INVESTIGATION ON SELF-HEALING CAPACITY OF GEOSYNTHETIC CLAY LINER

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INVESTIGATION ON SELF-HEALING CAPACITY OF

GEOSYNTHETIC CLAY LINER

by

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ABSTRACT

Geosynthetic clay liners (GCLs) have been widely used in landfill liner and/or cover systems. In the field, local damages caused by heavy construction machines or sharp subjects such as stones existed in the field, or defects at the seam area between GCL panels cannot be completely avoided. The leachate from landfill may propagate through these local damages or defects and enter the surrounding ground or groundwater, and cause an environmental problem.

It is known that GCLs have self-healing capacity owing to the expansion of bentonite, which is a component of GCLs. Several studies have been conducted to investigate the self-healing capacity of GCLs. However, still there are some questions remained to be answered, e.g., under what kind of condition damages on GCLs can be self-healed, for a self-healed damage area, what is the magnitude of permeability and what is the effect of wet-dry cycles on self-healing capacity. Moreover, the reported results mostly are for geotextile encased GCL (GT-GCL), only few studies are reported regarding the self-healing mechanism of geomembrane supported GCL (GM-GCL). There is a need to investigate all important factors such as size of damage hole, type of liquid and overburden pressure on the self-healing capacity of GCL, either individually or combined in a systematic way.

This study investigated self-healing capacity of GCLs by laboratory leakage rate tests under constant head and falling head conditions. Two types of GCLs were tested. The first type is GM-GCL and the second is GT-GCL. The tests were carried out using 150 mm in diameter of GCL specimens. The diameters of damage hole investigated were 5 mm to 50 mm. Adopted overburden pressures ($p'$) were 0 ~ 200 kPa. Tap water, ethanol solution (10%), NaCl solution (1%) and CaCl$_2$ solution (1.1%) were used as liquids. In addition the effect of wet-dry cycles on the size of damage hole of GCLs was also investigated by laboratory tests. The repeated wet-dry tests were conducted using GM-GCL samples and subjected to 6 wet-dry cycles.

The test results indicate that for both the GM-GCL and GT-GCL, damages with diameters less than 30 mm can be self-healed providing the liquid is tap-water or the ethanol solution (10%). By using relative value of area healing ratio ($\alpha_h$), which is defined as the ratio of healed area divided by the area of the initial damage, it has been deduced that the size of hole can be healed for NaCl and CaCl$_2$ solutions are 20 mm and 15 mm in diameter, respectively. The test results indicated that the permittivity ($\psi$) value of a healed damage of GT-GCL, is more than 10 times of $\psi$ value of the intact GT-GCL. Whereas, from the result of repeated wet-dry tests, when wet, the size of the hole was
reduced but when dries, it was increased again. There is a slight tendency of reducing the size of hole with the increase of the number of cycles.

All factors which tend to reduce the thickness of diffusive double layer around particles of bentonite tend to reduce the self-healing capacity of GCLs and free swelling index of bentonite can be used to evaluate the relative influence of liquids. $\alpha_h$ values of using the 1% of NaCl and 1.1 % of CaCl$_2$ solutions are much lower than that of the tap-water or 10 % of ethanol solution. As for the effects of overburden pressure ($p'$), on the one hand it can squeeze the hydrated bentonite into the damage hole to increase the area healing ratio, on the other hand, it will limit the amount of hydration induced expansion of the bentonite in GCLs. For the conditions tested, up to $p' = 200$ kPa, $\alpha_h$ value increased with the increase of $p'$ value.
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Author
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NOTATIONS

$A$  Defect area  
$a$  Cross sectional area of the burette  
$A_i$  Initial area of damaged hole  
$A_f$  Final area of damaged hole  
$\alpha_h$  Area healing ratio  
$d$  Diameter of damaged hole  
$d_1$  Diameter of small damaged hole  
$d_2$  Diameter of big damaged hole  
$\rho_c$  Electric conductivity  
$\Delta h$  Head difference  
$\Delta t$  Duration of observation  
$h_1$  Water level at time (t)  
$h_2$  Water level at t+\Delta t  
$\frac{1}{K}$  Thickness of double layer  
$p'$  Overburden pressure  
$\psi$  Permittivity  
$Q$  Flow rate  
$Q_h$  Flow rate through the hole  
$Q_{int}$  Flow rate through the intact part of a specimen  
$Q_T$  Volume of leakage within a time interval of \Delta t  
$R_{h1}$  Diameter of wetted area for $d_1$  
$R_{h2}$  Diameter of wetted area for $d_1$  
$w$  Water content  
$w_L$  Liquid limit  
$w_P$  Plastic limit
CHAPTER 1
INTRODUCTION

1.1 General Background

Geosynthetic clay liners (GCLs) have been widely used in landfill liner and/or cover systems. However, local damages on GCLs which caused by heavy construction machines or sharp subjects such as stones existed in the field, or defects at the seam area between GCL panels, cannot be completely avoided. Several studies reported GCL damage was detected in the field (Mazzieri and Pasqualini 1997; Evans et al. 1998; Nosko and Tauze-Foltz 2000).

GCLs consist of a thin layer of bentonite sandwiched between two geotextiles or glued to a geomembrane. These products have become popular due to the low hydraulic conductivity to water and easily installation. It is widely believed that GCLs have self-healing capacity owing to the expansion of the bentonite. Bentonite has very high capacity of swelling when exposed with fluid, high ion exchange capacity and very low hydraulic conductivity (e.g. Egloffstein, 2001). Several studies have been conducted to investigate the self-healing capacity of GCLs (e.g. Mazzieri and Pasqualini 2000; Babu et al. 2001; Egloffstein 2001; Takahashi et al. 1999). The tests result confirmed the presence of self-healing capacity of bentonite used in GCLs. However, there are still some questions remained to be answered: 1) under what kind of condition damages on GCLs can be self-healed, 2) what is the magnitude of permeability of a self-healed damage area and 3) for a self-healed damage area, what is the effect of wet-dry cycles on self-healing capacity. Moreover, the reported results mostly are for geotextile encased GCL (GT-GCL), only few studies are reported regarding the self-healing mechanism of geomembrane supported GCL (GM-GCL). There is a need to investigate all important factors such as size of damage hole, type of liquid and overburden pressure on the self-healing capacity of GCL, either individually or combines in a systematic way.
1.2 Objective and scopes of this study

In this study, self-healing capacities of both geomembrane supported GCL (GM-GCL) and geotextile encased GCL (GT-GCL) are systematically investigated by a series of laboratory leakage rate tests under both constant head and falling head conditions. In addition, repeated wet-dry tests are also conducted on GM-GCLs to observe the change of size of a damaged hole during wet-dry cycles. Generally there are three objectives of this study:

(1) To investigate influenced of size of defect (a hole), overburden pressure and type of liquid on self-healing capacity of GCLs.

In principle, all factors influencing the amount of swelling of bentonite will affect the self-healing capacity of GCLs, such as chemical compositions of the liquid, overburden pressure etc. Most reported results in the literature are for the effects of some influencing factors, and there is a need to investigate all important factors individually or combined in a systematic way.

(2) To investigate the capacity of self-healing and main influential factors of both GM-GCLs and GT-GCLs

There are two types of GCLs used in engineering practice, GM-GCL and GT-GCL. Due to the different structures, their self-healing capacity and main influencing factors may be different. However, most test results in literature are for GT-GCL, there are only few results regarding to self-healing capacity of GM-GCL (e.g., Takahashi et al. 1999). This study intend to investigate capacity of self-healing of GM-GCLs and compare to GT-GCLs.
(3) To investigate effect of wet-dry cycles on the size of the damage hole on GM-GCLs.

In the field, GCL may experience wet-dry cycles due to the seasonal change, which can affect capacity of self-healing of GCLs. These tests intend to observe influence of repeated wet-dry cycles on the size of damage hole on GCLs.

1.3 Organizations of this thesis

This dissertation contains of five chapters. The first Chapter, Introduction describes general background, objectives and the scope of the study.

Chapter 2 reviews literatures that related to application of GCLs in landfills, effect of fluids and overburden pressure on the hydraulic performance of GCLs, possible causes and type of defect, mechanism of fluid through a damaged hole and self-healing capacity of GCLs.

Then, Chapter 3 describes the details of experimental investigation, i.e. equipments test, test procedures, materials and their properties.

Chapter 4 presents results of Constant head and Falling head leakage rate tests, repeated wet-dry tests included their interpretation, discussion and summary.

The last chapter, Chapter 5 presents conclusions from this study and recommendations for future works.
CHAPTER 2
REVIEW ON THE SELF-HEALING CAPACITY OF GCL

2.1 Introduction

Application of Geosynthetic clay liners (GCLs) as fluid barrier has been popular since last decade (EPA, 2001; Bouazza, 2002). GCLs are utilized in environmental application such as component liner or cover systems in solid waste containment. Furthermore GCLs are used also as groundwater protection for underground storage tanks at fuel stations, for canals, ponds or surface impoundments.

Utilization of compacted clay liners (CCLs) were replaced by GCLs mainly due to very low hydraulic conductivity to water, fast and easy installation. For regions where clay is not readily available, GCLs are cost effective.

However, due to improper installation of relining material and during operations, some defects unavoidably in GCLs. Inappropriate seaming in interconnection of relining GCL panels can cause leakage in composite liner. Moreover puncture in GCL by sharp objects such as gravel, nail or even heavy construction equipment which passing above relining system may cause defect.

Bentonite which is part of GCLs is believed possess self-healing capacity. Self-healing is the material property of having the capacity to close fissures caused by external influences, and maintaining the barrier effect which is required for a liner system over the long time (Savidis and Mallwitz, 1997). Related to this issue, this study observed self-healing capacity of GCL and its influencing factors.
2.2 Application of GCLs in landfills

2.2.1 History of landfills

The term of landfill refer to a final disposal for unwanted or unusable wastes. Until middle of 20th century, almost all wastes were disposed in open area without engineering designed to prevent the leakage of waste into the surrounding environment. Sometimes wastes were burned and the ash is disposed into the landfill to save space. At that time commonly wastes dumped were natural depressions (creeks, low-lying areas, and flood plains) and mining tails, e.g., sand or gravel quarries (Daniel, 1993).

After World War II landfill was established by a slightly engineering design (Daniel, 1993). By the end of 1970’s, impact of land filled waste on land and ground water started to be considered into landfills design (Bouazza et al. 2002). In this period, modern landfill began to develop in the United States and Europe. The improved waste treatment started in the beginning of 21st century as summarized in Table 2-1.

In Japan, incineration process has considered as the first step of treating the solid waste. The residue is usually disposed into landfill sites. Like USA and Europe, landfill in Japan was established without any engineering control, even after World War II (Tanaka et al. 2005). Sanitary landfill and technical regulation started and applied in most area in Japan after a famous accident in landfill called Yume-no-shima in 1965. Covering landfill with 300 mm-thickness soil was started since the accident. However until 1971 still no technical standard existed.

Then Japan set up solid waste management law in 1971. Based on this law, all landfills were constructed referred to standard of landfill disposal. In 1976, Technical standard of operation and construction was issued, but this standard was limited for landfill larger than 2000 m². Three years later, guidelines for MSW landfill were launched which included liner system, leachate collection, drainage system, and a leachate treatment facility.

The technical standard became minimum requirement to obtain financial support
from government, which covered 25% of construction cost. Later Guidelines for MSW landfill were revised in 1988 to strengthen the standard of liner and leachate treatment system. Even MSW landfill could get subsidy from government if follow requirement from guideline for performance of MSW landfills (Tanaka et al. 2005). In developing countries, since food, housing, health and education are still primary issues, the process of landfill evolution is slower compared to the developed countries.

Table 2-1. Summary of municipal landfill transformation (Bouazza et al. 2002)

<table>
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<th>Dates</th>
<th>Development</th>
<th>Problems</th>
<th>Improvement</th>
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<td>1970s</td>
<td>Sanitary landfills</td>
<td>Health/nuisance, i.e odour, fires, litter</td>
<td>Daily cover, better compaction, Engineered approach to containment</td>
</tr>
<tr>
<td>Late 1980s to early 1990s</td>
<td>Engineered landfills, recycling</td>
<td>Ground and groundwater contamination</td>
<td>Engineered liners, covers, leachate and gas collection system, increasing regulation, financial assurance</td>
</tr>
<tr>
<td>Late 1980s to 1990s</td>
<td>Improved sitting and containment, waste diversion and re-use</td>
<td>Stability, gas migration</td>
<td>Incorporation of technical, socio-political factors into siting process, development of new lining materials, new cover concepts, increased post-closure use</td>
</tr>
<tr>
<td>2000s</td>
<td>Improved waste treatment</td>
<td></td>
<td>Increasing emphasis on mechanical and biological waste pre-treatment, leachate recirculation and bioreactors, “smart landfill”</td>
</tr>
</tbody>
</table>

2.2.2 Design of landfills

The main difference between conventional and modern landfill design is usage of
liner system. Conventional landfill was designed often without liner system, while for modern landfill, a liner system is a basic requirement. Modern landfills typically included three liner components: bottom, side and cover liners.

The bottom and side liners are designed to prevent or reduce advective and diffusive contaminant migration into the environment nearby. To control water and gas movement and minimize odors, disease and nuisance, cover liners are layered over the waste. The cover system controls water and gas movement and minimizes odors, disease vectors and other nuisances. In general, liner system is employed to control release of waste constituents (Daniel, 1993).

Presently, modern landfill facilities are commonly designed with a barrier system involving a composite liner system (Geomembrane/Compacted clay layer (CCL) or Geomembrane/Geosynthetic clay layer (GCL)), which are used in combination with cover systems to accomplish waste containment. A typical modern landfill liner system consists of bottom, side slope and cover liners as shown in Figure 2-1. Component of bottom liner system proposed by Daniel and Koerner (Daniel, 1993) is presented in Fig. 2-2.

Minimum requirement of bottom liner is a double composite liner system or more, which is used for containment of waste and especially the hazardous waste. Example of component of single and double composite is illustrated in Fig. 2-3. A primary liner system which is included in bottom liner consists of a geomembrane/GCL composite liner. A secondary liner system involves of geomembrane/CCL composite liner system. Twenty four percent (24 %) of MSW landfills in the USA and 14% of landfills worldwide had been designed with double lining system (Koerner, 2000). In Japan after 1997, the double composite liner system is mandatory for new landfills (Tanaka et al, 2005). Geomembranes (GM), GCLs and compacted clay liners are used in composite liners for preventing or reducing contaminant migration.

The leachate collection system which overlying the primary bottom liner typically consists of gravel and perforated pipe. Furthermore geocomposite drainage sheet is commonly placed on the side slope. The leak detection systems which is usually
geosynthetic-composite drainage systems were installed between primary and secondary liners.

![Diagram of landfill lining system]

**Fig. 2-1** Example of component of modern landfill

**Fig. 2-2** Lining system recommended by Daniel and Koerner (Daniel, 1993)

The design for landfill lining system depends on regulations and characteristic of site. However, regulation and requirement for a landfill system varies in every country. Generally minimum requirement of bottom liner system in the USA and Europe consist of:
(1) drainage layer, (2) mineral barrier, (3) leachate collection pipe, (4) Geotextile and (5) HDPE Geomembrane. While in Japan, requirement of bottom liner systems were simpler which consists of: (1) mineral barrier, (2) geotextile and (3) geomembrane.

![Composite liner diagram](image)

### a. Single composite with CCL

- Drainage layer
- Geomembrane
- Compacted clay layer (CCL)

### b. Single composite liner with GCL

- Drainage layer
- Geomembrane
- GCL

### c. Double composite liner system

- Leachate collection
- Geomembrane
- GCL
- Leak detection
- Geomembrane
- CCL

Fig. 2-3 Example of single and double composite liner systems (adapted from Daniel 1998)

### 2.3 Geosynthetic clay liners (GCLs)

#### 2.3.1 Definition and materials

A GCL is a thin layer of processed clay (typically bentonite) bonded to geosynthetic. The bentonite are either powder or granular, while geosynthetics are geomembrane or
Generally GCLs are classified into two groups, the first type is bentonite bonded into a geomembrane or geomembrane-supported GCLs (GM-GCLs) and the second type is bentonite sandwiched between two geotextiles or geotextile-encased GCLs (GT-GCLs). Whereas geomembranes and geotextiles have function to hold the bentonite staying in the place during handling, transporting, and installing.

### 2.3.2 Bentonite

Bentonite is known as a highly plastic, swelling clay material which is the product of volcanic ash. Bentonite has low hydraulic conductivity to water (Shackelford et al. 2000). For industrial purposes, commonly bentonite is divided into sodium bentonite and calcium bentonite. Content of Montmorillonite in bentonite normally ranging from 65 to 90 % (Shackelford et al. 2000). Beside that bentonite also containing quarts, feldspars, mica, cristobalite, carbonates material and some others minerals.

Montmorillonites have three layer minerals which consist of 1) alumina and 2) silica sheets. Alumina sheet is sandwiched by two silica sheets (tetrahedron-octahedron-tetrahedron sheets) as shown in Fig. 2-4. One silicon atom is surrounded by four oxygen atoms in the tetrahedron sheet. One aluminium atom is surrounded by six oxygen ions (OH-groups). The Oxide anions and the cations are shared between tetrahedron and octahedron sheets. Structure of montmorillonite can be changed due to replacement of Al$^{3+}$ by Mg$^{2+}$ in the tetrahedron and resulting charge deficiency. The process of ion replacement is known as Isomorphous substitutions.

A large specific area (about 800 m$^2$/g), high charge deficiency (80-150 meq/100 gr), and ability for interlayer swelling of montmorillonite are believed as the factors contributed to high swelling capacity and low hydraulic conductivity of bentonite when contacted with water (Shackelford et al. 2000). Correlation between hydraulic conductivity of bentonite and the swelling of montmorillonite particles is addressed to water volume that bound water to the clay surface (Jo et al. 2001). When the volume of bonded molecule of water increases, the fraction of the pore space contains of freely bulk water decreases and pathways for water flow become smaller and more serpentine. So increase of volume
of water bounded is manifested as an increased of swell volume and a decrease of hydraulic conductivity (Mesri and Olson 1971).

(a) Schematic diagrams of structures of montmorillonite (after Mitchell and Soga, 2005)

(b) Diagrammatic sketch of the Montmorillonite structure

Fig. 2-4 Montmorillonite structure (After Mitchell and Soga, 2005)
Fig. 2-5 Charge distributions in Montmorillonite structure (after Mitchell and Soga, 2005)

In geotechnical references, the volume of bond water and interaction between particles has been described in the term of diffusive double layer (Fig. 2-6). Theory which developed by Gouy (1910) and Chapman (1913) was mostly cited to describe diffusive double layer (Mitchell and Soga, 2005).

2.3.3 Geomembrane-supported GCLs (GM-GCLs)

For geomembrane-supported GCLs, the bentonite mixed with an adhesive is glued to a geomembrane using a non-polluting adhesive (Fig. 2-7). The geomembrane can be a smooth high density polyethylene (HDPE), texture geomembranes or very low density polyethylene (VLDPE). This type is not as popular as geotextile-supported GCLs. For inter-panel connection normally no mechanical seaming is needed since overlapped areas are believed to be self-healed at the bentonite/polyethylene contact. However polyethylene sheet could be welded if desired (Daniel 1993).
2.3.4 Geotextile-encased GCLs (GT-GCLs)

Geotextile-encased GCLs can be further divided into three categories, (1) needlepunched, (2) stitch-bonded and (3) adhesive-bonded (Fig.2-8). In needlepunched type, bentonite is kept in place between the carrier and cover geotextiles by a process of needlepunching. Fibers were punched from geotextile through the bentonite and embedded into the bottom geotextile. In stitch-bond products, similar with needlepunched products, the bentonite is kept in place between the carrier and cover geotextiles by process of stitching. While for adhesive-bonded type, the bentonite is covered with adhesive that glued to geotextile (Koerner, 1997). Needlepunched and stitch-bonded are often classified.
as reinforced GCLs compare to adhesive-bonded product.

![Diagram of geotextile-enhanced GCLs](image)

- **a)** Clay bound with adhesive to upper and lower geotextile
- **b)** Clay stitchbonded between upper and lower geotextile
- **c)** Clay needlepunched through upper and lower geotextile

Fig. 2-8 Scheme of geotextile-enhanced GCLs (Modified from EPA 2001)

### 2.3.5 Effect of liquid on Hydraulic performance

In the field, GCL as composite liner usually contact with liquids from landfill other than fresh water. It is well-known that GCL has low hydraulic conductivity if contact with water. However its hydraulic conductivity shows increasing if GCL exposed with some other chemical liquids such as salty water and organic liquid. Several studies have been reported regarding the effect of chemicals on hydraulic conductivity of GCL.

Petrov et al. (1997) investigated the effect of the fluid type on GCL hydraulic conductivity ($k_w$). Results shown that for final static confining stresses ranging from 34 to
37 kPa, average $k_w$ of tap water permeation was 23% greater than for distilled water permeation (Fig. 2-9). Average $k_w$ of tap water was $1.6 \times 10^{-11}$ m/s while average $k_w$ of distilled water was $1.3 \times 10^{-11}$ m/s.

Furthermore, Petrov et al (1997) also reported test result on effect of ethanol concentration on the hydraulic conductivity of GCLs. They found that significant increases in hydraulic conductivity for ethanol concentration $\geq 50\%$. While for ethanol concentration $\leq 50\%$, the hydraulic conductivity decreases (Fig. 2-10).
Fig. 2-10 Tap water permeated GCLs sequentially permeated with ethanol/water mixture (mass %); Confined hydraulic conductivity tests: a) Hydraulic conductivity; b) Intrinsic Permeability (after Petrov et al. 1997)
Jo et al. (2000) examined effect of single-species salt concentration on GCLs hydraulic performance. In general, the hydraulic conductivity increased as the salt concentration increased (Fig. 2-11).

![Fig. 2-11 Hydraulic conductivity as function of concentration (after Jo et al. 2001)](image)

To sum up, hydraulic conductivity of GCLs depends on the type of liquid. Hydraulic conductivity of GCLs become lower when used distilled water and tap water as liquid but higher for the salt water case. While for ethanol solution (concentration > 50%) as liquid, hydraulic conductivity increased. The hydraulic conductivity became lower when concentration was less than 50% (Petrov et al. 1997).

### 2.3.6 Effect of pressure on hydraulic performance

Numerous studies have been worked on effect of confining pressure ($p'$) on hydraulic performance issue. Thiel and Criley (2003) conducted series of tests on effect of $p'$ on hydraulic conductivity of GCLs. Partially prehydrated of Reinforced GCL samples were tested using three different leachates under different $p'$values. In general the result
tests showed that hydraulic conductivity reducing as confining stress increasing (Fig. 2-12).

Fox et al. (2000) measured hydraulic performance of adhesive-bonded (GCL-1) and needle-punched geotextile-encased GCLs (GCL-2). During observation, the specimens were covered with uniform graded fine, medium, and coarse gravel under different effective confining stress. The result tests showed that hydraulic conductivity decreased as increased of confining stress (Fig. 2-13).

Fig. 2-12 Hydraulic conductivity versus effective confining stress for different leachates (after Thiel and Criley, 2003)

Petrov et al. (1997) also assessed effect of static confining stress on hydraulic conductivity of GCLs. The test results confirmed trend of decreasing hydraulic conductivity of GCLs as increasing static confining stress (Fig. 2-14).

Data from various sources which was collected by Bouazza (2002) clearly showed the trend reduction of hydraulic conductivity as increased of confining stress (Fig. 2-15). Laboratory hydraulic conductivity of geotextile-encased GCLs for water case varies approximately in the range of $2 \times 10^{-12}$ to $2 \times 10^{-10}$ m/s depending on applied of confining pressure.
Fig. 2-13 Permittivity versus effective confining stress for incremental-load gravel (ILC) and single-load control (SLC)

Fig. 2-14 Hydraulic conductivity versus confining pressure stress for needle-punched GCLs (after Petrov et al 1997)
Shan and Chen (2003) reported permittivity of needle-punched and adhesive-bonded geotextile-supported GCL decreased with increasing confining stress, regarding type of subgrade materials (Fig. 2-16).

Fig. 2-15 Hydraulic conductivity versus confining stress (data from various sources, after Bouazza 2002)

Fig. 2-16 Permittivity of GCL specimens (after Shen and Chen, 2003)
2.4 Possible causes and types of defect

Usage of GCLs was spread widely. Some advantages of using GCLs are low hydraulic conductivity to water, limited thickness and easily installation. However GCL also has disadvantages. The disadvantages of GCLs are possible defects during placement, loss of bentonite during placement and increase of hydraulic conductivity when contacted with certain chemicals. In specific, possible defects in GCLs caused by: (1) on-site placement and seaming, (2) handling of GCL rolls, (3) the placement of drainage gravel over the liner system, (4) traffic over the liner or the overlying protection layer, (5) placement of the waste in a landfill, (6) manufacturing defects and etc.

In 1998, Evans et al. reported that GCL damage was discovered after waste removal in Mahoning landfill. Several large tears (1 to 6 ft) and numerous small tears (less than 1 ft) in the geomembrane which is in the part of GCL and two ruptured geomembrane seams were found. Some part of bentonite was removed randomly from geomembrane.

Geomembrane which is part of GCLs also has possibility to be damaged in landfill especially if GCLs are installed directly under primary leachate collection system (PLCS). Nosko and Tauze-Foltz (2000) reported result from electrical damage detection systems which installed at more than 300 sites from 16 countries (Fig. 2-17). The study showed that mainly (71%) damages of geomembrane were caused by stone during installation of PLCS and the rest by heavy equipment (16%), inadequate seam (6%), workers (6%) and cuts (1%).

Mazzieri and Pasqualini (1997) reported that puncturing by plant roots might induce negative impact on the permeability of adhesive-bonded GCLs (Fig. 2-18). A field study of installation damage for GCLs were done by Fox et al. (1998). Field tests were conducted to assess installation damage on GCLs. The study used two types of commercial GCLs. First type is an unreinforced adhesive-bonded GCL in which granular bentonite sandwiched between woven and nonwoven sheets. The second type is a reinforced GCL in which granular bentonite is held between a woven and a nonwoven sheet.
Fig. 2-17 Cause of defects in geomembrane liners after installation of the cover layer (data from Nosko and Touze-Foltz 2000)

In that field test, the GCLs were overlaid on subgrade, and then covered with sand and gravel. Then they were hydrated before bulldozers were driven over them. After that the tests site were dig up and GCLs samples were taken to laboratory to assess damage with referring to type of product, cover soil, soil thickness, bulldozer and passing number of bulldozer.
Table 2-2 presents value of hydraulic conductivity for GCLs after simulation of installation damage. It shows that under gravel soil cover, GCL-1 experienced the most damage has the highest value of $k$. These result proved that Geosynthetic may be damaged for lesser cover depths. In addition increasing cover soil particle size, decreasing thickness of cover soil, increasing water content and trafficking after hydration (10 bulldozer passes) was followed by increasing of installation damage.

Table 2-2. Hydraulic conductivity for GCLs after field simulation of installation damage (Fox et al 1998)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Soil cover</th>
<th>Initial thickness (mm)</th>
<th>Final thickness (mm)</th>
<th>Hydraulic conductivity, $k$ (m/s)</th>
<th>Fluid flux, $\nu$ (m$^3$/m$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCL-1</td>
<td>Sand</td>
<td>6.2</td>
<td>5.8</td>
<td>1.9 x 10$^{-11}$</td>
<td>5.4 x 10$^{-9}$</td>
</tr>
<tr>
<td>S-M, 10 passess</td>
<td>Gravel</td>
<td>10.4</td>
<td>8.9</td>
<td>3.6 x 10$^{-11}$</td>
<td>6.7 x 10$^{-9}$</td>
</tr>
<tr>
<td>GCL-1</td>
<td>Sand</td>
<td>9.0</td>
<td>8.4</td>
<td>2.3 x 10$^{-11}$</td>
<td>4.7 x 10$^{-9}$</td>
</tr>
<tr>
<td>G-M, 10 passess</td>
<td>Gravel</td>
<td>11.0</td>
<td>9.9</td>
<td>1.8 x 10$^{-11}$</td>
<td>3.2 x 10$^{-9}$</td>
</tr>
</tbody>
</table>

Wrinkles are also one of the causing factors of possible GCLs defects. Dickson and Brachman (2006) described that wrinkles of geomembrane can induce to non-uniform stress when vertical overburden pressure was applied and lead to damage the GCLs. Figs. 2-19 and 2-20 illustrated mechanism of GCL defects due to geomembrane wrinkle.

Another factor causing the increase of the hydraulic conductivity of GCLs is the defect at overlapped seam. The liquid will flow through the the defects at the overlaps. Typical of GM-GCLs installation proposed by Thiel (2001) are illustrated in Fig. 2-21. According to Thiel et al. (2002), installed GM-GCL lays flat on the subgrade will reduce wrinkles and result in excellent contact between overlapped panels at the seam area.
Fig. 2-19. a) Composite GM/GCL liner with a GM wrinkle, b) deformation of GCL from primary consolidation (after Dickinson and Brachman, 2006)

Fig. 2-20. a) Deformations of GCL from lateral extrusion of bentonite towards the wrinkle and primary consolidation away from the wrinkle, and b) deformations of GCL from lateral extrusion of bentonite towards the wrinkle and beneath gravel contacts (after Dickinson and Brachman, 2006)
2.5 Mechanism of fluid through a damaged hole

Mechanism of fluid through a damaged hole of GCL is illustrated in Figs. 2-22. As the fluid enters the hole, a part of it flows through the hole, other part percolates into the surrounding bentonite, GM/bentonite or GT/bentonite interface (Chai et al, 2005; Chai et al, 2008). For GT-GCLs, possibility of fluid seep laterally through GT-bentonite interface is more than through GM-bentonite interface in GM-GCLs.

2.6 Self healing capacity of GCLs

2.6.1 Definition

It is widely known that Geosynthetic clay liner has capacity to close the defect/damage hole which is called self-healing. Term of self-healing refers to ability of material to close fissured caused by external factors and sustain the barrier function of GCLs for long time. Self-healing proceeds automatically and sealed the damages in the GCLs while hydrating. The property of self-healing maintains the GCL in the low hydraulic conductivity.

2.6.2 Previous studies on self healing behavior of GCLs

Several previous studies have addressed issue of self-healing of GCLs. Mazzieri and Pasqualini (2000) reported results of an experimental test program for the permeability of a damaged, adhesive-bonded, geotextile-geosynthetic clay liner (GT-GCL). The specimens were cut in circular shape of 10 cm in diameter (Fig. 2-23). Two patterns of defects were simulated, the first one is damage resulting in bentonite loss from the geotextile casing, i.e. tearing and the second one is damage not resulting in bentonite loss, i.e. puncturing.
The experiment test simulated damage which occurred during handling and installation by generating hole in the centre of GCLs specimen. Permeability of damage specimens are compared with that of intact specimens (Fig. 2-24). Permeability tests on GCLs specimen were conducted in flexible wall permeameters under different effective stress. Fig. 2-24 showed typical permittivity with elapsed time. This study also found that self-healing capacity effected by confining stress and hole size. Self-healing capacity decreased as hole size increased (Fig. 2-25). While increasing of confining stress will also increasing self-healing capacity of GCL (Fig. 2-26 and 2-27). Moreover, the results showed that holes up to 0.03 m in diameter can be self-healed.
Fig. 2-22 Illustration of fluid through: a) GM-GCL; b) GT-GCL

Fig. 2-23 Simulated of hole in GCLs specimens
Fig. 2-24 Permittivity of damaged and undamaged GCL specimens under an effective stress of 50 kPa (Mazzieri and Pasqualini, 2000)

Fig. 2-25 Influence of hole diameter on the hydraulic conductivity of self-healed GCLs specimens (after Mazzieri and Pasqualini, 2000)
Fig. 2-26 Influence of the effective stress on the final hydraulic conductivity of damaged and undamaged GCL specimens (after Mazzieri and Pasqualini, 2000)

Fig. 2-27 Permeability of undamaged and punctured (when unhydrated) GCL specimens as a function of effective stress (after Mazzieri and Pasqualini 2000)
Babu et al (2001) assessed self-healing capacity of GCL using swell tests and direct measurements of hydraulic conductivity. The experimental tests were conducted on stitch-bonded and needle-punched GCL specimens. Percent of swelling were observed under different stress. Permittivity test were carried for hole size of 0.006, 0.015, 0.03 and 0.055 m-diameter. The results are shown in Fig. 2-28. The result also confirmed that GCLs with 0.03 m-diameter punctures or less still can be self-healed. Beside that this study observed relationship between swelling properties and self-healing of GCLs. They concluded that there was good relationship between swelling property and self-healing capacity of GCLs.

Fig. 2-28 Results of permittivity tests corresponding to different hole diameters (after Babu et al. 2001)

Visual examination of GCLs defect was conducted by Didier et al. (1999) in laboratory. Tests on GCL Bentomat were performed to qualify and quantify the self-healing process. The defects simulated were circular holes of 0.01, 0.02, 0.03 and 0.04 m. GCL and bentonite part was removed from the intact sample. The damaged samples were saturated.
between two draining layers under a normal confining stress of 10 kPa.

The observation shows that all defects are healed after 15 days. Average moisture of bentonite ranged from 262 % to 636% and was proportional with diameter of hole. Moisture content within the specimen around the sample is not much affected by the defect.

2.6.3 Squeezed Bentonite in GCLs

Mazzieri and Pasqualini (2000) proposed that the confining stress presumably squeezes the unhydrated bentonite against the surface of the puncturing body of GCL, and improve the sealing formation. Several studies were conducted regarding to squeezing of bentonite in GCLs. Some studies used term of bentonite migration in placed of squeezing of bentonite. Fox et al. (1996) investigated lateral bentonite displacement within hydrated GCLs under concentrated load. They confirmed lateral movement of bentonite may occur within hydrated GCL when subjected to concentrated load.

Another study was conducted by Stark et al. (2004). They studied effect of stress concentration on GCLs. The study concluded that unconfined hydrated bentonite would migrate to areas of lower normal stress in the presence of stress concentration or non-uniform stresses. Stress concentration on GCLs was mainly due to the gravel cover soils in the field. Increasing cover soil particle size and rate of loading would increase the amount of bentonite migration (Fox et al. 2000).

2.7 Effect of wet-dry cycles on GCLs

Melchior (1997) found higher leakage rates than predicted from a GCL which placed in a final cover test. He reported that the swelling capacity of Na-bentonite in the GCL was reduced to the value of typical Ca-bentonite after several wet-dry cycles. Reducing of swelling capacity of the bentonite was due to the exchange of Ca\(^+\) ions from the water pore. The reduced swell capacity of the GCL would reduce capacity of seal preferential flow paths formed during desiccation and led to excessive leakage.
Lin et al. (2000) investigate effect of wet-dry cycling on swelling and hydraulic conductivity of GCLs. They conducted Atterberg limits, free swell and hydraulic conductivity tests to assess affects of wet-dry cycling on the plasticity and swell of bentonite, and hydraulic conductivity of geosynthetic clay liners (GCLs) hydrated with deionized (DI) water, tap water, and CaCl$_2$ solution (Figs. 2-29~2.30). The study found that 7 cycles of wet-dry in DI water and tap water had little effect on swelling of bentonite. However, if 0.0125M CaCl$_2$ solution is used as fluid, swelling of bentonite decreased significantly after two wetting cycles (Fig. 2-31). After 5 cycles of wetting, hydraulic conductivity of GCLs increased dramatically (Fig. 2-32). They concluded that hydraulic conductivity increased due to the cracks which formed during dessication, but not fully heal when dehydrated.

![Graph](image_url)

Fig. 2-29 Liquid limit as function of number of wetting cycles (Lin et al. 2000)
Fig. 2-30 Plastic limit as function of number of wetting cycles (Lin et al. 2000)

Fig. 2-31 Amount of swell at each wetting cycles (Lin et al. 2000)
2.8 Summary and comments

A literature review on the self-healing capacity of GCL has been presented in this chapter. GCLs are well-known as fluid barrier mainly used to protect environment from contamination. Low hydraulic conductivity and easily installation are main reason for adopting GCLs in the environment and geotechnical application.

One of critical issues of GCLs performance is possible defects during placement and operation. The main cause of GCL defects is improper installation in the field, although defects also can occur during operation. One of the characteristics of GCLs is healing ability to the certain defects due to the expansion of bentonite in GCLs while hydration, and it is called self-healing capacity.
The main factors influencing the self-healing capacity of GCLs are: 1) size of damaged, 2) type of liquid and 3) confining pressure. The previous studies concluded that there is a certain size of damaged that GCL cannot compromised. Moreover, GCL was proved to be sensitive to liquid type. While for confining pressure, increasing the confining pressure increased self-healing capacity.

However, effect of confining stress on the self-healing mechanism still could not be explained clearly in the previous studies. Increasing of confining pressure was followed by reducing of the size of the defect. Meanwhile increasing of confining pressure will reduce swelling volume of bentonite around the defect. According to Mazzieri and Pasqualini (2000) and Babu et al (2001), the self-healed mechanism is governed by swelling of the bentonite in the damaged area. Based on these facts, this study intended to further investigate all influencing factors of self-healing capacity of GCLs individually or combined in a systematic way.

As mentioned earlier in this chapter, there are two types of GCLs used in engineering practice, namely GM-GCL and GT-GCL. Self-healing capacity and main influencing factors may be different for each of these two types. However, most test results in previous studies are for GT-GCLs while only few results worked on GM-GCLs (e.g., Takahashi et al. 1999). In this study, self-healing capacities of both GM-GCL and GT-GCL are systematically investigated by laboratory leakage rate test under constant head and falling head conditions. The factors investigated are: 1) overburden pressure, 2) type of fluid, and 3) size of damage on GCLs. Conditions for self-healing can be expected will be discussed later in the chapter 4.
CHAPTER 3
LABORATORY LEAKAGE RATE TESTS

To assess self-healing capacity of GCLs, leakage rate tests were conducted underConstant head and Falling head conditions. These two tests were carried to provide cross check of test results. The test equipments, material used, test procedures as well as case tested are described in this chapter. The test results and discussion will be presented in the next chapter.

3.1 Test Equipments

3.1.1 Constant head leakage rate test device

The equipment for Constant head test is shown in Figs. 3-1, 3-3, 3-4 and 3-5. The device consists of:

(1) a transparent cylinder made of acrylic resin with an inner diameter of 150 mm (wall thickness of 5 mm) and height of about 400 mm;
(2) upper and lower pedestals made of stainless steel, and a porous stone with a diameter of about 120 mm is fixed at the top of the lower pedestal;
(3) a piston made of stainless steel, which is perforated with 3 mm diameter holes at 20 mm pitch to allow for drainage, and a ceramic porous stone with a diameter of 120 mm is inserted at the centre of the bottom of the piston; and
(4) a bello-fram fixed to the top of the upper pedestal for applying overburden pressure ($p'$).

Sealing between the cylinder and the piston is achieved by a 4 mm diameter ‘O’ ring lubricated with silicone grease and fixed around the piston. Schematic of Constant head leakage rate test is given in Fig. 3-2.
Fig. 3-1 Device of Constant head leakage test

Fig. 3-2 Schematic diagram of Constant head leakage test
Fig. 3-3 Bello-frame of Constant head leakage rate test

Fig. 3-4 Cylinder resin of Constant head leakage rate test
3.1.2 Falling head leakage rate test device

The photo of Falling head leakage rate test device is given Figs. 3-6 and 3-7 and a schematic description of the Falling head leakage rate test device is shown in Fig. 3-8. The main body of the device is made of copper, and consists of lower and upper parts. The lower part consists of a container with 150 mm inner diameter. A porous stone, 50 mm in diameter, is inserted at the center of the bottom of the container. The upper part of the device is a loading plate, 150 mm in diameter, with a porous stone, 120 mm in diameter, inserted at the center and in turn connected to a burette. The cross-sectional area of the burette is $2 \times 10^{-4} \text{ m}^2$. 
Fig. 3-6 Photo of device of Falling head leakage rate test

Fig. 3-7 Photo of main body of device of Falling head leakage rate test
3.1.3 Repeated Wet Dry test Device

In Repeated wet-dry tests, GCL samples are placed on a 0.0045 m thick sheet of smooth aluminium (Fig. 3-9). The aluminium sheet has dimension of 0.4 m x 0.4 m which is attached by two of 0.025 m wide channels section clamps at each edge. These channel section clamps are installed to secure the GCL samples during tests.

Fig. 3-9 Photo of equipment of repeated wet-dry test
3.2 Test Procedures

3.2.1 Preparation of GCL specimen

Cut GCL specimen of 150 mm-diameter and make a hole of 0.005 to 0.05 m in diameter in the center by a driller and/or cutter (Figs. 3-10 and 3-11). Thought shapes of actual defect are various, it is necessary for doing laboratory tests to represent various defects by one shape. Circular shape was employed to the test as the simplest and easiest defect model. Removing a circular part of GCL brings us maximum loss of bentonite. This means that the tests were conducted by taking into consideration of the most unfavorable situations. Taking into account of actual defects, more successful responses are expected than the testing results. For GM-GCL, the GM side is glued to the piston (Constant head test) or the loading plate (Falling head test) on an annulus area along the outer periphery to prevent flow at GM/piston or GM/loading plate interface (Fig. 3-12). Whereas for GT-GCL, the specimen is placed in the lower part of the device, and to prevent leakage through the possible gap between the periphery of the specimen and the equipment, bentonite is then carefully put around the periphery of the specimen.

Fig. 3-10 GM-GCL specimen
Fig. 3-11 GT-GCL specimen

Fig. 3-12 GM-GCL was glued on piston
3.2.2 Falling head leakage rate test

Set up the test and apply the desired overburden pressure (25, 50, 100 and 200 kPa) and maintain for 1 hour before start the leakage rate test. Set up water head of about 1000 mm on the top of the specimen through burette. Open the valve for inlet flow and start the test; and record water level in the burette periodically. The flow rate is calculated using the amount of inlet water flow and the corresponding water heads. The test is continued until the calculated apparent hydraulic conductivity became stable.

3.2.3 Constant head leakage rate test

Install the piston (with GCL specimen attached in case of GM-GCL) into the cylinder. Then install the loading system and apply desired pressure (0, 50, 100 and 200 kPa) and maintain for 1 hour. Pour fluid into the cylinder with a water head of 320 mm above the GCL specimen and start the test. Measure the outlet flow rate periodically until it is stable. The fluid is added periodically to maintain a constant water head. Volume of leakage through defect of GCLs was measured within a time interval.

3.2.4 Repeated wet-dry test

Effects of repeat wet-dry of GCLs to self-healing capacity of GCLs were conducted on GM-GCLs. The GM-GCLs were cut rectangular in the size of 30 cm x 30 cm, then put on the steel plate. Bentonite side was put up. A hole with bentonite lose was generated in the centre of GCLs tested with 0.010, 0.02 and 0.030 m-diameter. To prevent GCLs wrinkle during tests, the GCLs were clamped by fours bolt-nuts at both of the left and right side.

In the wet stage, water was sprayed above the GCLs about 10 cm from bentonite surface. Moisture content of the GCLs was adjusted into 100% for wet stage. Then the samples were covered with the plastic to prevent evaporation. After one week, hole size and water contents were measured. Then, the samples were inserted into the oven at
temperature of 50° C for a week then measured the hole size and water content again. These tests were repeated until 6 times.

3.3 Materials used and their properties

3.3.1 GCLs

The GM-GCL tested consists of 4 mm-thickness of granular bentonite layer that glued onto a 0.0005 m thickness of high density polyethylene geomembrane (HDPE). The GT-GCL tested consists of granular bentonite powders encased by geotextiles (one side woven and other side nonwoven). The woven and non-woven geotextiles are connected by needle punched fibers with pitches of 0.003 m × 0.0045 m. The weight of GM-GCL and GT-GCL are about 53 and 49 N/m² respectively. The photos of the GCLs are given in Fig. 3-13 and 3-14. The same type of bentonite was used in both the GM-GCL and GT-GCL. The bentonite used by the manufacturers from two locations and their chemical compositions are listed in Table 3-1. Properties of GM-GCLs and GT-GCLs were shown in Table 3-2, 3-2, 3-4 and 3-5.

Fig. 3-13 GM-GCL
Table 3-1. Chemical composition of the bentonite (X-ray semi-quantitative analysis)  
(The data are provided by the manufacturer)

<table>
<thead>
<tr>
<th>Wt (%)</th>
<th>Colony*</th>
<th>Lovell*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si as SiO₂</td>
<td>66.32</td>
<td>64.06</td>
</tr>
<tr>
<td>Al as Al₂O₃</td>
<td>21.16</td>
<td>20.56</td>
</tr>
<tr>
<td>Ca as CaO</td>
<td>0.80</td>
<td>1.08</td>
</tr>
<tr>
<td>Na as Na₂O</td>
<td>2.09</td>
<td>2.52</td>
</tr>
<tr>
<td>Mg as MgO</td>
<td>2.59</td>
<td>2.27</td>
</tr>
<tr>
<td>Fe as Fe₂O₃</td>
<td>1.73</td>
<td>1.87</td>
</tr>
<tr>
<td>K as K₂O</td>
<td>0.29</td>
<td>0.30</td>
</tr>
<tr>
<td>Cr as Cr₂O₃</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Mn as MnO</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Ti as TiO₂</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>V as V₂O₅</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Quartz</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Potassium feldspar</td>
<td>Trace</td>
<td>----</td>
</tr>
<tr>
<td>Plagioclase feldspar</td>
<td>Trace</td>
<td>4</td>
</tr>
<tr>
<td>Calcite</td>
<td>----</td>
<td>Trace</td>
</tr>
<tr>
<td>Opal</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Clinoptilolite</td>
<td>----</td>
<td>Trace</td>
</tr>
<tr>
<td>Dioctahedralsmectite</td>
<td>91</td>
<td>85</td>
</tr>
<tr>
<td>Illite</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

(*Samples from Colony and Lovell at Wyoming, USA)
Table 3-2. Properties of GT-GCL (The data are provided by the manufacturer)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Standards</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>ASTM D5993</td>
<td>6118 gr/m$^2$</td>
</tr>
<tr>
<td>Grab Strength</td>
<td>ASTM D4632</td>
<td>1067 N</td>
</tr>
<tr>
<td>Grab Elongation</td>
<td>ASTM D4632</td>
<td>100 %</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>ASTM D6768</td>
<td>9.8 kN/m</td>
</tr>
<tr>
<td>Peel Strength</td>
<td>ASTM D6496</td>
<td>1751.3 N/m</td>
</tr>
<tr>
<td>Index Flux</td>
<td>ASTM D5887</td>
<td>&lt; 1E-8 m$^3$/m$^2$/sec</td>
</tr>
<tr>
<td>Permeability</td>
<td>ASTM D5084</td>
<td>&lt;5E-9 cm/s</td>
</tr>
</tbody>
</table>

Table 3-3. Properties of Bentonite of GT-GCLs (Data provided by Manufacturer)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Standards</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content</td>
<td>ASTM D4643</td>
<td>9.0%</td>
</tr>
<tr>
<td>Swelling Index</td>
<td>ASTM D5890</td>
<td>29.0 ml</td>
</tr>
<tr>
<td>Fluid Loss</td>
<td>ASTM D5891</td>
<td>14.4 ml</td>
</tr>
<tr>
<td>Bentonite Mass Per Unit Area</td>
<td>ASTM D5993</td>
<td>17 kg/m$^2$</td>
</tr>
</tbody>
</table>

Table 3-4. Tensile Properties of HDPE in GM-GCLs (Data provided by Manufacturer)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Standards</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (ppi)</td>
<td>ASTM 0638-89</td>
<td>3925</td>
</tr>
<tr>
<td>Break Strength (ppi)</td>
<td>ASTM 0638-89</td>
<td>3500</td>
</tr>
<tr>
<td>Yield Elongation (%)</td>
<td>ASTM 0638-89</td>
<td>13</td>
</tr>
<tr>
<td>Break Elongation (%)</td>
<td>ASTM 0638-89</td>
<td>700</td>
</tr>
<tr>
<td>Puncture Resistance</td>
<td>Fed - 101</td>
<td>95</td>
</tr>
</tbody>
</table>
Table 3-5. Properties of Bentonite in GM-GCLs (Data provided by Manufacturer)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Standard</th>
<th>Value</th>
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<tbody>
<tr>
<td>Moisture (%)</td>
<td>ASTM D4643</td>
<td>8.8</td>
</tr>
<tr>
<td>Swelling Index</td>
<td>ASTM D5890</td>
<td>34</td>
</tr>
</tbody>
</table>

### 3.3.2 Liquids

Tap water, 10 g/l of NaCl solution, 100 ml/l of ethanol solution and 11.1 g/l of CaCl₂ solution were used as liquids in the tests. pH and electric conductivity of the liquids are given in Table 3-6. Device for measuring pH of fluid tested was shown in Fig. 3-15. While for measuring EC, Conductivity meter was used (Fig. 3-16).

Table 3-6. Properties of liquids and interact properties of liquids and bentonite

<table>
<thead>
<tr>
<th>Types of liquid</th>
<th>pH</th>
<th>$EC$ (µS/cm)</th>
<th>$w_L$ (%)</th>
<th>$w_p$ (%)</th>
<th>Swelling index (ml/2 gr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>7.02</td>
<td>105</td>
<td>537</td>
<td>45.8</td>
<td>21.5</td>
</tr>
<tr>
<td>Ethanol</td>
<td>7.46</td>
<td>85</td>
<td>560</td>
<td>67.4</td>
<td>30</td>
</tr>
<tr>
<td>NaCl</td>
<td>7.24</td>
<td>17600</td>
<td>235</td>
<td>46.3</td>
<td>16.5</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>7.60</td>
<td>199</td>
<td>165</td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>
Fig. 3-15 pH meter

Fig. 3-16 Conductivity meter
3.4 Interaction behavior of bentonite and the fluids

3.4.1 Liquid limit ($w_L$), plastic limit ($w_P$) and free swelling index

The liquid limit ($w_L$) and plastic limit ($w_P$) of the bentonite with the three types of fluids were tested per JIS A 1205 by using Atterberg devices. Whereas free swelling index tests were referred to ASTM D 5890. The result of the tests was listed in Table 3-6.

In free swelling index test, bentonite which was removed from GCLs was grinded to 100% passing a 100 mesh U.S Standard Sieve and a minimum of 65% passing a 200 mesh U.S. Standard Sieve with a ceramic mortar. Then bentonite was placed in oven at 105 ± 5°C for 24 hours. After that, weigh 2.00 ± 0.01 gr of dried bentonite and put on a weighing paper. Add 90 ml water tested to the clean 100 ml graduated cylinder (Fig. 3-17).

Grab ± 0.1 gr increment of bentonite powder with a spoon from weighing paper and carefully dust it over the entire surface of water in the graduated cylinder over a period of approximately 30 seconds. After bentonite wet, hydrate and settle to the bottom of graduated cylinder for a minimum period of 10 minutes. Additional increment of bentonite powder are added by following procedure mentioned above until the entire 2.0 gr bentonite has been added.

Rinse any adhering particles from sides of the cylinder into the water column carefully after the final increment has settled. Add the water into 100 ml in graduate cylinder. Then measure carefully temperature of water without disturbing the settled bentonite and record the temperature to ± 0.5°C.

The cylinder is placed undisturbed for minimum 16 hours from the last incremental addition. Check the hydrating bentonite column for trapped air or water separation after 2 hours from last additional bentonite powder. Tip the Cylinder at a 45° angle gently and roll slowly to homogenize the settled bentonite.
Finally record the volume of hydrated bentonite and its temperature after the cylinder was allowed undisturbed for minimum 16 hours. Record the volume level in milliliters at the top of the settled bentonite to the nearest 0.5 ml. Check the distinct change in appearance at the upper surface of the settled bentonite. Ignore low-density flocculated material (sometimes lighter in coloration to white) for measurement.

![Fig. 3-17 Photo of swelling free index test](image)

### 3.4.2 Free volume expand

To further confirm the mechanism of self-healing due to bentonite expansion, a simple free expansion test was conducted using the same bentonite as used in the GCLs tested. Bentonite was compacted inside of 0.07 m-diameter of PVC container. Then water content of compacted clay was adjusted into 20, 40, 60 and 80% by spraying water over the surface of bentonite. After 24 hours, height increment of compacted bentonite was recorded. The results are shown in Fig. 3-18.
It can be seen in Fig. 3-18 that bentonite tested expanded after adding water. The bentonite indicated more expands when water content was higher. For the fluid type, ethanol (10 % concentration) has the most volume expanded compare to tap water, salt water (1% concentration) and CaCl2 (1.1% concentration).

Fig. 3-18 Water content versus volume expand after 24 hours observation

3.4.3 Consolidation test

To observe effect of overburden pressure to volume increment of bentonite during hydration were conducted on Oedometer. Constant overburden pressure was applied during Consolidation tests. The results were shown in Fig. 3-19.

3.4.4 Swelling pressure

Swelling pressures of the bentonite were tested using an Oedometer device (Fig. 3-20) and basically following the procedure of Method-C of ASTM D 4546-96. Firstly, initial water content of the bentonite was adjusted to about 30% - 100% and put into a mold 0.060 m in diameter 0.02 m in height. Then apply a vertical pressure of 300 kPa for 2 hours to compress the sample. The resulting sample had a dry density of 760 kg/m$^3$ – 1020 kg/m$^3$. Then cut the sample into 0.005 m in thickness and reset it into the equipment for
swelling pressure test. The tests were conducted with constant volume condition and fluids were supplied until there was no more pressure change. Then the final pressure was recorded and the water content of the specimen was measured. Some typical swelling pressure versus elapsed time curves are presented in Fig. 3-21. The swelling pressure versus final water content curve for using tap water case is given in Fig. 3-22. The result shows that the tap-water and the ethanol solution have about the same swelling pressure, but the salt water has much lower swelling pressure when compared under the same water content condition.

As comparison, another swelling pressure test was conducted on Oedometer as per ASTM D4546-C. Bentonite was allowed to swell and compress during test. The result of the tests was shown in Fig. 3-23.
Fig. 3-20 Device of Swelling pressure test

Fig. 3-21 Typical swelling pressure with elapsed time
Fig. 3-22 Relationship between swelling pressure and water content of bentonite

Fig. 3-23 Water content versus Pressure
3.4.5 Undrained shear strength ($S_u$) of the bentonite

Fundamentally, the self-healing of GCL is the expansion of bentonite into a damage hole and/or squeezing of hydrated bentonite into the hole by overburden pressure. $S_u$ value is a key parameter affecting the squeezing effect. $S_u$ values of the bentonite with different water content of using the tap water, NaCl and CaCl$_2$ solutions were measured by a laboratory vane shear device and the results are shown in Fig. 3-24. The blade of the vane has a diameter of 0.020 m and height of 0.04 m. It can be seen that under the same water content condition, $S_u$ values of using the NaCl and CaCl$_2$ solutions are lower. This is because the bentonite with the NaCl and CaCl$_2$ solutions has lower $w_L$ values as indicated in Table 3-6. At a water content of about 200%, it is close to the $w_L$ value for the NaCl solution, but it is only about 1/3 of $w_L$ of the tap water case.

Fig. 3-24 Undrained shear strength ($S_u$) of bentonite versus water content
### Table 3-7. Cases tested

<table>
<thead>
<tr>
<th>GCL</th>
<th>Type of the test</th>
<th>Fluid</th>
<th>Diameter of hole (d), mm</th>
<th>Overburden pressure ($p'$), kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM-GCL</td>
<td>Falling head</td>
<td>Tap water</td>
<td>5</td>
<td>100, 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water</td>
<td>10</td>
<td>25, 50, 100, 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water</td>
<td>20</td>
<td>100, 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NaCl</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CaCl$_2$</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water</td>
<td>40</td>
<td>25, 200</td>
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<tr>
<td></td>
<td></td>
<td>Tap water</td>
<td>40</td>
<td>50, 200</td>
</tr>
<tr>
<td></td>
<td>Constant head</td>
<td>Tap water</td>
<td>40</td>
<td>0, 25, 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NaCl</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ethanol</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CaCl$_2$</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
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<td>Tap water</td>
<td>30</td>
<td>200</td>
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<td>0, 50, 100, 200</td>
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<td>NaCl</td>
<td>40</td>
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<tr>
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<tr>
<td></td>
<td></td>
<td>CaCl$_2$</td>
<td>40</td>
<td>0</td>
</tr>
</tbody>
</table>

#### 3.5 Test program

The test program was designed to investigate the effect of overburden pressure ($p'$), types of fluid and the size of the damaged hole on self-healing capacity of both GM-GCL and GT-GCL. The leakage rate tests conducted are summarized in Table 3-7. It can be seen that the range of $p'$ considered was 0 ~ 200 kPa, diameter of damaged hole (with bentonite lose) was 0.005 ~ 0.05 m; and four types of fluid, tap water, 10 g/l of NaCl solution, 100 g/l of ethanol solution and 11.1 g/l of CaCl$_2$ solution were used.
CHAPTER 4
RESULTS OF LEAKAGE RATE AND REPEATED WET-DRY TESTS

4.1 Introduction

This chapter presented results from falling head and constant head leakage rate tests and repeated wet-Dry tests of Geosynthetic Clay Liner (GCL) with defects. For falling head and constant head leakage rate tests, two types of GCL i.e. geomembrane supported GCL (GM-GCL) and geotextile encased GCL (GT-GCL), were tested. While for Repeat Wet-Dry test, the test conducted only on GM-GCLs type.

For Falling head and constant head leakage rate tests, the results are presented in the form of flow rate ($Q$) and permittivity ($\psi$) variations with time. Comparisons hole size ($d$), liquid type and overburden pressure ($p'$) on $Q$ and $\psi$ values. Whereas for Repeated Wet-Dry tests, the results is presented in hole size ($d$) and water content ($w$) of GCLs with respect to the number wet-dry cycles.

4.2 GM-GCL

The flow rates ($Q$) of the falling head leakage rate tests, are calculated based on Darcy law. For comparison purpose by assuming the same head difference as for the constant head tests using the following equation:

$$Q = \frac{2.3a\Delta h}{\Delta t} \log \left( \frac{h_1}{h_2} \right)$$

(4-1)

where $a$ is the cross sectional area of the burette ($2 \times 10^{-4} \text{ m}^2$), $\Delta h = 0.32 \text{ m}$ (head difference) which is the same value as used for the constant head test, $\Delta t$ is duration of observation, $h_1$ is the water level at time ($t$) and $h_2$ is the water level at $t + \Delta t$.

For the constant head leakage rate test, flow rate through defect of GCL is determined by using following equation:
where $Q_T$ is the volume of leakage within a time interval of $\Delta t$.

Since it is not easy to measure accurately thickness of GCLs during leakage rate test, it is considered that permittivity is preferable to assess hydraulic performance of GCLs (e.g. Gartung and Zanzinger, 1998). Term of *Permittivity* refers to flux, that is the quantity of liquid permeates through an area under a certain hydraulic gradient in certain duration.

In this study, to quantify the liquid flow through the healed or partially healed damaged hole, the apparent permittivity ($\psi$) of the damaged hole is defined as;

$$\psi = \frac{Q}{A\Delta h}$$  \hspace{1cm} (4-3)

where $A$ is the defect area and $\Delta h$ is head difference.

### 4.2.1 Typical flow rate ($Q$) – time ($t$) curves

Typical leakage rate versus elapsed time curves are given in Figs 4-1 and 4-2 for the falling head and Fig. 4-3 for constant head conditions respectively. As shown in Fig. 4-1 and 4-2, for the falling head tests, flow rate ($Q$) reduced sharply in the first three days of the test and then became more or less stable. While for the constant head tests, the flow rate gradually reduced as shown in Fig. 4-3. The initial faster reduction of the flow rate of the falling head test is partially due to the use of the inlet water volume to calculate the flow rate, i.e. the amount of the water absorbed by the bentonite in earlier period of hydration is included as part of the flow rate.
Fig. 4-1 Flow rate with elapsed time for $p' = 200$ kPa

Fig. 4-2 Flow rate with elapsed time for $p' = 100$ kPa
4.2.2 Effect of hole-size

To observe the influence of hole size to self-healing capacity of GM-GCLs, a serial of test was conducted on GCLs with the hole size \(d\) of 0.005 to 0.050 m in diameter. Overburden pressure of 25 to 200 kPa was applied during leakage rate tests. Result of the Falling head tests was presented in Figs. 4-4 (a) and (b) in terms of flow rate \(Q\) and permittivity \(\psi\) respectively. Relationships between \(\psi\) and the diameter of the damaged hole from Falling head test was depicted in Fig. 4-5.

It can be seen that up to \(d = 0.02\) m, \(\psi\) reduced with the increase of \(d\). For further increase of \(d\), \(\psi\) reversely increased. Increasing of \(\psi\) with increasing of \(d\) value is easy to understand because the larger the \(d\) value, the higher the possibility that part of the damaged area might not be “healed“ due to the expansion of the bentonite.
Flow rate with elapsed time

Permittivity with elapsed time

Fig. 4-4 Influence size of hole to self-healing capacity of GM-GCLs
However, for $d$ less than 0.02 m, $\psi$ increased with the decrease of $d$ value, needs an explanation. As illustrated in Fig. 4-6, when liquid enters the hole, some part will flow through the hole, and the other part may percolate into the surrounding bentonite or GM/bentonite interface (Chai et al. 2005; Chai et al. 2008).

![Graph showing relationships between permittivity and size of hole](image)

Fig. 4-5 Relationships between permittivity and size of hole

Especially after some bentonite had expanded into the hole, the lateral percolation/spreading effect will be enhanced. The percentage contribution of the lateral percolation/spreading on total flow rate is more significant for a smaller hole, and it increased apparent $\psi$ value of the smaller hole.

Post-test inspections of the healed area in the GCLs tested revealed that up to $d = 0.03$ m, the hole was completely filled by hydrated bentonite. While for $d \geq 0.03$ m, the damaged hole could not be healed completely. Apparently continuous bentonite layer of uniform thickness had reformed in the damaged hole as shown in Fig. 4-7. For some tests, the bentonite in the healed area was collected and the water contents were measured. The water content of the healed area was found much higher (typically 2~4 times) than
surrounding area of healing. Water content of the bentonite in a GCL sample around defect was lower than that in the defect hole. It is caused by two factors. First, overburden pressure limited the expansion of bentonite vertically and prevented the full hydration. Second, bentonite in GM-GCL was compacted initially and the amount of the heaving is limited for a compacted sample. Fig. 4-8 shows moisture distribution of bentonite in GCLs after the leakage rate test.

Fig. 4-6 Illustration of flow through a damage hole

Relationships of hole size \(d\) - water content \(w\) in healed area is plotted in Fig. 4-9. It shows that water content in the healing area increased with the increased of the hole size.
Fig. 4-7 Photo of GCLs for $d = 0.01$ m and $p' = 100$ kPa after Falling head test

Fig. 4-8 Moisture distribution of bentonite in GCLs
4.2.3 Effect of liquids

The effect of type of liquid on self-healing capacity of the GM-GCL is investigated by constant head tests and falling head test. For the constant head condition, tests were performed under damaged hole \(d = 0.04\) m, and \(p' = 0\) kPa condition. While for falling head condition, tests were conducted under \(d = 0.03\) m, and \(p' = 200\) kPa. Flow rates and \(\psi\) values versus elapsed time curves from constant head test are compared in Figs. 4-10, while for \(\psi\) values versus elapsed time curves from falling head test is shown in Fig. 4-11. Photo of GCL sample after constant head tests are presented in Figs. 4-12 ~ Fig. 4-14.

It can be seen from Fig. 4-10 and Fig. 4-11 that CaCl\(_2\) solution case has the highest \(\psi\) value for both condition tested, while ethanol solution has the lowest \(\psi\) value (Fig. 4-10). The final \(\psi\) value of CaCl\(_2\) solution case is about 2 orders higher than value of ethanol case. To further quantify the self-healing capacity, a parameter of area healing ratio \((\alpha_h)\) is defined as:
\[
\alpha_h = \left(1 - \frac{A_f}{A_i}\right) \times 100\%
\]

(4-4)

where \( A_f \) is the final unhealed area of the damaged hole which can be measured after a test, and \( A_i \) is the initial area of the hole. For \( d = 0.04 \text{ m} \) and under \( p' = 0 \text{ kPa} \) condition the \( \alpha_h \) values of using the tap water, ethanol solution, NaCl solution and the CaCl₂ solution case are 88, 90, 43 and 23 \% respectively. They are the same order as those of free swelling index in Table 3-7. Relatively the larger the free swelling index, the higher the \( \alpha_h \) value. For the case in Fig. 4-10, roughly \( \alpha_h \) value (percent) is about 3 times of the corresponding of free swelling index. For Falling head test the \( \alpha_h \) values of using the Tap water, NaCl solution and CaCl₂ are 100 \%, 59 \% and 33.5 \% respectively.

Fig. 4-10 Comparison of flow rate with different type of liquids
Fig. 4-11 Permittivity versus elapsed time curves for different type of liquids

Fig. 4-12 Photo of GCLs after constant head test for Tap water as liquid
After the leakage rate test, the water contents of the bentonite expanded into the hole, as well as around the hole were measured and the results are depicted in Fig. 4-15. The dashed lines in the figure just provide a guide for getting a picture of water content variation pattern. For \( d = 0.04 \) m, \( p' = 0 \) kPa cases (constant head), water contents of the \( \text{CaCl}_2 \) solution case were obviously lowest among other cases. The water contents of the bentonite around the hole are about 120 % for salt water and \( \text{CaCl}_2 \) and about 220 % for
the tap water and ethanol respectively. From the result in Fig. 3-22 Su values for about 220% (extrapolating) of the tap water and about 120% of CaCl$_2$ solution are about the same.

The effect of liquid type on the self-healing capacity of GM-GCL can be explained by theory of Diffuse Double Layer (DDL) (e.g. Gray and Mitchell, 1967; Gray and Schlocker, 1969). The thickness (1/K) of DDL is related to square root of dielectric constant, $D$, and $D$ is reversely related to electric conductivity, $E_c$ ($D \propto 1/E_c$) of the solution, and then:

$$\frac{1}{K} \propto \frac{1}{E_c^{1/2}} \quad (4-5)$$

The $E_c$ value of NaCl and CaCl$_2$ solution tested are more than 2 orders higher and two times than that of the tap water and the ethanol solution (Table 3-6), which will have a thinner double layer around the surface of the bentonite particles. In addition, cation concentration and valence of cation also influence $1/K$ value, and the qualitatively NaCl and CaCl$_2$ case tend to result in a smaller $1/K$ value in term of cation concentration and valence for CaCl$_2$ case.

A direct indication of $1/K$ value may be the free swelling index in Table 3-6, in which the value for the salt water and CaCl$_2$ solution are 16.5 ml/2 gr and 9 ml/2 gr, which is about 75% and 40% of the value for the tap water case. The thinner double layer means that under a given condition the bentonite will expand less, and leaves a relative larger portion of the damaged hole not being healed. Another point that may contribute to the smaller $\psi$ value for the ethanol solution compared to the tap water case is the viscosity of the solution. Petrov et al. (1997) reported that ethanol-water mixture with concentrations < 50% increased viscosity of the liquid and decreased hydraulic conductivity of GCL.
Comparing the results in Figs. 4-10 and Fig. 4-11, it indicates that the effect of type of liquid is not significantly influenced the overburden pressure. Moreover, under \( p' = 200 \) kPa, the water contents of the bentonite around the damage hole of the GM-GCL samples are about 50% for tap water, salt water and CaCl\(_2\) solution as shown in Fig. 4-16, which is much lower compare to condition under \( p' = 0 \) kPa (Fig. 4-15), due to the constrain effect.
It seems that for tap water case, the hydration might be not finished yet. Water content of NaCl in the healed area indicated higher than \( w_L \) (Fig. 4-15), even higher than water content of tap water (Fig. 4-16). It might be due to incidentally collecting both of bentonite and free water surround of bentonite for measuring moisture content. However, for the case of tap water, water content reduced as \( p' \) increasing. Thicknesses of the bentonite in the sample after test were about 0.008 m and 0.004 m for \( p' = 0 \) kPa and 200 kPa respectively. Assuming that due to the combination between hydration and pressure squeezing effects, the amount of the bentonite entered the hole is about the same for both \( p' = 0 \) and 200 kPa conditions. Under \( p' = 0 \) kPa, the bentonite had a larger space to fill and can freely expand, and resulted in a water content of about 500 % (Fig. 4-15) compared with \( w = 200 \) % for \( p' = 200 \) kPa case (Fig. 4-16). If the area healing ratio is about the same, the lower water content means lower void ratio and lower permeability. However, this kind of effect may depend on the size of a damage hole.

4.2.4 Effect of overburden pressure \((p')\)

Effect of overburden pressure to self-healing capacity of GCLs was observed by conducted leakage rate test under several value of \( p' \). Comparison of permittivity with elapsed time subjected by different \( p' \) is shown in Fig. 4-17. It shows that permittivity decreased as \( p' \) increased.

Two possible effects of \( p' \) can be considered. One is squeezing effect which intends to push the hydrated bentonite into the damaged hole and increasing healing ratio, and the other is the constraining effect which intends to limit the expansion of the bentonite vertically and hinder the full hydration of the bentonite. This is especially when \( p' \) is larger than the swelling pressure of the bentonite with a given initial density and water content. The constraining effect of \( p' \) may reduce the self-healing capacity of a GCL. With the results in Fig. 4-17, it seems that the squeezing effect is more important for the conditions tested.
For $d = 0.04$ m cases, the water contents of the bentonite in and around the hole are shown in Fig. 4-18. For $p' = 0$ kPa case, the water content of the bentonite in the hole is close to its liquid limit. The results of $p' = 25$ kPa and 50 kPa cases are similar, while $p' = 200$ kPa case had resulted in lowest water content of the bentonite.
After the tests, the samples were photographed and the pictures are shown in Figs. 4-19 and 4-20. The figures showed clearly that increasing of $p'$ value increased the self-healing capacity (reducing of unhealed area).

![Images of samples after tests]

(a) $p' = 0$ kPa  
(b) $p' = 25$ kPa

Fig. 4-19 Shape of holes after leakage rate test at $p' = 0$ and 25 kPa ($d = 0.04$ m)

4.3 GT-GCLs

4.3.1 Typical flow rate ($Q$) – time ($t$) curves

Typical flow rates ($Q$) - time ($t$) curves for GT-GCL are given in Figs. 14-21 and 4-22. The tendency is the same as that of the GM-GCL where the values of flow rate are also comparable with that of the GM-GCL (Fig. 4-4). For GM-GCL, the liquid can only flow through the hole.
However for GT-GCL, the liquid can also flow through the undamaged area even it may be a very small portion. For convenience to investigate the effect of the hole-size, the flow rate through the hole ($Q_h$) of GT-GCLs is defined as follows:

$$Q_h = Q - Q_{\text{int}}$$

(4-6)

where $Q$ is the total flow rate and $Q_{\text{int}}$ is the flow rate through the intact part of a specimen. The flow rate ($Q$) – $p’$ relationship of the intact GT-GCL is depicted in Fig. 4-21. The $Q$ values in Fig. 4-23 correspond to the steady value. These data will be used to calculate $Q_{\text{int}}$ in Eq. (4-6).
Fig. 4-21 Flow rate with elapsed time of GT-GCLs for $d = 0.03$ m

Fig. 4-22 Flow rate with elapsed time of GT-GCLs for $d = 0.04$ m
Fig. 4-23 Comparison of flow rate under $p'$ value of Intact GT-GCLs

4.3.2 Effect of hole-size

Comparison of flow rate through GCLs for several $d$ is showed in Fig. 4-24. The steady $\psi$ value versus the diameter of the hole is depicted in Fig. 4-25. The water contents of bentonite in the sample tested are plotted in Fig. 4-26.

For the case of $d = 0.03$ m, $\psi$ value is lower than $d = 0.04$ m and 0.05 m cases. The $\psi$ value of the hole of $d = 0.03$ m case is more than 10 times of that of the intact GT-GCL. After the test, inspection of sample tested showed that for $d = 0.03$ m case, the hole was almost healed, but for $d = 0.04$ m and 0.05 m cases, there were un-healed portions as shown in Fig. 4-27 and 4-28. The figures show that $d = 0.05$ m case has a larger unhealed area, but the $\psi$ value in Fig. 4-25 is slightly smaller than that of $d = 0.04$ m case, which may due to the spatial variation of the GT-GCL samples tested.
Fig. 4-24 Influence of hole size on the flow rate through GCLs

Fig. 4-25 $\psi$ versus $d$ for GT-GCLs after Constant head test
For the GT-GCL tested, there were certain variations of thickness of the bentonite layer in it. The apparent inconsistency for the results in Fig. 4-27 and the pictures in Fig. 4-28 for \(d = 0.04\) m and \(d = 0.050\) m cases may be due to the possible variation of the samples used.

Fig. 4-27 Photo of GT-GCLs specimens after Constant head test

(a) \(d = 0.03\) m \((p' = 200\) kPa\)

(b) \(d = 0.04\) m \((p' = 200\) kPa\)

Fig. 4-26 Moisture Distribution of GT-GCLs under \(p' = 200\) kPa
4.3.3 Effect of liquids

Unlike GM-GCL, for GT-GCL, the liquid can flow through the undamaged area even the flow rate maybe very small. Using eq. (4-6), and considering the steady state condition, $\psi$ values for four different types of liquid are compared in Fig. 4-29. It shows that NaCl and CaCl$_2$ cases are more than 4 and 3 orders higher than that of the tap water case. The degree of the effect is more than GM-GCL, might be due to different structure of the GT-GCL samples which were not very uniform.

Photo of the GT-GCL samples after leakage rate tests are shown in Fig. 4-31 ~ Fig. 4-34. They are similar with that of GM-GCLs in Fig. 4-12 ~ Fig. 4-14. The area healing are 95 %, 99 % and 28 % for the tap water, ethanol solution and NaCl respectively. The water contents of the bentonite in the healed area and surrounding area of GT-GCLs tested were measured and shown in the Fig. 4-30. The values are comparable with that of GM-GCL (Fig. 4-15), but little bit lower. It is considered may be due to some restriction from the needle punched fibres connecting two layers of geotextile. The bentonite in GT-GCL specimen was obtained cutting sub-sample from GT-GCL specimen at appropriate locations and then separated the bentonite and geotextiles of the sub-samples.
The effect type of liquid is more than that of the GM-GCL, partially because the liquid not only influences the permittivity of the damage hole but also the intact part of GT-GCL sample.

![Permittivity of GT-GCLs by different liquids](image)

Fig. 4-29 Permittivity of GT-GCLs by different liquids

Increasing the concentration of Na\(^+\) in water can also increase the hydraulic conductivity of GT-GCL (e.g. Petrov and Rowe, 1997; Shackelford et al. 2000). As compared to the tap water case, $Q$ value of the ethanol solution case is slightly higher for the condition considered. This tendency is different from that of the GM-GCL. Since the GT-GCL tested was not very uniform owning to its structure, it is considered that the slight higher or lower is within the limit of the spatial variation of the samples.

![Moisture distribution of bentonite in GCLs after test for different liquids](image)

Fig. 4-30 Moisture distribution of bentonite in GCLs after test for different liquids
Fig. 4-31 Photo of GT-GCL specimens after test for tap water case ($d = 0.04$ m, $p' = 0$ kPa)

Fig. 4-32 Photo of GT-GCL specimens after test for Ethanol case ($d = 0.04$ m, $p' = 0$ kPa)
Fig. 4-33 Photo of GT-GCL specimens after test for NaCl case ($d = 0.040$ m, $p' = 0$ kPa)

Fig. 4-34 Photo of GT-GCL specimens after test for CaCl$_2$ case ($d = 0.04$ m, $p' = 0$ kPa)
4.3.4 Effect of overburden pressure ($p'$)

The effect of $p'$ on the self-healing capacity of GT-GCL was investigated under $p' = 0$ kPa, 50 kPa, 100 and 200 kPa. Results of the test are plotted in the Figs. 4-34 ~ 4.37. The deduced $\psi$ values of the hole are compared in Fig. 4-38. Distribution of water content is showed in Fig. 4-39 while photo after the tests are shown in Figs. 4-40 ~ 4-43.

As shown in Fig. 4-36, the $\psi$ values tend to reduce with the increase of $p'$ value. Mazzieri and Pasqualini (2000) reported that for damaged GT-GCL, its hydraulic conductivity reduced with the increase of $p'$ value up to 200 kPa and had remained almost constant for higher $p'$ value. Although the data from this study are limited, the trend seems similar with the results by Mazzieri and Pasqualini (2000).

![Graph showing the influence of $p'$ on Permittivity of GT-GCLs](image)

**Fig. 4-35 Influenced of $p'$ on Permittivity of GT-GCLs**
Fig. 4-36 Comparison of permittivity between intact and damaged GCLs at $p' = 0$ kPa

Fig. 4-37 Comparison of permittivity between Intact and damage GCLs at $p' = 100$ kPa
Fig. 4-38 Comparison of permittivity between Intact and damage GCLs at $p' = 200$ kPa

Fig. 4-39 $\psi$ versus $p'$ for GT-GCLs after Constant head test
Fig. 4-40 Influence of $p'$ on moisture distribution of GT-GCLs for $d = 0.05$ m

Fig. 4-41 Shape of hole of GT-GCLs after tests for $d = 0.05$ m at $p' = 0$ kPa
Fig. 4-42 Shape of hole of GT-GCLs after tests for $d = 0.05$ m at $p' = 50$ kPa

Fig. 4-43 Shape of hole of GT-GCLs after tests for $d = 0.05$ m at $p' = 100$ kPa
Fig. 4-44 Shape of hole of GT-GCLs for \( d = 0.050 \) m at \( p' = 200 \) kPa

### 4.4 Repeated wet dry Test

Effect of Repeated wet-dry test was conducted to investigate the effect of wet-dry cycles on the size of the damaged hole. A hole of 0.01, 0.02 and 0.03 m in diameter was created at the centre of each GCL sample. Photos of samples are showed in Figs. 4-44 for \( d = 10 \) mm. The result of the tests is plotted in Figs. 4-45 and 4-46.

In the first cycle of wet test, the size of the holes was reduced for \( d = 0.03, 0.02 \) and 0.01 m in diameter, the area healing ratios are 27, 35 and 40 % respectively. However, during dry test, bentonite in GM-GCLs cracked and size of hole increased. Although in the further wet tests (2\(^{nd}\) ~6\(^{th}\)), there was further reduction of the size of the hole, but the incremental reduction was much lower than the first cycle. In the 6\(^{th}\) wet test, GCLs with 30, 20 and 10 mm-diameter shown area healing ratios of 43, 60 and 80 % respectively.
(a) Wet Test

Fig. 4-45 Photo of repeat wet-dry test

(a) Dry test
Repeated Wet-Dry test
Tap water
GM-GCL

Number of wetting-drying cycles

Fig. 4-46 $d$ versus wet-dry cycles
Fig. 4-47 Water content versus wet-dry cycles
4.5 Discussions

In engineering practice, an important question is what kind of damage on GCLs under what kind of conditions can be self-healed. Although there is no simple answer for this question, based on the test results presented in this chapter, some general tendencies and reference numbers are discussed in this section.

4.5.1 The size of a hole can be self-healed

Although there is no universal agreement or definition on the relative leakage rate (or permittivity) of a self-healed hole, based on the test results presented in the previous section, a damaged hole with a diameter \( d \) less than 0.03 m can be self-healed if the liquid is fresh water or the mixture ethanol and tap water. For the GT-GCL tested under \( p' = 200 \) kPa and \( d = 0.03 \) m, visually the hole was filled by the expanded bentonite (Fig. 4-27), and for the GM-GCL, when \( d = 0.04 \) m, there was an unhealed portion at the end of the test (Fig. 4-12). Regarding the test result for \( d = 0.03 \) m, compare to \( \psi \) value of undamaged GT-GCLs (intact), \( \psi \) value of both of GM-GCL and GT-GCLs is about ten times higher. Referring to this number we would like to suggest that a self-healed damaged hole of GCL should have a value of permittivity less than about 10 times of the intact GCL.

For GM-GCL tested, the initial thickness of the bentonite layer was about 0.004 m with an initial total unit weight of the bentonite of about 9.4 kN/m\(^3\) and water content of about 10%. Assuming the specific gravity of the bentonite of 2.7, an initial void ratio of about 1.9 can be calculated. After the leakage rate test, the water contents of the bentonite inside the hole are about 300 % for \( p' > 25 \) kPa (Fig.12). Assuming the thickness of bentonite inside the hole is about 0.004 m, then for \( d = 0.03 \) m case, about 1 gr bentonite needs to be squeezed into the hole, which is about 1.5 % of the bentonite in a 0.15 m diameter specimen. If the diameter of the hole is increased to 0.04 m, under the same condition, the amount of the bentonite required will be almost doubled.

The number of \( d = 0.03 \) m was the same as suggested by Mazzieri and Pasqualini (2000) and Babu et al. (2001). Mazzieri and Pasqualini (2001) showed that the hydraulic conductivity of GCLs with damage is not change significantly compare to that of the intact GCLs. They reported that up to \( d = 0.03 \) m-diameters, damaged of GCLs could be healed properly with distilled water as liquid. However, if the liquid is a cation rich solution, a hole can be self-healed will be smaller. By using relative value of \( a_h \) and under area equivalent assumption, size of hole can be healed for 10 gr/l of NaCl and 11.1 g/l of CaCl\(_2\) are 0.02 m and 0.015 m in diameter, respectively.
4.5.2 Influence of liquid types on self-healing capacity of GCLs

As mention in the earlier section, the mechanism of self-healing of GCLs is bentonite expanded into the hole during leakage rate tests. Overburden pressure which applied during tests push the hydrated bentonite into the damaged hole and increased healing ratio. Mazzieri and Pasqualini (2000) proposed that bentonite hydrated and migrated from the adjacent portion of specimen into the hole during hydration. The bentonite particles accumulate at the effluent end and form a seal by free swelling rapidly. Egloffstein (2001) added that to close the cracks, bentonite absorbed water, expand and plastification.

For \( d = 0.04 \) m and under \( p' = 0 \) condition, the healing ratio \((\alpha_h)\) values of using the tap water, ethanol solution, NaCl solution and the CaCl\(_2\) solution case are 88, 90, 43 and 23 % respectively. They are the same order as those of free swelling index in Table 3-6. Relatively the larger the free swelling index, the higher the \( \alpha_h \) value. Similar conclusion was drawn by Babu et al. (2001) which state that self-healing capacity of GCLs can be investigated from percent swell values. The swelling of clay particles is attributed to the volume of water molecules that are bound to the clay surface (Jo et al. 2001). Volume of bound water on clay mineral surface is influenced by chemical properties of liquid (Mesri and Olson 1971).

In this study, when NaCl solution was used as liquid, permittivity of GCLs is 17 times higher than that of tap water case. This occurred due to increasing of electric conductivity \((EC)\) of NaCl solution of about 150 times of the tap water, leads to reducing of free swelling index of bentonite (about 50%) from value of tap water case, and resulting in smaller free swelling index of bentonite. According to theory of Diffusive Double Layer (DDL), increasing of cation concentration in the fluid will reduce thickness of DDL. The thinner of DDL means bentonite swells less and leaves relative large portion of damage hole not to be healed.

4.5.3 Influenced of the overburden pressure on self-healing capacity

Result of the tests shows that for the case of size of damaged hole \( (d) \) up to 0.03 m in diameter, overburden pressure \((p')\) of 200 kPa is appeared sufficient to close the damaged
hole for both of GM-GCLs and GT-GCLs. For the case of $d = 0.04$ m and $0.05$ m in diameter for GM-GCL and GT-GCL respectively, increasing of overburden pressure increases healing ratio ($\alpha_h$).

As mention in the previous chapter, overburden pressure plays mainly two significant roles. First, pushes the hydrated bentonite into damaged hole and increases healing ratio ($\alpha_h$). Several studies on bentonite migration have been reported (e.g. Fox et al. 1996; Fox et al. 1998; Fox et al. 2000; Stark, T.D., Choi, H., Akhtarshad, R. 2003). The stress concentration, caused by an overlying layer of gravel could induce bentonite migration (Fox et al. 2000). Moreover, hydrate bentonite could migrate to areas of lower normal stress due to the stress concentration or non-uniform stresses (Stark et al. 2003). The potential for bentonite movement will increase with increased moisture content (Jeffries and Jones. 2003).

Another role of overburden pressure is constraining effect with intends to limit the expansion of the bentonite vertically and hinder the full hydration of the bentonite, especially if $p'$ value is larger than the swelling pressure of bentonite with a given initial density and water content. In fact, the constraining effect of $p'$ may reduce the self-healing capacity of a GCL.

4.5.4 Different healing mechanism of GM-GCL and GT-GCL

For GM-GCL, the liquid can percolate into the bentonite from a damaged hole and the underlying soil (porous stone as for the laboratory tests conducted). While for GT-GCL, liquid can enter the bentonite from the whole sample. This difference has two consequences. The first is bentonite in GT-GCL will be hydrated faster than that GM-GCL and resulting in a quicker healing. Another is the distribution of overburden pressure over the sample is different between GM-GCL and GT-GCLs.

For GM-GCL, when the bentonite around the hole is hydrated, it tends to expand and some kind of temporary “pressure concentration” can be developed around the hole under laboratory test condition (equal vertical displacement). For GT-GCL, liquid can enter the bentonite layer from the surface of whole sample, and there should be less or no “pressure concentration” phenomenon. However, the test results do not show obvious difference of the effect of $p'$ on the self-healing behavior of the both types GCLs tested.
4.6 Summary

Result of Falling head and Constant head leakage rate tests and Repeated Wet-Dry tests for GCL samples have presented in this chapter. For the leakage rate tests, tow type of GCLs, e.g. geomembrane supported GCL (GM-GCL) and geotextile encased GCL (GT-GCL), were tested. And for Repeated wet-dry test, only GM-GCL was used. For Falling head and Constant head leakage rate tests, the results are presented in the terms of flow rate ($Q$), permittivity ($\psi$) versus elapsed time, moisture distribution ($w$) and photo of the GCL samples after the leakage rate tests. Whereas for repeated wet-dry test, relationships of hole size ($d$) and water content ($w$) of GCLs with the number of wet-dry cycles are presented.

(1) Flow rate versus elapsed time

Typically, for both of GM-GCLs and GT-GCLs, flow rate was high in the first day of the leakage rate test, and then reduced with elapsed time until approached more or less a stable value. For Falling head leakage rate test, flow rate reduced sharply in the first three days while for Constant head leakage rate test, flow rate reduced gradually. The initial faster reduction in the Falling head condition partially due to the use of the inlet water volume to calculate the flow rate. The amount of the water absorbed by the bentonite in earlier period of hydration is included as part of the flow rate.

(2) Effect of the size of damaged hole ($d$)

In the range of $d = 0.005 \sim 0.03$ m, $\psi$ reduced with the increased of $d$ value. However for $d > 0.03$ m, $\psi$ increased with the increased of $d$ value. For $d > 0.03$ m, $\psi$ increased with increased of $d$ value is understandable since the higher $d$ value, possibility of part of damaged area to be “healed” is also lower. As for $d = 0.005 \sim 0.03$ m, $\psi$ reduced with the increased of $d$ value, it is considered due to the effect of lateral percolation/spreading of flow. The percentage contribution of the lateral percolation/spreading on total flow rate is more significant for a smaller hole, and it increased apparent $\psi$ value of the smaller hole.

For both the GM-GCL and GT-GCL samples, it is suggested that a hole up to a
diameter of 0.03 m can be self-healed. However, if the liquid is a cation rich solution, a hole can be self-healed will be smaller. By using relative value of $\alpha_h$ and under area equivalent assumption, size of the hole can be healed for 10 gr /l of NaCl and 11.1 g/l of CaCl$_2$ solutions are 0.02 m and 0.015 m in diameter, respectively. In addition, for a healed hole, the $\psi$ value is more than 10 times of the value of the intact GT-GCL.

(3) Effect of the type of liquid

Effect of liquid types on self-healing capacity of GM-GCLs is investigated by Constant head leakage rate test. The results shows that under $d = 0.04$ m and $p' = 0$ kPa condition, 11.1 g/l of CaCl$_2$ and 100 gr/l of ethanol solutions resulted in the highest and the lowest $\psi$ value respectively. The final $\psi$ value of CaCl$_2$ case is almost 2 orders higher than ethanol solution case. The $\alpha_h$ values of using the tap water, ethanol, NaCl and CaCl$_2$ solutions are 88, 90, 43 and 23 % respectively. They are the same order as those of free swelling index.

Similar with the results of GM-GCLs, under the same condition, for GT-GCLs, $\psi$ value of NaCl and CaCl$_2$ solution are more than 4 and 3 orders higher than tap water case. The degree of the effect of GT-GCLs is more than that of GM-GCL, and it may due to different structure of GT-GCLs compare to GM-GCLs.

(4) Effect of overburden pressure ($p'$)

Effect of overburden pressure ($p'$) to self-healing capacity of GCLs was observed by conducted leakage rate test under various $p'$. For both of GM-GCL and GT-GCL type, the $\psi$ value tends to reduce with increase of $p'$ value. Two possible effect of $p'$ can be considered. One is squeezing effect which intend to push the hydrated bentonite into the damage hole and increasing healing ratio, and the other is the constraining effect which intends to limit the expansion of the bentonite vertically and hinder the full hydration of the bentonite with a given initial density and water content. The constraining effect of $p'$ may reduce the self-healing capacity of a GCL.
(5) Repeated wet-dry test

From repeated wet-dry test, the results show that up to 6 wet-dry cycles, there is a tendency of slightly reducing size of damage hole with the increase of the number of cycles when wet. However, when the sample was dry, the size of the hole was increased again.
CHAPTER 5
CONCLUSIONS

5.1 Conclusions

Self-healing capacity of Geosynthetic Clay Liners (GCLs) both geomembrane supported, GM-GCL, and geotextile encased, GT-GCL, has been investigated by laboratory leakage rate tests. The effect of wet-dry cycles on the size of the damage on GCLs has been investigated by laboratory repeated wet-dry test. The influential factors on self-healing capacities of GCLs investigated are overburden pressure ($p'$), types of liquid and the size of damage hole ($d$). Based on the test results, the following conclusions can be drawn.

(1) Variation of flow rate with time. For both of the GM-GCL and GT-GCL samples tested with a damage hole, flow rate was high in the first day of the leakage rate test, and then reduced with elapsed time until approached a more or less stable value. It is considered that the gradual reduction of the flow rate due to the gradual hydration/expansion of the bentonite in the GCLs and part of the hydrated bentonite will enter the damage hole.

(2) Size of a damage hole can be self-healed. For both the GM-GCL and GT-GCL, a damage hole up to 30 mm in diameter can be self-healed if the fluid is tap water or ethanol solution (10%). For 1% of NaCl and 1.1% of CaCl$_2$ solutions, the size of a hole can be self-healed is estimated to be 20 mm and 15 mm in diameter, respectively. The test results indicate that a healed damage hole (area) has a permittivity about 10 times of the corresponding intact GCL.

(3) Effect of the types of liquid. All factors influence the thickness of the diffusive double layer around particles of bentonite will affect the self-healing capacity of GCLs. The free swelling index of the bentonite can be used to evaluate the relative effect of the liquids. For the conditions considered in this study, 1% of NaCl and 1.1% of CaCl$_2$ solutions case had lower self-healing capacity due to higher cation concentration in the
liquid, lower free swelling index and liquid limit \(w_L\) of the bentonite.

(4) Effect of overburden pressure \(p'\). Conceptually \(p'\) has two effects on the self-healing capacity of GCLs. One is squeezing the hydrated bentonite into a damage hole to increase self-healing capacity; while other is restricting effect which tends to restrict the amount of expansion of the bentonite in GCL and reduce self-healing capacity. Up to \(p' = 200\) kPa, the area healing ratio, \(\alpha_h\) (ratio between the healed area and the initial total area of a damage hole) increased with the increase of \(p'\) value.

(5) Effect of GCL type. Both GM-GCL and GT-GCL samples tested have similar self-healing capacities, and the flow rates are comparable for the same size of damage holes. However, effect of the liquid type on GT-GCLs is more than that on GM-GCLs, partially because the liquid not only influences the behavior of the bentonite entered the damage hole but also in the intact part of GT-GCL sample.

(6) Effect of wet-dry cycles for the size of a damage hole. At wet condition, the size of the hole was reduced, but when dry, the size of the hole was increased again. Up to 6 cycles, there is a slight tendency of reducing the size of a damage hole with the increase of the number of cycles.

5.2 Recommendations for future work

A series of laboratory leakage rate tests was carried out to investigate the main influencing factors as well as their degrees of influence on self-healing capacities of GCLs. The conditions adopted in the laboratory may not the same as those in the field and the scenarios simulated are very limited. Following 3 topics are suggested for future study on self-healing capacities of GCLs.

(1) In the field, normally GCLs are placed above clayey soil layer. It is suggested to conduct leakage rate test with a set-up of a soil layer below a GCL sample.
(2) Considering the fact that leakage from a landfill contains several ions, and may be combination of organic as well as inorganic chemical components, the self-healing capacity may be investigated using actual leachate from landfills.

(3) Combining leakage rate test with Repeated Wet-Dry test to simulate field condition.
REFERENCES

ASTM D 4546-96. Standard test method for one-dimensional swell or settlement potential of cohesive soils.

ASTM D 2435-96. Standard test method for one-dimensional consolidation properties of soils

ASTM D 5890-02. Standard test method for swell index of clay mineral component of geosynthetic clay liners


EPA, Geosynthetic clay liners used in municipal solid waste landfills, December 2001.


JIS A 1205. Standard test method for Atterberg limit test (In Japanese)


