS

6.1 Conclusions and Recommendations

This study investigates and discusses MPUA based evaluation of hydration behavior and hydraulic performances of two types of GCLs, one of which is Na-GCL and the other is P-GCL. The findings are summarized below:

- After hydration, the final water contents of both GCLs increased, as the hydration duration increased. Higher water contents achieved for P-GCL than for Na-GCL.

- The final water contents of GCLs decreased, as the MPUA increased. In addition, higher MPUA for 30 days of hydration was required to achieve the same water content as with GCL hydrated for 7 days.

- Independent of GCL type, initial GCL heights increased as the MPUA increased. Significant GCL height changes during hydration were observed for P-GCL in comparison to Na-GCL.

- The final water contents of both GCL types were closely related to the final thickness and void ratios of GCLs. Increase in the MPUA means more stacking bentonite particles inside of GCL. Therefore, higher final GCL height and lower final void ratio were observed.

- P-GCLs exhibited better hydraulic performance than Na-GCL at any MPUA.

- While Na-GCL with MPUA of 3.0 kg/m^2 had high permeability, P-GCLs prepared with the same MPUA showed two different hydraulic performances (either higher or lower). This difference may be attributed to uneven distribution of bentonite particles in GCLs and/or availability of bundle of fibers in GCL. The bundles may trigger the formation of hole on GCL, resulting in high hydraulic conductivity.

- GCL type plays a significant role on the hydraulic conductivity of GCL, when MPUA ranged between 3.2 kg/m^2 and 6.2 kg/m^2.

- While Na-GCLs prepared with 3.0, 4.0 and 5.0 kg/m^2 and P-GCL with the MPUA of 3.0 kg/m^2 had high permeability (~1.0×10^{-6} m/s) under high hydraulic gradient (i=85-175), they had low permeability (~1.0×10^{-11} m/s) when hydraulic conductivity tests were initiated from 20.

- It can be concluded that GCLs having MPUA less than recommended value (i.e. 5.0 kg/m^2) may be used for the containment of water in pools and ponds. This study addresses some significant findings for this purpose. However, when the GCL contacts with aggressive leachate in the landfill, this MPUA level may not be enough to maintain low hydraulic conductivity during the post construction stage. Therefore, MPUA of GCL should be selected depending on the site-specific conditions. There is no information given in this study regarding to the hydraulic conductivity permeated with other leachates. Thus, it is suggested to perform such kind of tests using liquids other than DIW. For each leachate, the hydraulic performance may change depending on the MPUA and critical MPUA levels for each leachates and GCL types can be reported. This may be a good and interesting future study who wants to work on GCLs.

- The role of geotextile components of GCL on the hydration is unknown. This should be investigated with further study.

- The MPUA was accepted as “unchanged” when hydrated GCL was cut for the hydraulic conductivity tests. But, there may have some differences between MPUAs of samples subjected to hydration and those subjected to hydraulic conductivity test. Because, the movement of particles within GCL is resisted by the needle-punched fibers which may result in locally uneven distribution of bentonite in GCL. Thus, this point deserves more attention.

- The research on MPUA can be enlarged furthermore considering needle punching density and permeant type. These parameters may have an effect on the hydraulic conductivity of GCLs as well. The influence of permeant type should be investigated not only using DIW, but also using different pore fluids.

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