

INTERNAL EROSION OF GEOSYNTHETIC CLAY LINERS UNDER HIGH
HYDRAULIC HEADS

by

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ABSTRACT

INTERNAL EROSION OF GEOSYNTHETIC CLAY LINERS UNDER HIGH HYDRAULIC HEADS

A geosynthetic clay liner is a material composed of a thin layer of bentonite sandwiched between two layers of geotextiles. Low hydraulic conductivity of the bentonite in GCLs makes them more impermeable. Geosynthetic clay liners are primarily preferred as environmental protection barriers in cover systems with their low hydraulic conductivity, low cost and easiness of installment. When the level of water on the GCL increases after the installment of a GCL over a subgrade, the hydraulic head on the GCL also increases. Under high hydraulic heads, there is the possibility for the bentonite component to migrate out of the GCL which causes high increase in hydraulic conductivity. This process which causes for the GCL to lose its hydraulic barrier capability is called internal erosion.

Flexible wall triaxial permeability tests were performed on different types of geosynthetic clay liners placed over bases with uniform voids under high hydraulic heads up to 50 m in order to investigate internal erosion. The bases with uniform voids represent rounded coarse uniform gravel subgrades beneath the GCL samples. The effects of the geotextile component (woven or nonwoven) that was in contact with the base with voids, bentonite component (sodium bentonite or calcium bentonite), manufacturing type (needlepunched or not) of the GCL samples on internal erosion were investigated. Triaxial permeability tests showed that the performance of the GCL against internal erosion where the nonwoven geotextile component was in contact with the base with voids was better than that of the woven geotextile component when the tensile strengths of the geotextiles were almost the same. However, the performance of the GCL against internal erosion where the woven geotextile component was in contact with the base with voids was the best among all of the GCL types when the tensile strength of the woven geotextile was

relatively higher than that of the nonwoven geotextile. The performance of the GCL manufactured by needlepunching the nonwoven geotextile component through the bentonite to the woven geotextile component against internal erosion was found to be better than that of the GCL manufactured by bonding the woven and nonwoven geotextiles to the bentonite without needlepunching. According to the test results, type of the bentonite used in the GCL samples does not play an important role against internal erosion. Mass per unit area and moisture content of the bentonite component of the GCLs were also measured. Low mass per unit area and high moisture content obtained from the zones of the bentonite where the GCL sample faced the voids of the bases are indications of high amount of bentonite migration and internal erosion.

ÖZET

YÜKSEK HİDROLİK YÜKLER ALTINDAKİ GEOSENTETİK KİL KAPLAMALARIN İÇSEL EROZYONU

Geosentetik kil kaplama, iki geotekstil katmanı arasına ince bir bentonit tabakasının yerleştirilmesiyle oluşan bir malzemedir. Bentonitin düşük seviyedeki hidrolik geçirgenliği, GCL'ları oldukça geçirimsiz yapmaktadır. GCL'lar, öncelikle düşük hidrolik geçirgenlikleri ve maliyetleri, kolaylıkla dōşenebilmeleri sayesinde kaplama sistemlerinde çevresel koruma bariyerleri olarak tercih edilmektedirler. Herhangi bir doğal zemine serildikten sonra, GCL'nın üzerinde zamanla biriken su seviyesi artarsa GCL'ya etkileyen hidrolik yükler de artar. GCL'nın içindeki bentonitin, yüksek hidrolik yükler altında GCL'nın dışına kaçma ihtimali vardır. Bu durumda GCL'nın hidrolik geçirgenliği önemli oranda artmaktadır. Bentonitin GCL'nın dışına çıkarak GCL'nın hidrolik özelliklerini kaybetmesine neden olmasına içsel erozyon denir.

İçsel erozyonun oluşumunu belirlemek için üniform boşlukları olan bir tabanın üzerine yerleştirilen çeşitli GCL'lar üzerinde, en fazla 50 m'ye kadar yükselen su seviyesi altında esnek duvarlı, üç eksenli geçirimsizlik deneyleri yapılmıştır. Üniform boşluklu tabanlar, GCL'ların altında yer alan yuvarlak ve üniform iri daneli çakıl zeminleri temsil etmektedirler. GCL'ların boşluklu taban ile temasta olan geotekstil elemanlarının (örgülü veya örgüsüz), GCL'ların içinde bulunan bentonitin (sodyum bentonit veya kalsiyum bentonit), GCL'ların elemanlarının birbirleriyle birleşme şeklinin (iğneleme ile veya iğneleme olmadan) içsel erozyona etkileri incelenmiştir. Üç eksenli permeabilite deney sonuçlarına göre, çekme dayanımları hemen hemen aynı olan örgülü ve örgüsüz geotekstil elemanlardan örgüsüz geotekstil elemanın boşluklu taban ile temasta olduğu durumda içsel erozyona karşı dayanımı, örgülü geotekstil elemandan daha iyi çıkmıştır. Fakat çekme dayanımı örgüsüz geotekstil elemandan çok daha yüksek olan örgülü geotekstil elemanın boşluklu taban ile temas halindeyken içsel erozyona karşı dayanımı, test edilen bütün GCL çeşitlerinden daha iyi çıkmıştır. Örgüsüz geotekstilin bentonitin içinden geçerek örgülü

geotekstile iğnelenmesiyle üretilen GCL'ların içsel erozyona karşı dayanımları, GCL elemanlarının iğneleme olmadan birbirleriyle birleştirilmesiyle üretilen GCL'lara göre daha iyi sonuç vermiştir. Test sonuçlarına göre GCL'larda kullanılan bentonit türünün içsel erozyona karşı dayanıma çok fazla etkisi olmadığı gözlemlenmiştir. Ayrıca üç eksenli deneyler sonlandırıldıktan sonra GCL'larda kullanılan bentonitin kütle/birim alan ve su muhtevası değerleri de ölçülmüştür. GCL'ların altlarında bulunan tabanlardaki boşluklara oturan bölgelerden alınan bentonit numunelerin bir kısmında kütle/birim alan değerleri ortalamadan düşük, su muhtevası değerleri ise yüksek çıkmıştır. Bu sonuçlar, bu bölgelerde yüksek oranda bentonit kaybı ve içsel erozyon olduğunun göstergesidir.

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LIST OF SYMBOLS/ABBREVIATIONS

A	Cross-Sectional Area of the GCL Sample
$\text{\AA}$	Angstrom
C	Coefficient of the Geometry of Orifice
c	Cohesion
$c_{\text{extrusion}}$	Coefficient of Bentonite Extrusion
D_{pg}	Porous Media Diffusion Coefficient
d_v	Diameter of the Void among the Gravel Grains
G_s	Specific Gravity
h	Hydraulic Head on the GCL Sample
I_p	Plasticity Index
k	Coefficient of Permeability
k_{20}	Coefficient of Permeability Corrected at 20°C
L	Length of the GCL Sample
M_b	Dried Mass of the Bentonite Component of the GCL Sample
m_b	Mass per Unit Area of the Dried Bentonite Component of the GCL Sample
M_{GCL}	Dried Mass of the GCL Sample
n	Porosity
n_0	Electrolytic Concentration in the Pore Liquid
Q	Flow Rate
Q_D	Drainage Flow
q_i	Index Flux of the GCL Sample
Q_L	Seepage
Q_s	Surface Runoff
r	Radius of the Uniform Gravel Grain
R_T	Ratio of the Viscosity of Water at Test Temperature to the Viscosity of Water at 20°C
S_r	Degree of Saturation
T	Thickness of Diffuse Double Layer
w_{GCL}	Initial Moisture Content of the GCL Sample

$\emptyset$	Friction Angle
ΔQ	Average of Inflow and Outflow Quantities for a Given Time Interval
Δt	Interval of Time over Which the Flow ΔQ Occurs
Ψ	Permittivity of the GCL Sample
θ_a	Volumetric Air Content
θ_w	Volumetric Water Content
σ'_c	Effective Confining Stress
v	Valence of the Cations in the Pore Liquid

ASTM	American Society for Testing and Materials
CB	Calcium Bentonite
CCL	Compacted Clay Liner
CEC	Cation Exchange Capacity
CETCO	Colloid Environmental Technologies Company
CSU	Colorado State University
DIW	Deionized Water
DR	Double Ring
FR	Fixed Ring
GCL	Geosynthetic Clay Liner
HDPE	High Density Polyethylene
HQB	High Quality Bentonite
ILC	Incremental Load Control
LL	Liquid Limit
LLDPE	Low Density Polyethylene
LQB	Low Quality Bentonite
MDL	Method Detection Limit
MSW	Municipal Solid Waste
NW	Nonwoven
PF	Prehydrated Fluid
PL	Plastic Limit
RL	Real Leachate

SB	Sodium Bentonite
SL	Synthetic Leachate
SLC	Single Load Control
SLG	Single Load Gravel
TEM	Transmission Electron Microscopy
TW	Tap Water
UW	University of Wisconsin
W	Woven

1. INTRODUCTION

In the last twenty years, geosynthetic clay liners (GCLs) have gained popularity and been preferred instead of compacted clay liners with their lower hydraulic conductivity and lower cost in cover systems and composite bottom liners. Geosynthetic clay liners are also used as environmental protection barriers in transportation facilities (roads and railways) and geotechnical applications such as minimizing pollution of subsurface strata from accidental spills and seepage of chemicals from road accidents. GCLs are also used as single liners for canals, ponds or surface impoundments (Bouazza, 2001).

Geosynthetic clay liner is composed of a thin layer of sodium or calcium bentonite sandwiched between two layers of geotextiles or bonded to a layer of geomembrane. For the geomembrane-supported GCL, the bentonite is glued to a very thin geomembrane using a nonpolluting, water soluble adhesive and a thin, open weave geotextile is adhered to the bentonite for protection purposes during installation. For the geotextiles-based GCL, the bentonite is enclosed between two geotextiles which are held together by adhesives, stitching, or needlepunching. The needlepunching process causing some fibres from the top geotextile to extend through the bentonite and bottom geotextile, bonding the entire structure together (von Maubeuge and Heerten, 1994). The fibres which are punched through the bottom geotextile either rely on natural entanglement and friction to keep the GCL together or are heated causing them to fuse to the bottom geotextile, potentially creating a stronger bond between the two geotextiles and bentonite (Rowe and Jones, 2004). Alternatively, the reinforcement can be carried out by sewing the entire geotextiles–bentonite composite together with parallel rows of stitch-bonded yarns.

The primary differences between geosynthetic clay liners are the mineralogy and form of bentonite (e.g., powder versus granular, sodium versus calcium, etc.) used in the GCL, the type of geotextile (e.g., woven versus nonwoven geotextiles) or the addition of a geomembrane, and the bonding methods. The main advantages of the GCL are the limited thickness, the good compliance with differential settlements of underlying soil or waste, easy installation and low cost. On the other hand, the limited thickness of this barrier can produce vulnerability to mechanical accidents, limited sorption capacity, and an expected

significant increase of diffusive transport if an underlying attenuation mineral layer is not provided. Moreover, when hydrated with some types of leachates instead of pure water, bentonite will show a minor swelling that will result in reduced efficiency of the hydraulic barrier. Main advantages and disadvantages of GCLs are listed in table 1.1 (Bouazza, 1997).

The low hydraulic conductivity of thin layers of bentonite in GCLs makes them more impermeable than compacted clay liners (CCLs). However, the hydrated bentonite is highly compressible and has very low shear strength, especially under low effective stress. Furthermore, the thickness of GCLs has always generated concerns over their survivability in the field (Shan and Chen, 2003). When large-size particles, such as coarse-grained soils are pushed into a GCL, the bentonite may be squeezed and pushed aside. Because of this interaction, the GCL may be thinner and sometimes punctured which will cause a remarkable increase in permeability. Internal erosion occurs when high amount of bentonite is extruded from a GCL layer into the subgrade which causes high increase in hydraulic conductivity.

When compared to compacted clay liners (CCLs), geosynthetic clay liners (GCLs) have many advantages such as better leakage protection, greater resistance to desiccation, differential subsidence and freeze-thaw. Especially, in mining industry and mineral processing applications, GCLs are preferred because it is easy to install, cost-effective, resistant to many physical and climatic effects to use GCL instead of CCL (Miller and Hornaday, 1998).

Geosynthetic clay liners are relatively new materials which have had a very significant impact on many aspects of geotechnical and geoenvironmental engineering. Geosynthetic clay liners have been investigated in regard to their engineering properties such as hydraulic and diffusion characteristics, chemical compatibility, mechanical behaviour, durability and gas migration.

In general, 0,50-1 m of water is collected on a GCL, when the GCL is used as an environmental protection barrier in a landfill. However, maximum level upon a GCL might sometimes be up to 30-50 m, when the GCL is used over a mine leachate dam. When water

is collected up to the maximum level, very high hydraulic head over the GCL may cause high amount of bentonite extrusion or internal erosion.

Objectives of this thesis are to investigate internal erosion and high amount of bentonite migration from different types of geosynthetic clay liners placed over bases with uniform voids under high hydraulic heads up to 50 m and to investigate the parameters which have effects on internal erosion. These parameters are geotextile component, bentonite component and manufacturing type of a GCL. Flexible wall triaxial permeability tests were performed on the GCL samples in order to observe high amount of bentonite migration. Effect of the type of the geotextile component (woven or nonwoven) of a GCL that was in contact with the base with voids on internal erosion was investigated considering the engineering properties of the geotextiles such as tensile strength and rigidity. Effect of the needlepunched fibres of another GCL type on internal erosion was also investigated. Behavior of two different bentonite (sodium bentonite and calcium bentonite) components in terms of internal erosion was analyzed. The bases with uniform voids represent rounded coarse uniform gravel subgrades beneath the GCL samples.

Table 1.1. Advantages and disadvantages of GCLs (Bouazza, 1997)

ADVANTAGES	DISADVANTAGES
Rapid installation/less skilled labour/low cost	Low shear strength of hydrated bentonite (for unreinforced GCLs)
Very low hydraulic conductivity to water if properly installed	GCLs can be punctured during or after installation
Can withstand large differential settlement	Possible loss of bentonite during placement
Excellent self-healing characteristics	Low moisture bentonite permeable to gas
Not dependent on availability of local soils	Potential strength problems at interfaces with other materials
Easy to repair	Smaller leachate attenuation capacity
Resistance to the effects of freeze/thaw cycles	Possible post-peak shear strength loss
More airspace resulting from the smaller thickness	Possible higher long term flux due to a reduction in bentonite thickness under an applied normal stress
Field hydraulic conductivity testing not required	Possible increase of hydraulic conductivity due to compatibility problems with contaminant if not prehydrated with compatible water source
Hydrated GCL is an effective gas barrier	Higher diffusive flux of contaminant in comparison with compacted clay liners
Reduce overburden stress on compressible substratum (MSW)	Prone to ion exchange (for GCLs with sodium bentonite)
	Prone to desiccation if not properly covered (at least 0.6m of soil)

2. LITERATURE REVIEW

2.1. GCL Installation

GCL installation in the field and covering of GCL over the subgrade soil strata procedures must meet the design criteria and long-term performance of GCL must be maintained after installation. A geosynthetic clay liner is manufactured with adequate durability to survive construction and service loadings. Main steps of GCL installation process are subgrade preparation, installation, anchorage, seaming and cover placement.

2.1.1. Subgrade Preparation

Because of the relative thinness of GCLs, much more attention has to be given for subgrade preparation of geosynthetic clay liners than that of compacted clay liners. The subgrade surface must be smooth and free of vegetation, sharp-edged rocks, stones, sticks, construction debris, and other foreign matter that could contact the GCL. The subgrade should be rolled with a smooth-drum compactor to remove any wheel ruts greater than 25 mm in depth, footprints, or other abrupt grade changes. Furthermore, all protrusions extending more than 12 mm from the subgrade surface shall be removed, crushed, or pushed into the surface with a smooth-drum compactor or the placement of a protective soil/geotextile cushion layer prior to installation of the GCL. A good technique for difficult subgrade conditions is to water the subgrade approximately one hour in advance of GCL deployment, and then smooth-drum roll the area just before GCL deployment. The exact timing of watering, rolling and deployment depends on the site-specific soils and weather conditions (Greg Richardson et al., 2002).

Subgrade surfaces consisting of granular soils or gravel may damage the GCL due to their large void ratios and puncture potential. But the bentonite layer of GCLs generally has the swelling capacity to seal small punctures (generally less than 25 mm) induced from above or below the liner.

2.1.2. Installation

Equipment which could damage the GCL should not be allowed to travel directly on it. Acceptable installation, therefore, may be accomplished such that the GCL is unrolled in front of backwards-moving equipment (Figure 2.1). If the installation equipment causes rutting of the subgrade, the subgrade must be restored to its originally accepted condition before placement continues.

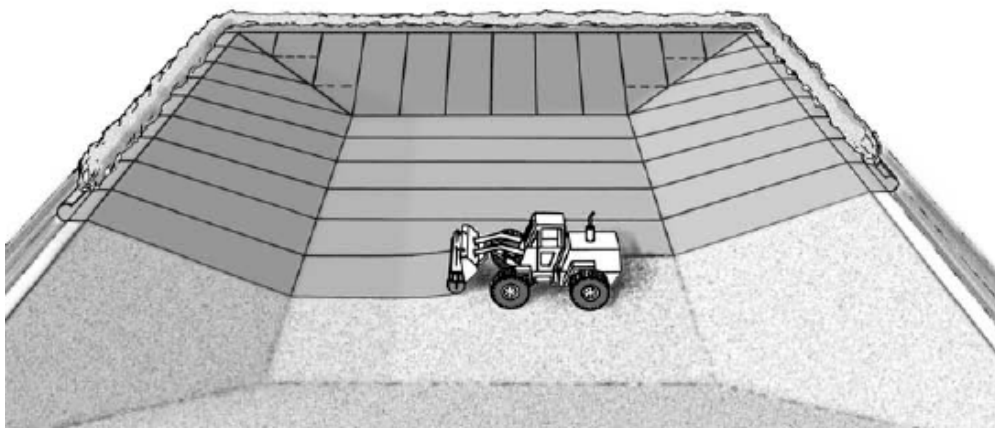


Figure 2.1. GCL installation equipment (Bentomat/Claymax Installation Guidelines, 2006)



Figure 2.2. Deployment of GCL with a group of laborers (Greg Richardson et al., 2002)

If sufficient access is available, GCL may be deployed by suspending the roll at the top of the slope with a group of laborers pulling the material off of the roll and down the slope (Figure 2.2 and 2.3).

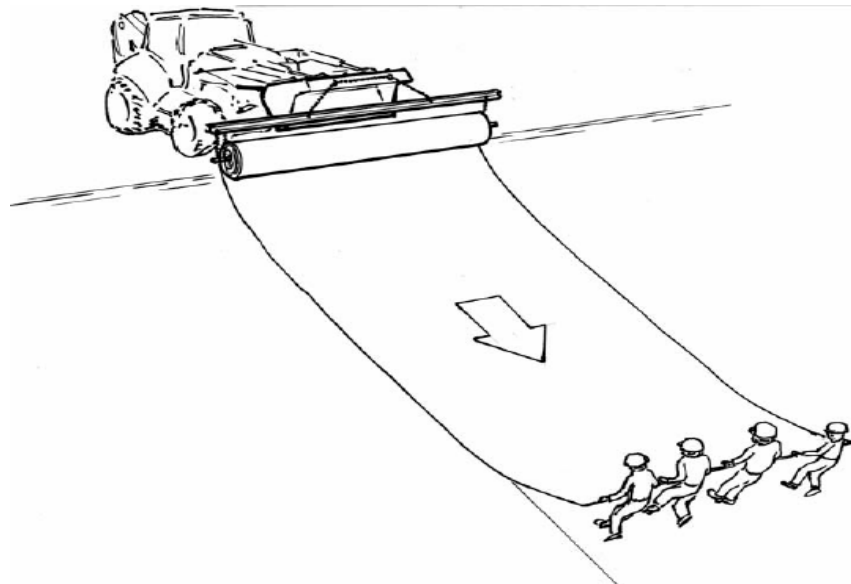


Figure 2.3. Unrolling of GCL (Bentomat/Claymax Installation Guidelines, 2006)

GCL rolls should not be released on the slope and allowed to unroll freely by gravity as shown in figure 2.4. The GCL should be placed so that seams are parallel to the direction of the slope. End-of-panel seams should also be located at least 1m from the toe and crest of slopes steeper than 4H:1V. End-of-roll seams on slopes should be used only if the liner is not expected to be in tension (Bentomat/Claymax Installation Guidelines, 2006).

2.1.3. Anchorage

If required by the project drawings, the end of the GCL roll should be placed in an anchor trench at the top of a slope. The front edge of the trench should be rounded to eliminate any sharp corners that could cause excessive stress on the GCL. Loose soil should be removed or compacted into the floor of the trench. If a trench is used for anchoring the end of the GCL, soil backfill should be placed in the trench to provide resistance against pullout. The size and shape of the trench, as well as the appropriate backfill procedures, should be in accordance with the project drawings and specifications. Typical dimensions are shown in Figure 2.5. The GCL should be placed in the anchor

trench such that it covers the entire trench floor but does not extend up the rear trench wall. Sufficient anchorage may alternately be obtained by extending the end of the GCL roll back from the crest of the slope, and placing cover soil. The length of this “runout” anchor should be prepared in accordance with project drawings and specifications (Bentomat/Claymax Installation Guidelines, 2006).



Figure 2.4. Unrolling of GCL on a slope (Greg Richardson et al., 2002)

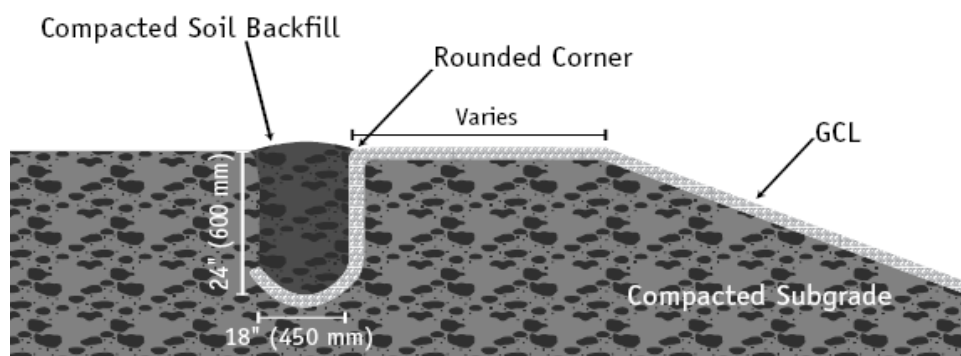


Figure 2.5. Typical anchor trench for a GCL (Bentomat/Claymax Installation Guidelines, 2006)

2.1.4. Seaming

GCL seams are constructed by overlapping adjacent panel edges and ends. Care should be taken to ensure that the overlap zone is not contaminated with loose soil or other

debris. For geomembrane-supported GCLs, no seaming bentonite is required because the bentonite is virtually exposed. Even the very light spunbonded geotextile sometimes adhered to the surface of the bentonite does not inhibit the sealing ability at seams. For geotextile supported GCLs, seaming bentonite is not required over woven-to-woven geotextile interface. It is not a requirement but is better to use seaming bentonite over woven-to-nonwoven geotextile interface. Seaming bentonite is required over nonwoven-to-nonwoven geotextile interface.

End-of-panel overlapped seams are constructed first by overlapping the adjacent panels, exposing the underlying panel, and then applying a continuous bead or fillet of granular sodium bentonite 300 mm from the edge of the underlying panel (Figure 2.6). The minimum application rate at which the bentonite is applied is 0.4 kg/m. If longitudinal bentonite enhanced seams are required as seen in figure 2.7, they are constructed first by overlapping the adjacent panels by a minimum 150 mm, exposing the underlying edge and applying a continuous bead of granular bentonite approximately 75 mm from the edge. The minimum application rate for the granular bentonite is 0.4 kg/m (Bentomat/Claymax Installation Guidelines, 2006).

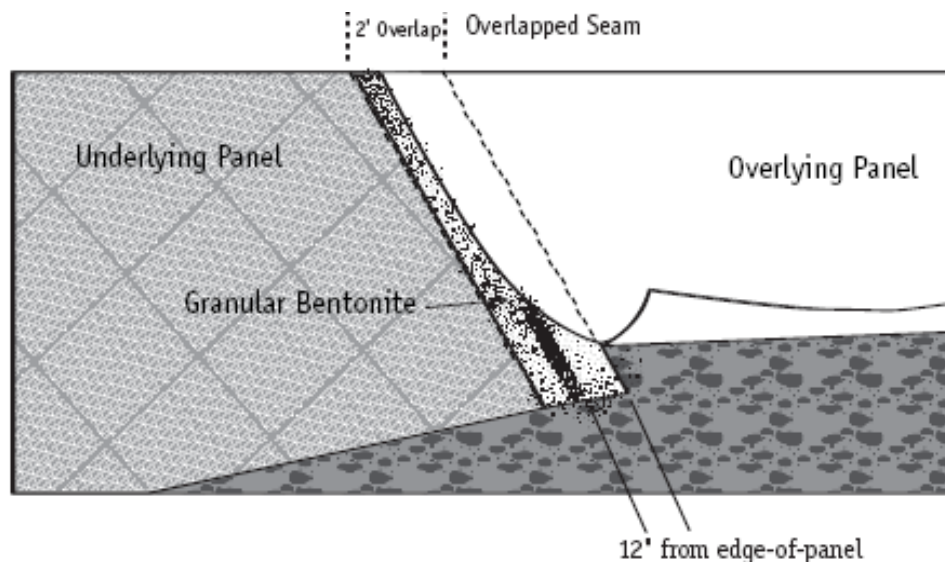


Figure 2.6. Overlapped seam for GCL installation (Bentomat/Claymax Installation Guidelines, 2006)

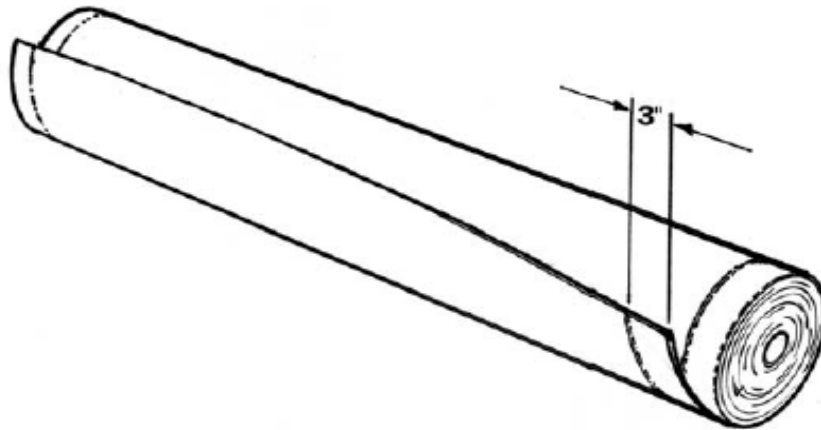


Figure 2.7. Longitudinal seam of a GCL (Bentomat/Claymax Installation Guidelines, 2006)

2.1.5. Cover Placement

All GCL installations must include a soil cover to eliminate bentonite free swelling and maintain the hydraulic performance of the bentonite. If the cover soil is granular drainage material, it should be free of sharp or angular objects greater than 12 mm that may cause damage to the liner. The cover should include a minimum 300- mm-thick soil layer placed after deployment of the GCL (Greg Richardson et al., 2002). Figure 2.8 illustrates typical soil cover placement over a GCL. In addition to physical protection of the installed GCL liner, the objective of soil cover placement is to prevent the bentonite from hydrating with no confining normal load.

Soil cover should be placed in a manner that prevents the soil from entering the GCL overlap zones. Soil cover should be pushed up slopes; not down slopes, to minimize tensile forces on the GCL. When a textured geomembrane is installed over the GCL, a temporary geosynthetic covering known as a slip sheet or rub sheet should be used to minimize friction during placement and to allow the textured geomembrane to be more easily moved into its final position. To avoid seam separation, the GCL should not be put in excessive tension by the weight or movement of textured geomembrane on steep slopes. If there is the potential for unconfined geomembrane expansion and contraction over an extended period of time, the longitudinal seam overlaps should be increased based upon the project engineer's recommendations.



Figure 2.8. Soil cover placement over a GCL (Greg Richardson et al., 2002)

2.2. Bentonite in Geosynthetic Clay Liners

2.2.1. Structure

Bentonite, a very highly plastic, swelling clay material composed of smectite group of minerals, is the sealing material in geosynthetic clay liners. Bentonite is a naturally occurring clay with high swelling potential, large surface area, high ion-exchange capacity and low hydraulic conductivity to water. Bentonites used in GCLs mainly consist of the three-layered (2:1) clay mineral montmorillonite. Bentonite consists of the three-layer clay minerals of the smectite group (Figure 2.9). The basic three-layer structure consists of silica tetrahedron, alumina octahedron, and silica tetrahedron layers where the octahedral sheet is sandwiched between the two silica sheets as shown in figure 2.9.

All the tips of the tetrahedra point towards the center of the unit cell. The oxygens forming the tips of the tetrahedra are common to the octahedral sheet as well. The anions in the octahedral sheet which fall directly above and below the hexagonal holes formed by the bases of the silica tetrahedra are hydroxyls. Three dimensional diagrammatic sketch of the montmorillonite structure is shown in figure 2.10 (Mitchell, 1975).

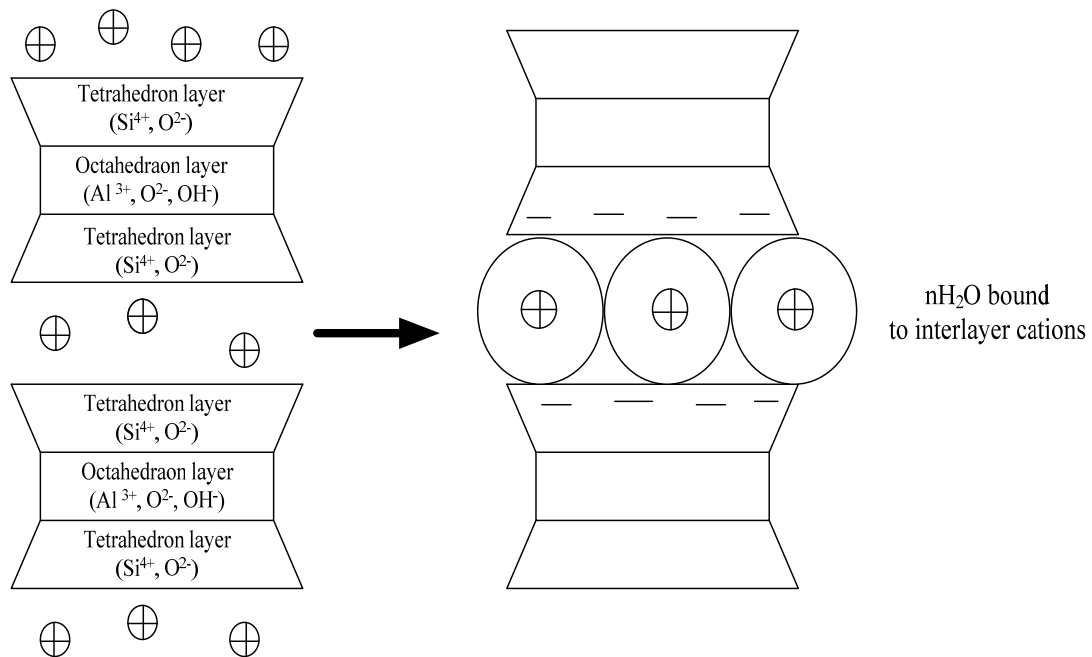


Figure 2.9. Three-layer structure of montmorillonite clay mineral

Bonding between successive layers is by van der Waals forces and by cations which balance charge deficiencies in the structure. These bonds are weak and easily separated by cleavage or adsorption of water or other polar liquids (Mitchell and Soga, 2005).

Further components of bentonite may be quartz, cristoballite, feldspars, mica (muscovite, biotite), illite, kaolinite, chlorite, carbonates (calcite, dolomite, siderite), zeolites, volcanic glass, amorph silicic acid and aluminium hydroxide, organic components, apatite, haematite, limonite, and heavy minerals (pyrite, magnetite, ilmenite, tourmaline, zircon, rutile) and others (Egloffstein, 1995). Typical properties of bentonites in geosynthetic clay liners are shown in Table 2.1 (Egloffstein, 2000).

Bentonite is used for a variety of purposes such as:

- a backfill during the construction of slurry trench walls
- a soil admixture for construction of seepage barriers
- a grout material
- a sealant for piezometer installations
- a soil amendment for compacted soil barriers in landfill liners and cover systems
- a low hydraulic conductivity component in geosynthetic clay liners

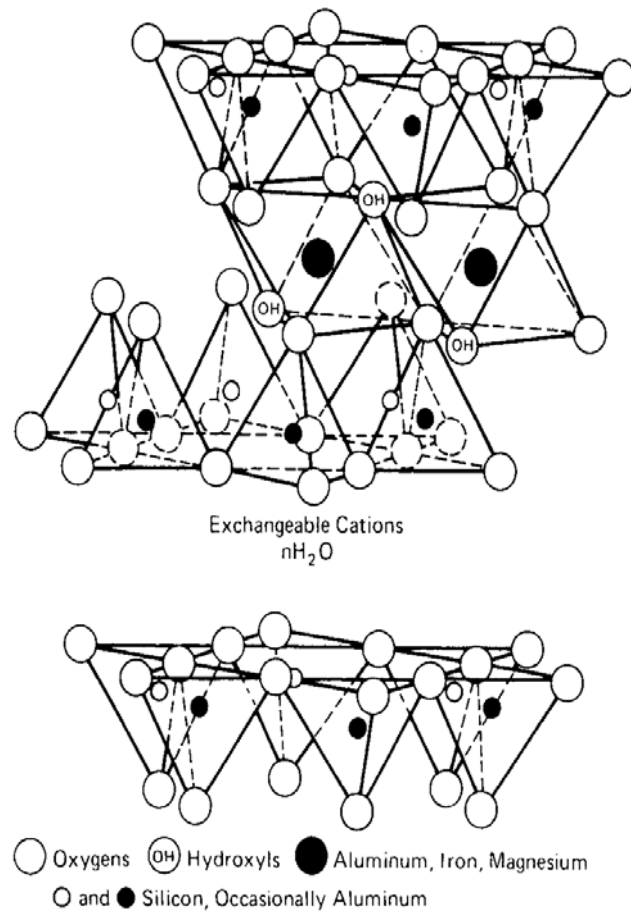


Figure 2.10. Three dimensional diagrammatic sketch of the montmorillonite structure
(Mitchell, 1975)

Table 2.1. Typical properties of bentonites in GCLs (Egloffstein, 2000)

Montmorillonite content (Methyleneblue method)	60-90%
Water absorption content	200-700 weight %
Swelling volume (ASTM D 5890-95)	7-30 ml
pH value (suspension)	9-10.5
Plasticity (I_p)	140-380%
Friction angle (ϕ) / cohesion (c)	3-15° / 3-10 kN/m ²
Permittivity (Ψ)	5×10^{-8} - 3×10^{-9} 1/s
Cation Exchange capacity (CEC)	60-90 mmol (eq)/100g

2.2.2. Morphology and Surface Area

Montmorillonite may occur as equidimensional flakes which are so thin as to appear more like films, as shown in Figure 2.11 (Tovey, 1971). Particles range in thickness from 10 Å unit layers upward to about 1/100 of the width. The long axis of the particle is usually less than 1 or 2 µm. When there is a large amount of substitution of iron and/or magnesium for aluminum, the particles may be lath or needle shaped because the larger Mg^{2+} and Fe^{3+} ions cause a directional strain in the structure. The specific surface area of smectite can be very large. The primary surface area, that is, the surface area exclusive of interlayer zones, ranges from 50 to 120 m²/g. The secondary specific surface that is exposed by expanding the lattice so that polar molecules can penetrate between layers can be up to 840 m²/g (Mitchell and Soga, 2005).

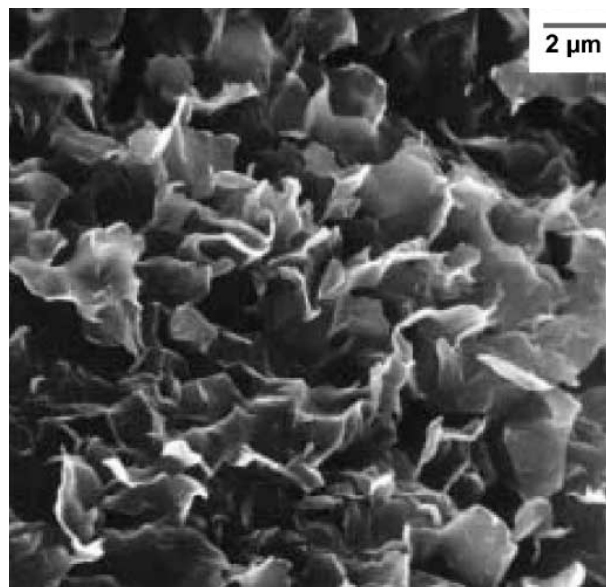


Figure 2.11. Electron scan microscope picture of montmorillonite in a pulverized natural sodium bentonite in a GCL (1 cm = 2µm) (Tovey, 1971)

2.2.3. Ion Exchange

There are two main types of bentonites used in industrial facilities, sodium and calcium bentonites, which depend on their dominant exchangeable cation. But sodium bentonite is usually preferred because of its lower hydraulic conductivity. Generally, the sodium bentonite is a mixture of other ions such as magnesium, potassium and calcium.

The main component of bentonite is montmorillonite which is a very good ion exchanger clay mineral. Montmorillonite has a high specific surface area, weak interlayer bonds, and high cation exchange capacity, which result in the high shrink and swell potential. Water and exchangeable cations can easily enter and separate the layers, causing montmorillonites to swell. Montmorillonite has negatively charged surfaces, as a result of the partial isomorphic substitution of Si^{4+} ions by Al^{3+} ions in the tetrahedron layers, and those of Al^{3+} ions by, for example, Mg^{2+} ions in the octahedron layer. The negative charge is balanced by cations, especially Na^+ , Ca^{2+} and Mg^{2+} ions, which are present both in the interlayer spaces and in the external surfaces (Mitchell, 1975).

There are more calcium bentonites than sodium bentonites on earth. This is also due to the fact that calcium has a higher affinity. It is a well known fact that when a sodium bentonite gets in touch with free calcium ions, the sodium ions in the bentonite will be exchanged with calcium ions. In order to receive better swelling properties of sodium bentonite, calcium bentonite is activated with soda (sodium carbonate) and thus the primary calcium ions are exchanged by sodium ions.

The properties of bentonite are greatly affected by the interactions between its particles and the surrounding pore fluid. The net electrical charge on bentonite particle is negative (Mitchell, 1993). These negative charges cause dissolved cations in the surrounding pore water to be attracted to the surfaces of the clay. The layer of water and adsorbed ions which surrounds a clay particle is called the electrical double layer or diffuse double layer.

Ion exchange processes are known as equilibrium processes. The occupation of a cation exchanger depends on the concentration and type of the cations available for the exchange. The size and most of all, the charge of the cations are important. For example, bivalent calcium (Ca^{2+}) is more easily exchanged against monovalent sodium (Na^+) than vice versa (Egloffstein, 2001). Evaluation of laboratory tests and field observations have shown that the ion exchange from calcium to sodium bentonite takes one to several years when GCLs are used in partly saturated areas (e.g. landfill cappings). The duration of the ion exchange depends on the primary cation amount of the bentonite, the quantity of bentonite per area unit, the geochemical conditions (concentration and ion distribution in

the leachate), the geohydraulic conditions (water flow in the GCLs, the quantity of water drained off the GCL) and soil physical conditions (rising ionic concentration in the pore water by reduction of the water content due to desiccation, possibly extension of the contact areas by desiccation cracks). The exchange continues until an adsorption balance between the ion distribution at the bentonite and the ionic concentration in the soil solution is achieved. The ion exchange from monovalent sodium ions to bivalent calcium ions reduces the spaces between the silicate layers is shown in figure 2.12 (Jasmund and Lagaly, 1993).

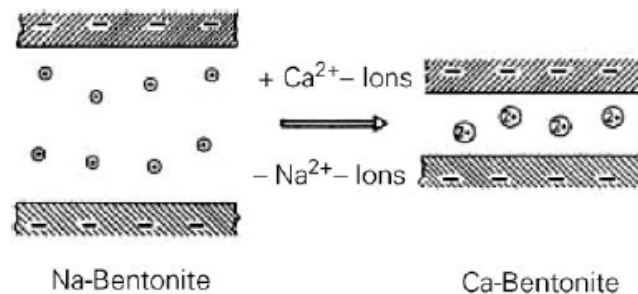


Figure 2.12. Ion Exchange from sodium bentonite to calcium bentonite (Jasmund and Lagaly, 1993)

The attraction of the bivalent cations to the negative charges of the bentonite particles leads to a certain reduction of volume and a change of the microstructure from smaller, finely distributed clay mineral flakes to larger clay mineral crystals which causes an increase in permeability of the bentonite. Because of the ion exchange, high water absorption and swelling capacity of the sodium bentonite reduces to a lower level.

While sodium bentonites have colloidal and fine-dispersed microstructure, calcium bentonites have more aggregate and coarse-dispersed microstructure as seen in figures 2.13 and 2.15. This observation results in a structure with more pores and longer flow paths around the clay particles. Due to their higher water binding capacity, sodium bentonites form thicker hydrated shells around the clay particles than calcium bentonites form. So, the flow of pore water is hindered through these hydrated shells as shown in figure 2.14 (Koch, 1994). With the help of these two effects, the permeability of calcium bentonites increase at least by one order of magnitude when compared to sodium bentonites.

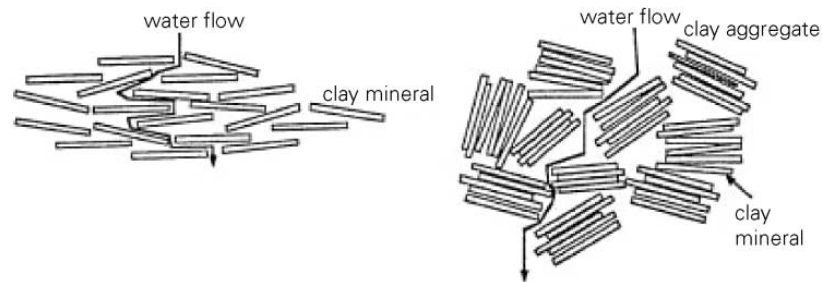


Figure 2.13. Microstructure of clay. Left-hand side: fine-dispersed sodium bentonite with a dispersed structure. Right-hand side: coarse-dispersed calcium bentonite with an aggregated structure (Hasenpatt, 1988)

Due to the decreasing distances between the montmorillonite flakes after the ion exchange from sodium to calcium bentonite takes place, a certain reduction in volume and a loss of water of approximately 6-12 per cent can be observed (Egloffstein, 2000). As a result, the microstructure is changed from smaller, finely distributed clay mineral flakes to larger clay mineral crystals as seen in figure 2.13 (Hasenpatt, 1988).

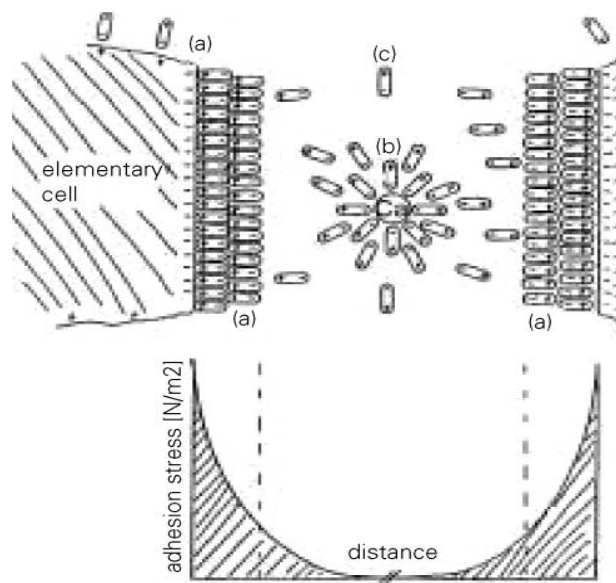


Figure 2.14. Binding water in bentonite crystal. a) non-movable, adsorbed water with high surface tension; b) hydration water surrounds the cations with a hydrated shell that is bounded by electrostatical forces; c) free movable pore water (Koch, 1994)

The coarser structure formed after the ion exchange has a higher permeability. Egloffstein (2001) performed laboratory permeability tests on geosynthetic clay liners by using highly concentrated calcium chloride solutions (CaCl_2). Ion exchange from sodium

bentonite to calcium bentonite resulted in an increase of the permeability by approximately a factor of 3–6 (factor 3.1 with 8000 g and 6.4 with 4700 g bentonite/m²) compared to the permeability of the original sodium bentonite.

In figure 2.15, natural, pulverized sodium bentonite (Wyoming bentonite) with a honeycombed structure is shown at the top left-hand side. The same Wyoming bentonite ion exchanged with 0.3-molar CaCl₂ solution is shown at the bottom left-hand side where the honeycombed structure is preserved and the montmorillonite flakes, however, are a little bit coarser. In-situ ion exchanged sample (Landfill Hamburg–Georgswerder), excavated after 26 months is shown at the top right-hand side where the honeycombed structure is preserved to a large extent, however, its shape is a little bit coarser. Natural calcium bentonite (Calcigel) with coarser montmorillonite aggregates and a coarser structure is shown at the bottom right-hand side (Egloffstein, 2000).

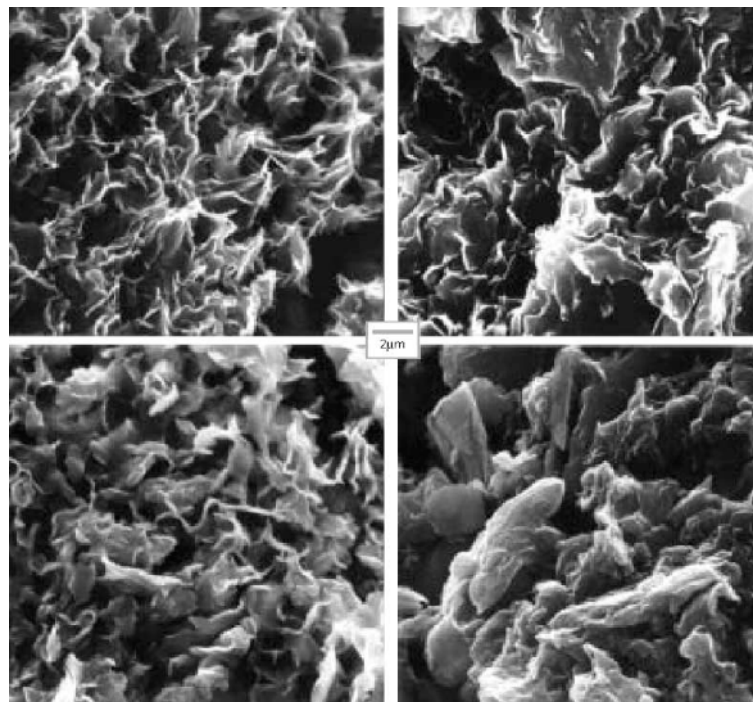


Figure 2.15. Comparison of the microstructures using electron scan microscope pictures (1cm=2µm). (Egloffstein, 2000)

Egloffstein (2001) also conducted field investigations and found that the natural sodium bentonite of the tested GCL was completely changed into a calcium bentonite after the

GCL had been in partial hydration conditions for approximately 2 years. He also found that the duration of completed ion exchange depended on various factors such as types and the mass per area of bentonite, ion concentration in the pore water and the quantity of infiltrating water. High ionic strength pore water contributes to the reduction of the diffuse double layer, the zone of absorbed water, and the swell volume of bentonite. The thickness of the diffuse double layer (T) could be evaluated according to the Gouy-Chapman equation expressed as follows:

$$T \propto \left[\frac{D}{n_0 \nu^2} \right]^{1/2} \quad (2.1)$$

The thickness of the diffuse double layer depends on the dielectric constant of the pore liquid (D), electrolytic concentration in the pore liquid (n_0), and the valence of the cations (positively charged ions) in the pore liquid (ν). The permeability is also affected by the thickness of the diffuse double layer. When the extension of the flow paths between two clay particles is increased or decreased, both the thickness of the diffuse double layer and the permeability of the clayey material change. The factors which affect permeability are expressed as follows:

$$k \propto \left[\frac{n_0 \nu^2}{D} \right]^{1/2} \quad (2.2)$$

Since the valence of Ca^{2+} is twice as high as that of Na^+ , it changes the permeability coefficient (k) by a factor of two. The concentration of the solution also affects the permeability coefficient as a root function which means that an electrolytic concentration four times higher results in a permeability two times higher.

However, when sodium bentonite is used in GCL and the hydration process takes place immediately, the structure of the bentonite will be that of a sodium bentonite, namely a dispersed structure. Even if due to ion exchange, gradually the sodium ions will be replaced by calcium ions and therefore the bentonite will become a calcium bentonite, it will retain its original structure.

2.3. Hydraulic Conductivity

In most cases, the hydraulic performance of geosynthetic clay liners depends on the permeability of the bentonite. The only exception is the usage of a geosynthetic clay liner with a geomembrane layer which is seamed during construction. In general, permeability coefficients of different types of geosynthetic clay liners differ from 2×10^{-12} to 2×10^{-10} m/s when water is used as the permeation liquid under different confining stresses. High confining stress causes a reduction in both bulk void ratio and hydraulic conductivity.

Geosynthetic clay liners are often in touch with liquids other than water which contain chemical solutions. Most of the time, the chemical solutions tend to increase the hydraulic conductivity of a GCL. There are also other factors which affect the hydraulic conductivity of a GCL such as aggregate size, content of montmorillonite, thickness of adsorbed layer, prehydration and void ratio of the mineral component. On the other hand, the concentrations of monovalent and divalent cations are the main factors related to the permeation liquid which affect the hydraulic conductivity of a GCL.

Diffusion is a chemical process involving contaminant migration from areas of higher concentration to areas of lower concentration even if there is not a water flow. The diffusive behaviour of inorganic contaminants through a GCL has been reported recently by Rowe (1998) and Lake and Rowe (2000). Their main findings can be summarized as follows:

- void ratio and related confining stress have a strong influence on diffusion coefficient.
- the solute concentration level can give significant variation in the diffusion coefficients due to the modification of the microstructure of the sensitive mineral component as observed in sodium bentonite.
- GCL manufacture process does not significantly affect the diffusion coefficient.

Lee and Shackelford (2005) performed triaxial permeability tests on GCLs with two different qualities of sodium bentonites using flexible wall permeameters. Hydraulic permeabilities are evaluated by permeation with water and chemical solutions containing 5, 10, 20, 50, 100 and 500 mM CaCl_2 . Tests are performed in accordance with the falling-head procedure as described in ASTM 5084. The GCL with the higher quality bentonite (GCL-HQB) is characterized by a greater content of sodium montmorillonite (86 versus 77 per cent), a higher plasticity index (548 versus 393 per cent) and a higher cation exchange capacity (93 versus 64 meq/100 g) when compared with the GCL with the lower quality bentonite (GCL-LQB).

Based on the results of the tests when the GCLs are permeated with water, the hydraulic conductivity of GCL-HQB is approximately three times lower than the hydraulic conductivity of GCL-LQB (Figure 2.16).

However, when the GCLs are permeated with the CaCl_2 solutions, the hydraulic conductivity increases for both GCL-HQB and GCL-LQB as the CaCl_2 concentration of the permeant liquid increases. Furthermore, the hydraulic conductivities for GCL-HQB based on permeation with the CaCl_2 solutions are always higher than those for GCL-LQB due to the higher cation exchange capacity of GCL-HQB (Figure 2.17).

Guyonnet et al. (2005) tested two types of GCLs in contact with three different fluids in oedometer cells and investigated the microstructure of the GCLs by using transmission electron microscopy. Both types of the GCLs were needle-punched. One of the GCLs contained natural sodium bentonite and named as GCLa and the other one contained sodium-activated calcium bentonite and named as GCLb. One of the three fluids used in contact with the GCLs was the prehydration fluid (PF) which had a low ionic strength ($I=10^{-3}$ mol/L) NaCl solution. The ionic strength of PF is similar to that of soft water. Second fluid was a CaCl_2 solution with a high ionic strength ($I=0.3$ mol/L). This fluid was designated as synthetic leachate (SL). Finally, the last fluid was a real leachate (RL) with an ionic strength of 0.25 mol/L collected from the leachate pond of a municipal solid waste disposal site. The GCL specimens were placed between the porous plates and permeated with fluid using a Mariotte tube (Figure 2.18).

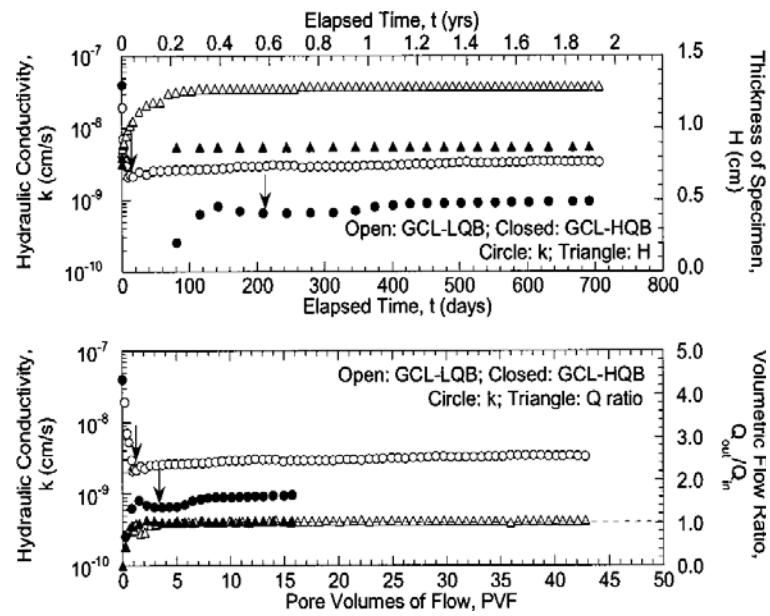


Figure 2.16. Triaxial permeability test results for both GCL-HQB and GCL-LQB when permeated with water (arrows designate time at compliance with ASTM 5084 termination criteria) (Lee and Shackelford, 2005)

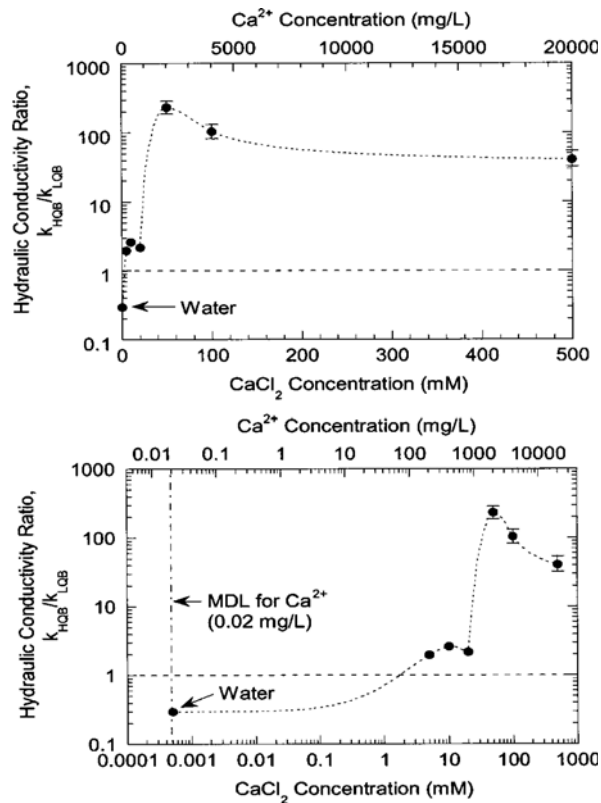


Figure 2.17. Ratio of hydraulic conductivity for GCL-HQB relative to that for GCL-LQB versus CaCl_2 Concentration (MDL=method detection limit) (Lee and Shackelford, 2005)

A vertical confining stress was applied by a piston during the tests. The confining stress was 10 kPa and the tests were composed of two different phases. First, swelling phase took place, then a percolation phase where the GCL sample was permeated with the fluid took place. During the percolation phase, hydraulic head was increased up to 80 cm. Test durations were between five and eight months.

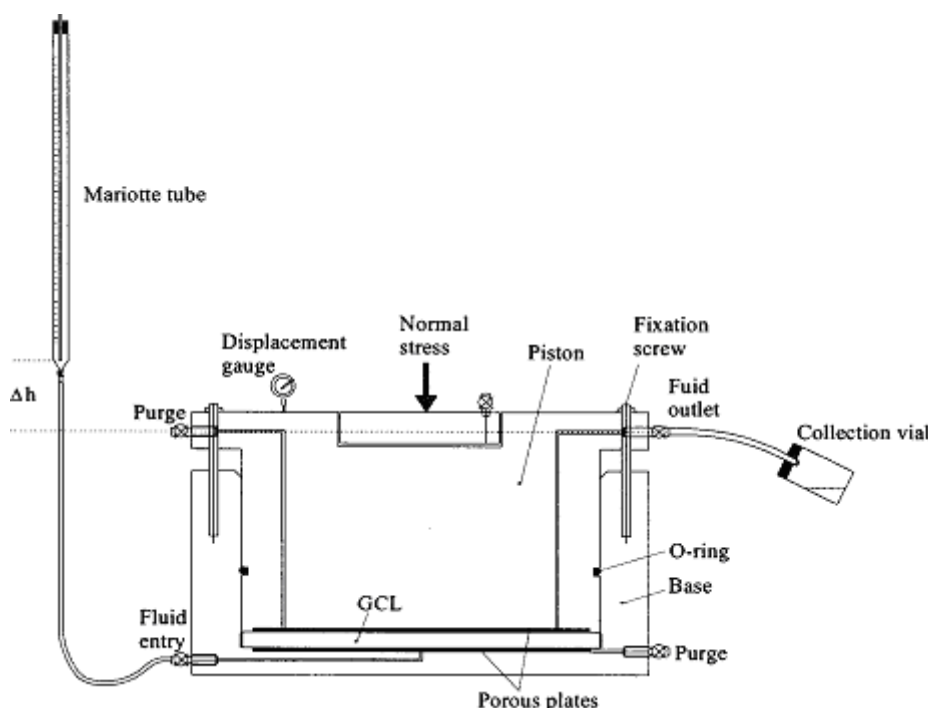


Figure 2.18. Schematic view of the oedometer cell (Guyonnet et al., 2005)

With the help of transmission electron microscopy (TEM), images of the clay microstructure are obtained by transmitting a beam of electrons through a sample. Because the wavelength of electrons is much smaller than that of light, TEM can reveal very fine details of internal structure. In order to obtain samples that can transmit the electron beam, the samples must undergo a preparation to obtain ultrathin sections. Sections of about 50 nm (nanometer) thickness are prepared after successive replacement of the clay–water by acetone, propylene oxide, and finally epoxy resin (Spurr 1969; Tessier 1984).

During the interaction between Ca^{2+} ions in leachate and Na^{+} ions in bentonite, calcium ions began to exchange with sodium in clay. This ion exchange caused the low permeable, gel phase microstructure of the bentonite to change into a more permeable hydrated-solid phase (Figures 2.19 and 2.20).

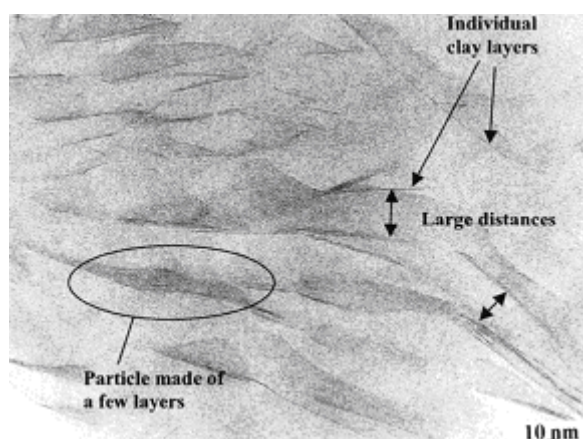


Figure 2.19. Transmission electron microscope view of gel phase in GCL after test PF-PFa (Spurr, 1969)

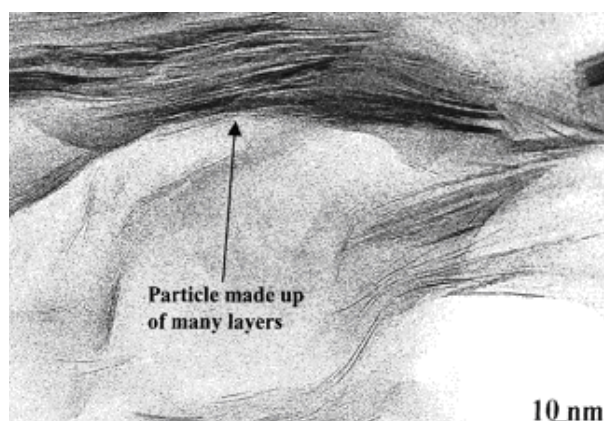


Figure 2.20. Transmission electron microscope view of hydrated-solid phase in GCL after test PF-PFb (Spurr, 1969)

PF-PF means that prehydration fluid was used in both swelling and percolation period during oedometer tests. Figure 2.19 shows a TEM picture of the gel phase in the natural sodium bentonite GCL. Individual clay layers and clay particles which were composed of a few layers were separated by large distances from each other. This type of microstructure was almost homogenous as seen in figure 2.19 and the gel-like structure had low permeability. But the upper part of figure shows a large clay particle composed of a series of closely spaced clay particles which caused the permeability of the bentonite increase. When the synthetic leachate was percolated through the GCLs, high permeability values and hydrated-solid phase were obtained due to the ion exchange of sodium ions with calcium ions.

As shown in figure 2.21, the natural sodium bentonite GCL (GCLa) showed much better performance in terms of permeability compared to the sodium-activated calcium bentonite GCL (GCLb) during all oedometer tests. In figure 2.21, PF-SL means that the swelling fluid was prehydration fluid and the percolation fluid was synthetic leachate. PF-RL means that the swelling fluid was prehydration fluid and the percolation fluid was real leachate. Following contact with the synthetic leachate, both GCLs displayed a significant increase in hydraulic conductivity with or without prehydration with PF during the swelling period. But the permeability performance of the GCLs was much better with the real leachate than that with synthetic leachate. But if the test period is much longer, it would result in higher permeability values. The swelling period with the prehydration fluid was also one of the main reasons which caused low permeability and gel phase for the real leachate.

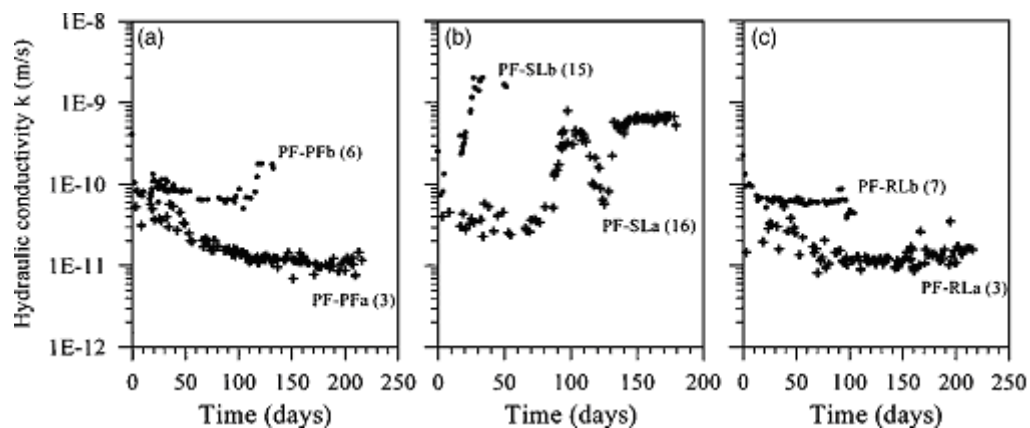


Figure 2.21. Hydraulic conductivity-time graphs for three different fluids and two different GCLs (Number of pore volumes attained at the end of each test are indicated in parantheses) (Spurr, 1969)

Ruhl and Daniel (1997) investigated the effect of hydration and the effects of leachates and chemical solutions on hydraulic conductivity of geosynthetic clay liners. Lower hydraulic conductivities were obtained when the first hydration liquid was water rather than the chemical solution or leachate. Because permeant liquids which are rich in calcium tend to shrink the diffuse double layer and cause an increase in permeability. GCLs were permeated with different types of chemical solutions such as a municipal solid waste (MSW) leachate rich in calcium, a strong acid solution, a strong base solution, a real

leachate, a simulated hazardous waste leachate and a simulated fly ash leachate. The GCLs which were used in these experiments were needlepunched and geotextile-encased containing sodium bentonite GCLs. Triaxial permeability tests were performed in flexible wall permimeters on specimens which had 100 mm diameters. Hydraulic gradients were between 100 and 200 in most of the tests and test durations were up to one year.

The hydraulic conductivity to tap water was measured between 3×10^{-10} and 2×10^{-9} cm/s in these triaxial permeability tests. The GCLs were permeated with a simulated MSW leachate which was rich in calcium (1000 mg/L Ca^{+2}). When the GCLs were permeated directly with this simulated MSW leachate, the hydraulic conductivity was measured between 10^{-6} and 10^{-5} cm/s which is approximately four orders of magnitude higher than that the hydraulic conductivity to water. Replacement of sodium ions by calcium ions is the main reason for the high hydraulic conductivity. When the GCLs had been hydrated with water before they were permeated with the simulated leachate, lower permeability values were obtained. But the permeation period was up to one year. If longer tests had been performed, there would have been enough time for sodium ions to be fully replaced by calcium ions which would have increased permeability.

Low hydraulic conductivities were obtained when the GCLs were permeated with a real MSW leachate. The real MSW leachate appeared to be less aggressive than the simulated MSW leachate because the real MSW leachate contained almost equal amounts of monovalent and polyvalent cations, contained suspended solids and microorganisms which tended to plug the pores of the bentonite, produced gases which tended to block flow paths.

When the GCLs were directly permeated with a strong acid or a strong base, high hydraulic conductivities between 10^{-6} and 10^{-7} cm/s were also obtained. But when water was used as the prehydration liquid before permeation, lower permeability values were obtained again.

When the GCLs were permeated with simulated hazardous waste leachate, low hydraulic conductivity values between 10^{-9} and 10^{-10} cm/s which were similar to those obtained when the GCLs were permeated with tap water were measured. The simulated

hazardous waste leachate contained 10000 mg/L of organic substances. But this amount was not high enough to change the dielectric constant of the simulated leachate and to cause an increase in permeability.

When the GCLs were permeated with simulated fly ash leachate, low hydraulic conductivity values which were also similar to those obtained when the GCLs were permeated with tap water were measured.

The relation between hydraulic conductivity of geosynthetic clay liners and index properties such as liquid limit and swell index of the bentonite used in the geosynthetic clay liners was investigated by Lee et al. (2005). Three index properties; liquid limit, swell index and sedimentation volume of two sodium bentonites from geosynthetic clay liners were correlated with the hydraulic conductivity of the same GCLs. Two different liquids; deionized water (DIW) and calcium chloride (CaCl_2) solutions were used as the hydration fluid for index tests and permeation fluid for hydraulic conductivity tests.

Two different types of GCLs were chosen according to their bentonite qualities. One of them contained higher quality bentonite (HQB) with greater sodium montmorillonite content (86 per cent versus 77 per cent), higher plasticity index (548 versus 393), greater cation exchange capacity (93 meq/100 g versus 64 meq/100 g) relative to the lower quality bentonite (LQB).

Triaxial permability tests were performed in flexible wall permeameters using DIW and CaCl_2 as the permeation liquid on two different GCLs. GCL samples were trimmed to a diameter of 100 mm. The tests where CaCl_2 was used as the permeation liquid continued until chemical equilibrium obtained. It took 1-900 days depending on the amount of CaCl_2 in the solution. The tests which took 900 days were performed with the highest amount of CaCl_2 in the solution.

The increase in permeability with increasing CaCl_2 concentration, as also seen in figure 2.22 is due to the decrease in thickness of the adsorbed layer of cations that results in larger pore volumes and higher permeability values. Higher quality bentonite GCL samples had slightly higher permeability values and more susceptibility to chemicals

because of their greater cation exchange capacity and other bentonite quality properties. Higher permeability values were also obtained for the tests on lower quality bentonite GCL samples performed at UW than those performed at CSU due to the difference in effective stresses used in the two laboratories.

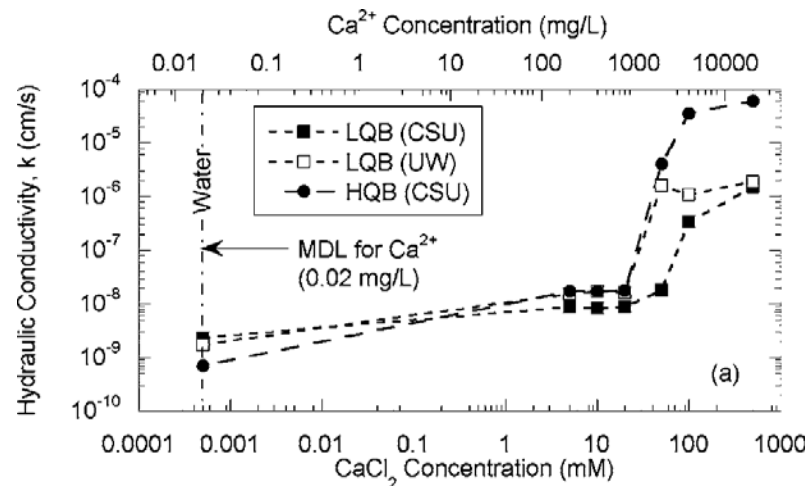


Figure 2.22. Hydraulic conductivity test results on two different GCLs (HQB and LQB) permeated with two different liquids (water and CaCl₂ solution) obtained from two different sources (Lee et al., 2005)

The decrease in liquid limit with increasing CaCl₂ concentration as shown in figure 2.23 can be attributed to the increasing predominance of calcium (Ca²⁺) on the exchange complex of the bentonite particles resulting from cation exchange with sodium (Na⁺) that causes stronger net interparticle forces (Lambe and Whitman, 1969).

The decrease in sedimentation volume with increasing CaCl₂ concentration as shown in figure 2.24 is due to compression of the adsorbed layer of cations resulting in the formation of flocculated particles, faster settling and lower sedimentation volume.

The decrease in swell index with increasing CaCl₂ concentration as shown in figure 2.25 is consistent with the individual granules of bentonite becoming smaller due to compression of the interlayer region induced by the elevated calcium concentration in the bulk solution (Shackelford et al., 2000).

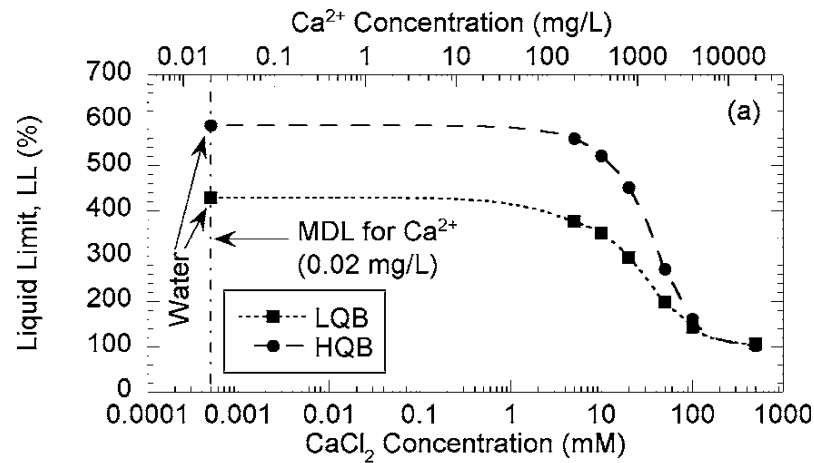


Figure 2.23. Liquid limit test results on two different GCLs (HQB and LQB) permeated with two different liquids (water and CaCl_2 solution) (Lee et al., 2005)

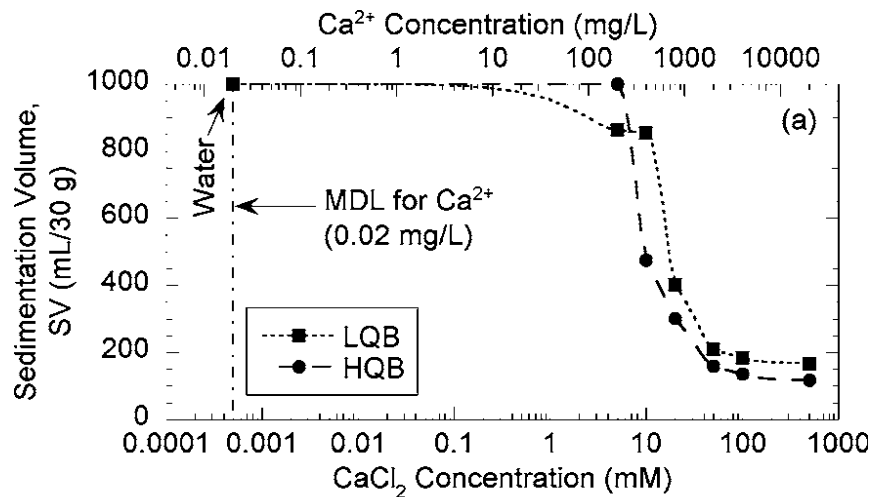


Figure 2.24. Sedimentation volume results on two different GCLs (HQB and LQB) permeated with two different liquids (water and CaCl_2 solution) (Lee et al., 2005)

According to the results obtained from the index and hydraulic conductivity tests, an increase in CaCl_2 concentration resulted in a decrease in liquid limit, sedimentation volume or swell index and an increase in hydraulic conductivity of the GCL as shown in figure 2.26. However, little or no change in an index property did not necessarily ensure that there was no change in permeability, and significant changes in an index property occurred without significant changes in permeability (Lee et al., 2005). Results of the tests also showed that the effective stress used in the triaxial permeability tests may play an important role in terms of the correlation between hydraulic conductivity and an index property.

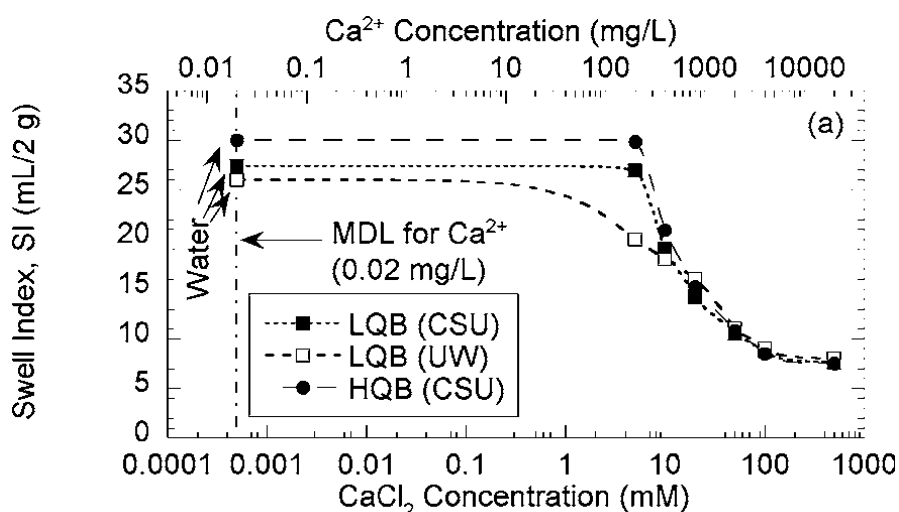


Figure 2.25. Swell index results on two different GCLs (HQB and LQB) permeated with two different liquids (water and CaCl_2 solution) (Lee et al., 2005)

Vasko et al. (2001) conducted falling head permeability tests with constant tailwater level on geosynthetic clay liners using flexible wall permeameters. The aim of these permeability tests was to determine how prehydration affects the hydraulic conductivity of geosynthetic clay liners permeated with calcium chloride (CaCl_2) solutions.

Geosynthetic clay liners used in this study were composed of granular sodium bentonite sandwiched between one woven and one nonwoven geotextiles which were needlepunched together. 0.005, 0.01, 0.025, 0.1 and 1 M CaCl_2 solutions were used as permeation liquids. Most of the GCLs were prehydrated with deionized water without confinement. Confinement was applied to some of the GCLs by a cylindrical lead weight which gave an average stress of 8 kPa. This stress level was chosen to simulate the confining stress provided by a leachate layer in a landfill. The average confining stress and hydraulic gradient applied in the permeability tests were 20 kPa and 100 kPa, respectively.

As seen in figure 2.27, hydraulic conductivity increases as CaCl_2 concentration in the permeation liquid increases. The increase in permeability is due to the exchange of Ca^{2+} cations for Na^+ cations. Hydraulic conductivity of GCLs when permeated with the weaker solutions is almost the same as that obtained when permeated with deionized water (DI). Hydraulic conductivity is independent of the prehydration water content for the intermediate and weaker solutions. But the hydraulic conductivity decreases from 1×10^{-4}

cm/s to 3×10^{-7} cm/s as the prehydration water content increases from 9 per cent to 150 per cent and then remains constant at 3×10^{-7} cm/s as the prehydration water content is increased further. The reason for the decrease in permeability when the GCLs had been prehydrated with diionized water before they were permeated with CaCl_2 solutions is that the film of hydration water surrounding particles in a prehydrated GCL hinders the chemical solution from interacting with the particle surface which prevents a reduction in the volume of the adsorbed water.

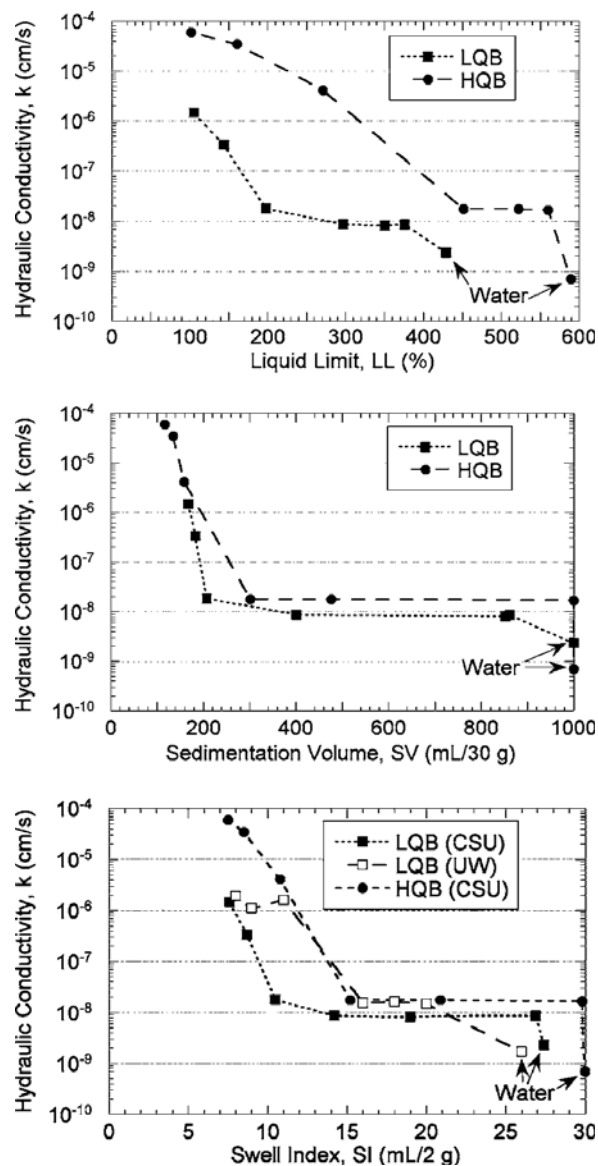


Figure 2.26. Correlations between hydraulic conductivity and three index properties on two different GCLs (HQB and LQB) permeated with two different liquids (water and CaCl_2 solution) obtained from two different sources (Lee et al., 2005)

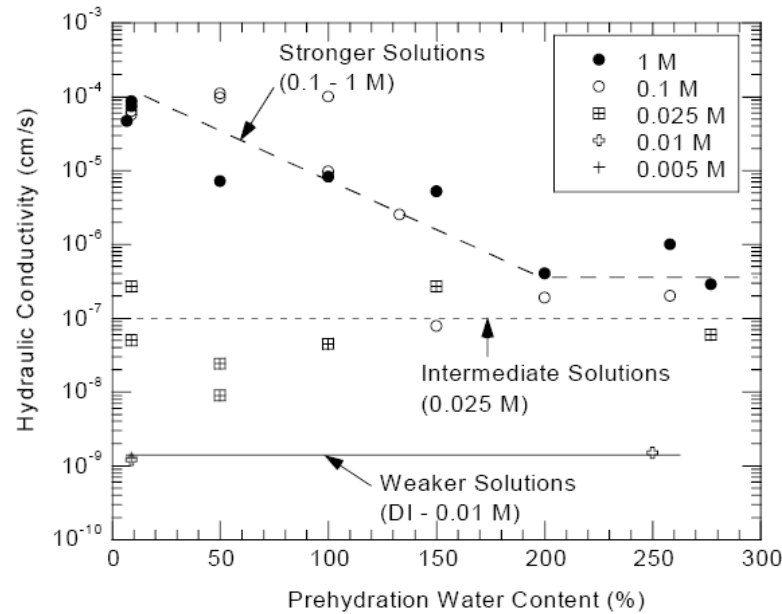


Figure 2.27. Hydraulic Conductivity versus Prehydration Water Content graph for Unconfined Specimens (Vasko et al., 2001)

A series of tests were conducted with confinement during prehydration. There is a tendency for lower hydraulic conductivities under confinement when the prehydration water contents are higher. When the prehydration water content was 100 per cent, hydraulic conductivity was obtained as 5.2×10^{-7} cm/s for the samples which were confined during hydration and 9.6×10^{-6} cm/s for the samples which were not confined during hydration. When the prehydration water content was 133 per cent, hydraulic conductivity was obtained as 2.6×10^{-7} cm/s for the samples which were confined during hydration and 2.5×10^{-6} cm/s for the samples which were not confined during hydration. Possible reason for the lower hydraulic conductivities obtained under confinement is the compression of softer bentonite granules that exist at higher prehydration water contents. But at prehydration water content of 50 per cent, higher hydraulic conductivity was obtained as 1.0×10^{-4} cm/s under confinement where the hydraulic conductivity was 9.7×10^{-5} cm/s under no confinement. All of these values were measured with 0.1 M of CaCl_2 solution.

The relation between hydraulic conductivity and void ratio was also investigated. It is expected that lower void ratios correspond to lower permeability. But hydraulic conductivities of GCLs tested with stronger CaCl_2 solutions were inversely correlated with void ratio as shown in figure 2.28 in this study (Vasko et al., 2001).

The decrease in permeability is because of the texture behavior and the position of the pore spaces of bentonite particles. When a GCL was fully prehydrated, bentonite granules became individual particles and formed a structure called gel. The gel structure had a void ratio between 5 and 7 and had a low hydraulic conductivity because most of the voids were filled with immobile bound water that were combined with the bentonite particles. But when a GCL was partially prehydrated, there was not enough water to form a gel. Gel structure did not form during even permeation period because Ca^{2+} ions prevented expansion of the interlayer region. Thus, the void ratio of a partially prehydrated GCL was between 3 and 5 and these values are lower than that obtained from a fully prehydrated GCL.

But the voids between the bentonite granules were larger and provided the liquid to flow easier than those in a gel structure which caused higher permeability for partially prehydrated GCLs even though they had lower void ratio than fully prehydrated GCLs.

Cazzuffi et al. (2004) conducted hydraulic conductivity tests on four GCL samples (shown with A, B, C and D in table 2.2) installed as capping in a polluted area in Southern Italy. The capping system of the site was composed of a 0.5 m vegetated surface layer. An additional hydraulic conductivity test was also performed on a partial part of a GCL sample (shown with C with root in table 2.2) penetrated by a vegetable root crossing in order to compare the hydraulic conductivity of undamaged GCLs samples with that of a damaged GCL sample with a root penetration. Furthermore, hydraulic conductivity tests were performed on three GCL samples (shown with 1, 2 and 3 in table 2.2) of the virgin material before the application on the same site in 1997 in order to compare the time effect on permeability of GCLs.

Hydraulic permeability tests were carried on 100 mm diameter GCL samples placed in permeameters and the applied hydraulic head difference and cell pressure were 50 kPa and 100 kPa, respectively. The average permeability coefficient values obtained from the results shown in figure were $3,73 \times 10^{-11}$ m/s for the tests performed in 1997 and $8,63 \times 10^{-11}$ m/s for the tests performed in 2004.

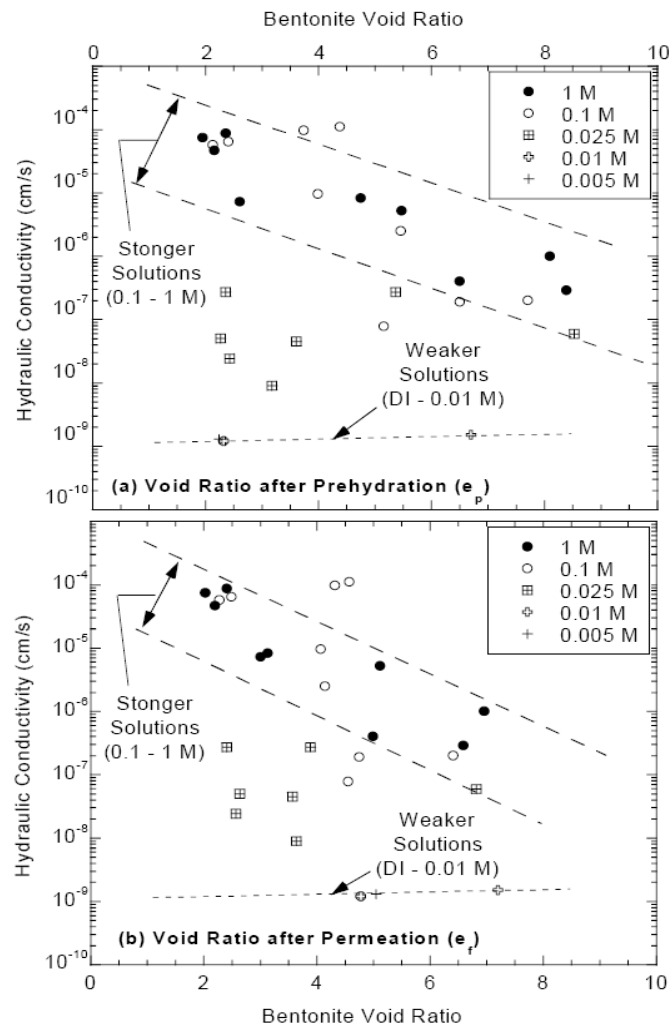


Figure 2.28. Hydraulic Conductivity versus Void Ratio graph (Vasko et al., 2001)

The results show that higher hydraulic conductivity values were obtained on GCLs tested in 2004 than those tested in 1997 with the exception of the sample D (Table 2.2). For example, the GCL samples B and C had permeability coefficient values of $1,01 \times 10^{-10}$ m/s and $1,32 \times 10^{-10}$ m/s, respectively while the virgin GCL sample 1 had permeability coefficient value of $2,88 \times 10^{-11}$ m/s, nearly an order of magnitude lower than those obtained from the GCL samples B and C.

A hydraulic equivalency in terms of thickness between the GCL and a clay compacted liner (CCL) was established. The results showed that the average permeability coefficient obtained on GCLs tested in 1997 was equivalent to a layer of compacted clay liner of 0,47 m that had a permeability coefficient of 1×10^{-9} m/s while the average permeability coefficient obtained on GCLs tested in 2004 was equivalent to a layer of

compacted clay liner of 0,11 m. Thus, the usage of GCL as a barrier for a capping system is not good because of the considerable increase in permeability of GCL in seven years.

Table 2.2. Permeability coefficients obtained from hydraulic conductivity tests on GCL samples A, B, C, C with root and D carried out in 2004 and on GCL samples 1, 2 and 3 carried out in 1997 (Cazzuffi et al., 2004)

GCL samples	Unit	Permeability coefficient
A	m/s	$8,61 \times 10^{-11}$
B	m/s	$1,01 \times 10^{-10}$
C	m/s	$1,32 \times 10^{-10}$
C with root	m/s	$7,92 \times 10^{-11}$
D	m/s	$3,30 \times 10^{-11}$
1	m/s	$2,88 \times 10^{-11}$
2	m/s	$3,20 \times 10^{-11}$
3	m/s	$5,13 \times 10^{-11}$

One of the main reasons for the increase in permeability of the GCL is the desiccation of the bentonite layer in GCL due to wet-dry cycling. GCLs that are exposed to wet-dry cycling may fail in the long-term if cation exchange caused by divalent cations takes place. When the swell potential of the bentonite in GCL decreases, desiccation may cause cracks on the bentonite which can not be sealed. The GCL was covered with a geomembrane layer in order to prevent desiccation and increase in permeability of the GCL.

The hydraulic conductivity of the GCL sample C with root is even lower than that of the GCL sample C. The result shows that the damage from root puncturing did not cause an increase in permeability due to the self-healing and swelling capacity of the bentonite in GCL sample C with root.

Mellies and Gartung (2004) performed large-scale field tests on a landfill in Bavaria, Germany in order to test the effectiveness of landfill capping systems. Large-scale lysimeters were installed on a landfill site where the amount of water was measured

through the system precisely. Two different test fields were chosen for the tests. Test field 1 consists of 0,2 m of topsoil underlain by 1,5 m of a low-quality mineral cover made of cohesive sand. Hydraulic conductivity of the mineral cover is between 10^{-7} m/s and 10^{-10} m/s. A seepage collection system consists of a drainage layer and geomembrane is placed below the mineral cover. Two water flows are collected and measured separately. Surface runoff (Q_S) is obtained from the topsoil and seepage (Q_L) is obtained through mineral cover.

Test field 2 consists of two restoration layers with a loamy sand topsoil (0,2 m) and slightly loamy sand subsoil (0,8 m), a drainage geocomposite, a GCL layer, a regulating layer with loamy sand and a seepage collection system with drainage geocomposite and HDPE geomembrane. A profile of the cover system in the test field 2 is shown in figure 2.29.

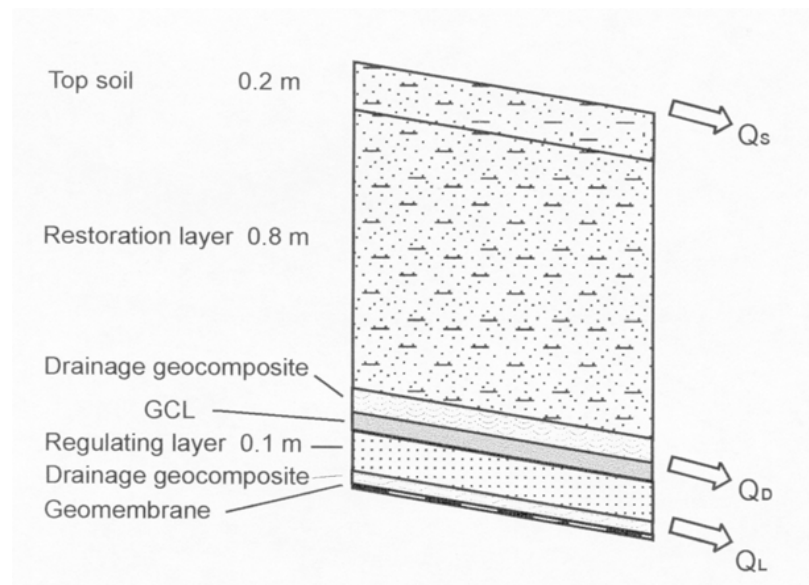


Figure 2.29. Profile of the test field 2 (Mellies and Gartung, 2004)

A calcium bentonite GCL is used with a mass per unit area of 9500 g/m^2 and a permittivity (Ψ) of $8,3 \times 10^{-9} \text{ s}^{-1}$. Surface runoff (Q_S) is obtained from the topsoil, seepage (Q_L) is obtained through the GCL and drainage flow (Q_D) is obtained through the drainage geocomposite.

The water balance of the two landfill capping systems were measured with the help of lysimeters during four years. At the end of the four-year period, a large amount of

precipitation percolated through the cap into the landfill in test field 1. But only 0,9 per cent of precipitation seeped through the GCL in test field 2. As a result, the landfill capping design of test field 2 with a drainage composite layer and a calcium bentonite GCL proved to be an effective application as a landfill cover system.

The effect of needle-punching on permeability and swell characteristics of geosynthetic clay liners was investigated by Fratalocchi (2005). He performed confined constant swell tests under different overburden pressures in oedometer cells and hydraulic conductivity tests in flexible wall permeameters on two needle-punched GCLs both consisting of natural powdered sodium bentonite. According to the results, considerably low swell and hydraulic conductivity values were obtained due to the fibers of needle-punching at low confining stresses.

As the bentonite swell increases, needle-punched fibers are loaded and at the end of swelling, many of the fibers are pulled out. Low void ratios were also obtained at low hydraulic conductivities. The influence of the fibers on permeability is more evident when the hydration pressure is low which means that the needle-punching is effective at low confining stresses. For overburden pressures greater than 40 kPa, the needle-punching is ineffective. Thus, the use of needle-punched GCLs can be recommended in lagoons or cover systems for landfills because of the low permeability behavior of a needle-punched GCL in low stress condition which is the worst case for a GCL. But Fratalocchi (2005) used water as the hydration and permeation liquid in his experiments. The usage of chemical solutions other than water for determining the permeability characteristics of needle-punched GCLs must also be investigated.

Petrov et al. (1997) also performed confined swell and hydraulic conductivity tests on a needle-punched GCL with water as the hydration liquid and water mixed with different amounts of ethanol concentrations as the permeation liquid. Increase in static confining stress and needle-punching both restricted swelling of the GCL and resulted in low bulk void ratios and low permeability coefficients as seen in figure 2.30. Lower final GCL height means that lower swelling occurs and due to the lower swell of the GCL, lower hydraulic conductivity values are obtained. Lower hydraulic conductivities are also

obtained at lower bulk GCL void ratios. According to figure 2.30, DW means distilled water, TW means tap water, FR means fixed-ring and DR means double-ring.

For small amounts of permeation liquid flow, hydraulic conductivities of all of the ethanol/water mixtures decrease. As seen in figure 2.31, at or near chemical equilibrium, low ethanol concentration mixtures (25 per cent and 50 per cent) continue to show low permeability behavior due to the increase in viscosity of the permeation liquid. Contrarily, permeabilities of high ethanol concentration mixtures (75 per cent and 100 per cent) begin to increase due to the contraction of the double diffuse layer.

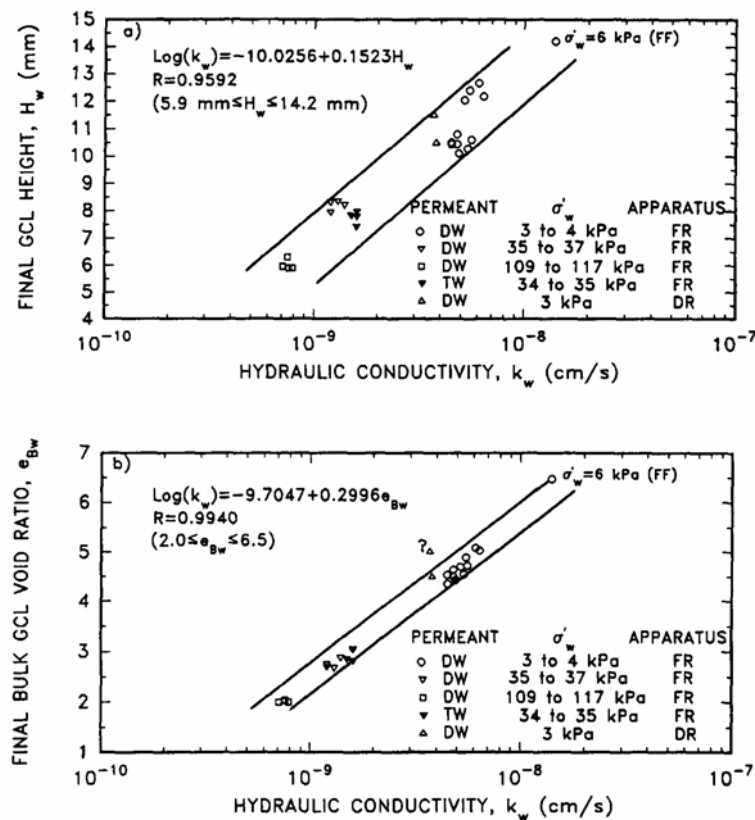


Figure 2.30. Hydraulic conductivity versus a) final GCL height; b) final bulk GCL void ratio graphs when the GCL is permeated with water (Petrov et al., 1997)

An experimental study was conducted on flow rates through composite liners involving GCLs due to defects in the geomembrane by Barroso et al. (2006). Experiments were performed at three different scales where flow rate was measured. Small-scale tests were conducted using 0.2 m diameter cell. Intermediate-scale tests were conducted using 1 m diameter cell, and large-scale tests were conducted in a square 2.2 m wide test pit facility. The purpose of these tests was to examine the influence of prehydration of the

GCLs, the increase in confining stress and the hydraulic head on flow rates through composite liners due to defects in the geomembrane, as well as to compare different scale test results and, thus, to check the feasibility of an extrapolation of results obtained from small-scale tests to field conditions (Barroso et al., 2006).

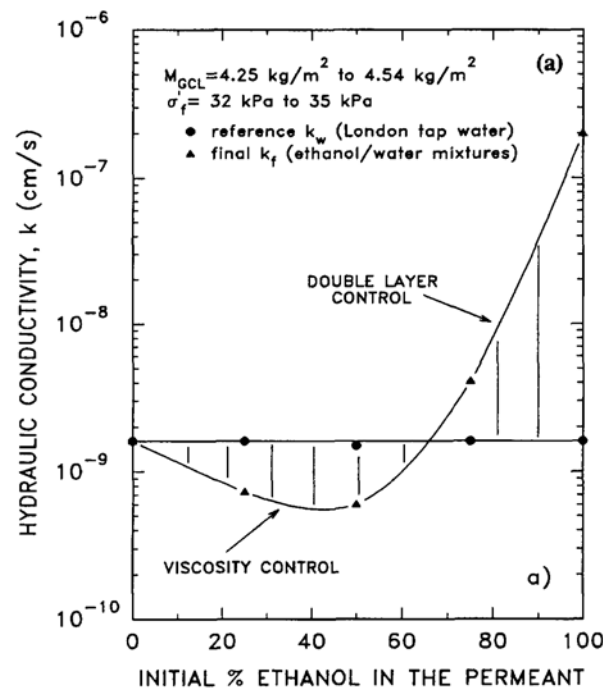


Figure 2.31. Hydraulic conductivity versus ethanol concentration amount in the permeation liquid (Petrov et al., 1997)

Small-scale tests were performed in a circular cell which consists of a bottom plate supporting the compacted soil layer, a base cylinder with a diameter of 0.2 m and 0.08 m high, a granular cover plate to simulate the presence of a granular drainage layer and an upper part of 6 cm high that accommodates the granular cover plate as seen in figure 2.32.

GCL specimen was placed on top of the soil, usually with the non-woven geotextile on top. Then, geomembrane was installed on top of the GCL with a 3 mm circular hole at its center. Then, the granular cover plate was placed above the geomembrane. The cell was placed in a press, which allowed the application of confining stresses. Finally, the top cell was connected to a water supply reservoir, which fed the test during the first hours when the water flow through the composite liner was large. When the water flow decreased, the water reservoir was replaced by a Mariotte bottle, which is more accurate at low flows.

Both water reservoir and Mariotte bottle can be set to a specified hydraulic head that can be kept constant during the constant head tests (Touze-Foltz et al., 2002).

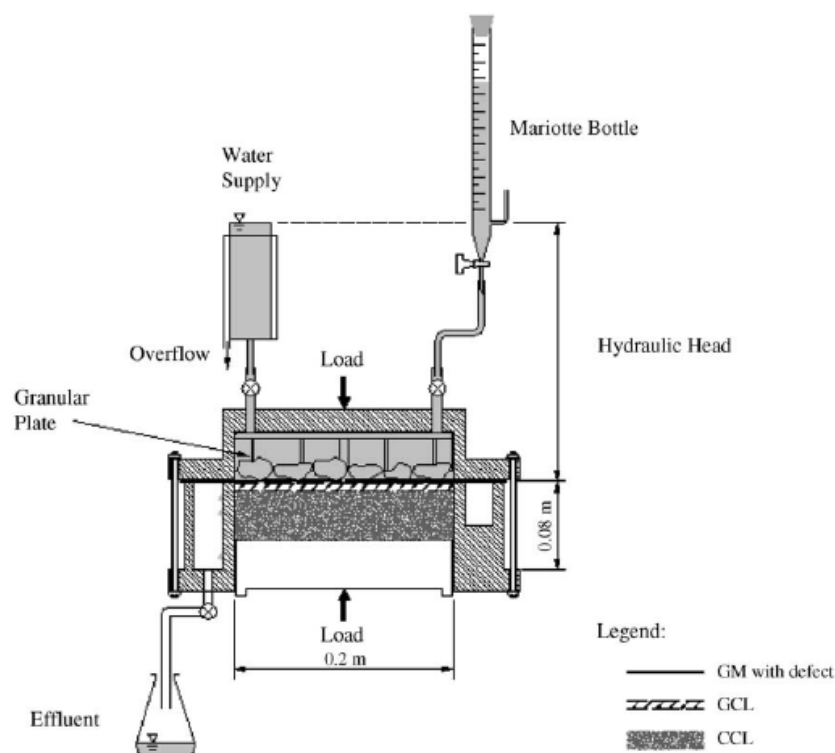


Figure 2.32. Schematic figure of the small-scale test apparatus (Barroso et al., 2006)

GCL specimens used in the experiments were both needle-punched and adhesive-bonded. Bentonite in the GCL specimens were both granular and powdered. GCL-1 was a needle-punched GCL with granular bentonite and flow rate-time graphs for GCL-1 specimens were shown in figures 2.33 and 2.34 under different conditions in terms of prehydration, confining stress and hydraulic head. The influence of prehydration on flow rates was determined by performing tests either with non-prehydrated (as supplied) or with prehydrated specimens (moistened to water content of 100 per cent). The effect of confining stress was studied by performing tests under 50 and 200 kPa. The effect of hydraulic head was evaluated by conducting tests with two different hydraulic heads of 0.3 m and 1.2 m.

According to the results and figures 2.33 and 2.34 obtained from the tests, prehydration affected the flow rate. As the confining stress was increased, the flow rate

decreased. This effect was higher for prehydrated GCL specimens. The results also show that the flow rate increased when the hydraulic head was increased.

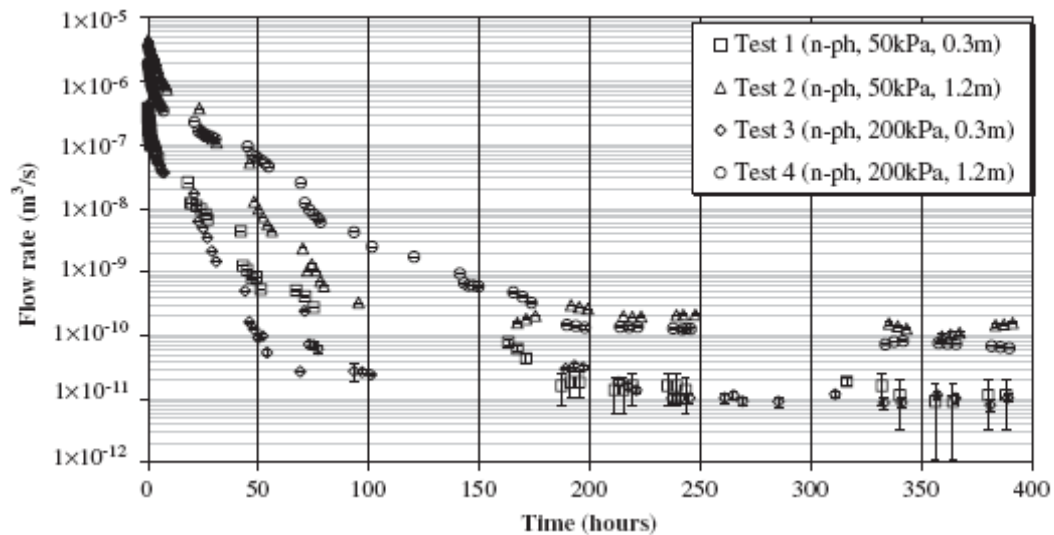


Figure 2.33. Flow rate-time graphs obtained from tests conducted on nonprehydrated GCL-1 specimens (Touze-Foltz et al., 2002)

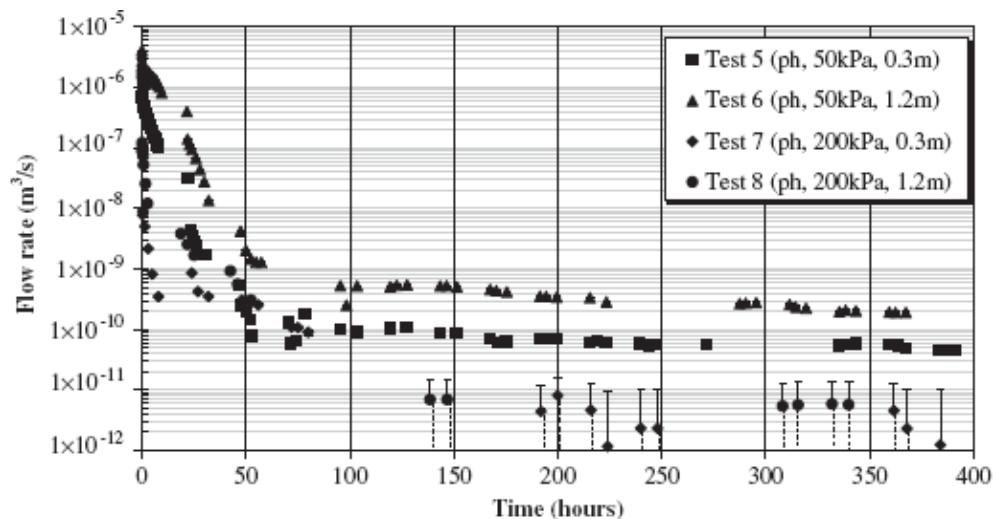


Figure 2.34. Flow rate-time graphs obtained from tests conducted on prehydrated GCL-1 specimens (Touze-Foltz et al., 2002)

A needlepunched, nonwoven GCL overlain by a HDPE geomembrane and a 60 cm thick compacted clay liner were tested to be used as a final cover for a hazardous waste landfill. The usage of the composite landfill cover with GCL and geomembrane instead of the 60 cm thick CCL has caused an increase of the facility capacity by 55000 m³. The

measured quantities of leachate collected at the landfill decreased dramatically with the introduction of the composite cover. When 78 per cent of the landfill was covered with the GCL overlain by the geomembrane, leachate generation was reduced by 71 per cent. The GCL cover was also easier to construct than the CCL. A saving of \$ 42000/acre resulted with the use of the composite cover system (GCL overlain by geomembrane). As a conclusion, the use of a GCL instead of a CCL in a hazardous waste landfill resulted in accelerated construction time, significant cost savings and improved performance in terms of hydraulic conductivity.

Laboratory tests were performed on GCLs in order to investigate the effect of freeze-thaw cycles on GCLs. According to the laboratory test results, the GCLs could resist 20 freeze-thaw cycles without any deterioration in hydraulic conductivity. Ice lenses were randomly presented in the cross-section of the frozen GCLs. But there were not any cracks on the thawed GCLs and these GCL samples were identical to the GCL samples that were hydrated but not frozen. As a result, the cracks formed by the ice lenses during freezing were sealed after thawing process. The soft bentonite in the GCL samples helped the sealing process to occur (Olsta and Friedman, 2002).

Hydraulic conductivity of bentonite does not increase due to freezing and thawing process because of the molecular composition of bentonite. Weak bonds in montmorillonite clays result in interlayer expansion when polar molecules such as water interact with the clay. But most of the natural occurring clays do not show such a behavior. When these clays interact with water, they do not expand or swell. Permeability of such compacted clays increases upon several freeze/thaw cycles due to the flow channels formed by the micro lenses during the freezing process. Drawing of the water which forms the micro lens from the clay results in desiccation of the clay. The desiccated zones in non-montmorillonite clays do not swell enough when the water is released during thawing. Due to not enough swelling, the hydraulic conductivity of the non-montmorillonite clays increases. Contrarily, bentonite, which is a montmorillonite clay, swells during thawing and the hydraulic conductivity of the bentonite does not increase.

2.4. Mechanical Behavior

A waste containment facility liner or a cover system must not only have low hydraulic conductivity but also be stable during construction and after placement of waste. A GCL must resist stresses applied from the waste product and must not collapse or fail during longterm usage. Interface friction between a GCL and a soil must be high enough in order to transmit shear stresses during the lifetime of the cover system. Another concern about the mechanical behavior of GCLs is the internal failure of the GCL which is observed by the failure of the bentonite in the GCL or at the interface between the bentonite and geosynthetics in the GCL.

Peak shear strength of reinforced (needle-punched and stitch bonded) GCLs and unreinforced GCLs were compared and low values were obtained when unreinforced GCLs were tested (Shan and Daniel, 1991). Low internal shear strength causes instability on slopes and it was not recommended to use unreinforced GCLs on slopes steeper than 10H:1V. On the other hand, presence of fibers causes reinforced GCLs to have higher internal peak shear strength which is maintained by the resistance of the fibers against pull-out. Although internal shear strength failure of a reinforced GCL was observed in the laboratory, there are not any slope failure cases because of internal shear failure of a reinforced GCL. Interface friction was also evaluated by performing interface shear tests between GCLs and soils. A reduction was obtained in frictional resistance between a GCL and a geomembrane due to bentonite migration through both woven and nonwoven geotextiles of the GCL.

Tanays et al. (1994) and Feki et al. (1997) reported results about an experimental study of a stitch-bonded GCLs installed over slopes inclined at 2H:1V and 1H:1V. Displacements of the GCL was measured during a period of 500 days for both of the slopes. The GCL over 2H:1V slope remained almost unchanged at the end of the test but the GCL over 1H:1V reached an average strain of 5.5 per cent one day after its installation. The displacements occurred at the top of the slope and they began to decrease during the observation period of 3 months. Partial failure of the GCL occurred when the strain exceeds 2 per cent. Daniel et al. (1998) investigated interface behavior of reinforced and unreinforced GCLs over slopes. Both the reinforced and unreinforced GCLs tested over a

slope inclined at 3H:1V performed well but three slides occurred when the GCLs were tested over a steeper slope with an inclination of 2H:1V. Among the three slides, one slide occurred internally in a geomembrane backed, unreinforced GCL due to bentonite hydration and two slides occurred at the interface between a geomembrane and a reinforced GCL due to bentonite extrusion through the woven geotextile of the GCL which reduced the interface shear strength (Bouazza, 2001).

Vukelic et al. (2007) conducted interface shear tests between needle-punched GCLs and textured geomembranes at normal stresses ranging from 10 to 400 kPa. The woven geotextile of the GCL was in contact with the geomembrane. The shear device to perform shear tests is seen in figure 2.35. One half of the tests were conducted on non-prehydrated GCLs and the other half of the tests were conducted on prehydrated GCLs. Bentonite migration through the geomembrane was observed when the shear tests were performed on prehydrated GCLs at normal stresses of 100 kPa and above. The amount of bentonite migration increased with an increase in normal stress and lubrication of the interface part between GCL and geomembrane caused decrease in shear strength. Prehydrated GCL samples tested at lower shear rates resulted in lower interface shear strengths and more bentonite migration to the contact area where shear rate did not affect the test results for non-prehydrated samples.

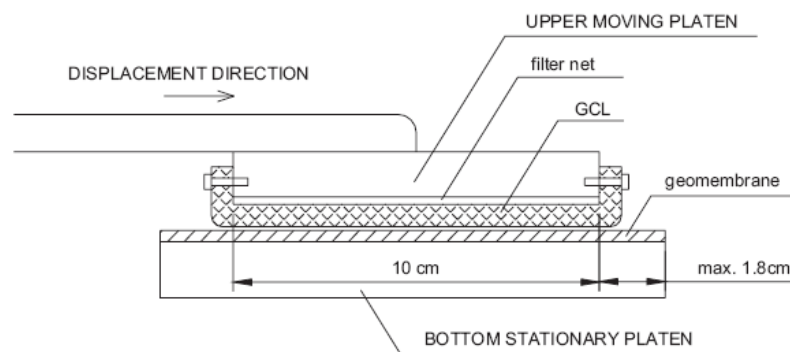


Figure 2.35. Cross-section of the shear device (Vukelic et al., 2007)

Vukelic et al. (2007) defined bentonite extrusion coefficient ($c_{\text{extrusion}}$) as follows:

$$c_{\text{extrusion}} = \frac{\text{area of the the geomembrane covered with bentonite}}{\text{total contact area of the geomembrane}} \quad (2.3)$$

As seen from the bentonite extrusion coefficient formula, the area of the geomembrane covered with bentonite is directly proportional to the quantity of extruded bentonite from the GCL and the coefficient of bentonite extrusion.

According to the test results, bentonite extrusion coefficient values higher than zero were obtained on prehydrated GCL samples tested under normal stresses of minimum 100 kPa which means that the amount of bentonite migration through the geomembrane increases as the normal stress increases. But the bentonite extrusion coefficient was equal to zero when the non-prehydrated GCL samples were tested.

Deformations of dry and hydrated GCLs installed under a 50 mm coarse gravel soil layer and a 1.5 mm high-density polyethylene, wrinkled geomembrane were examined (Dickinson and Brachman, 2006). The effect of the wrinkle in the geomembrane on the deformation behavior of the GCL and the protection layers over the GCL in order to minimize GCL deformations were investigated.

If a GCL sample without any wrinkle in the geomembrane was subject to uniformly distributed load such as a thick, sand layer above the geomembrane, then vertical deformation of the GCL would occur due to the consolidation of the bentonite. The void ratio of the bentonite would decrease and result in a lower hydraulic conductivity. If there is a wrinkle in the geomembrane, there would be both lateral extrusion of bentonite towards the region beneath the wrinkle and deformation of the GCL due to the consolidation of the bentonite. The presence of the wrinkle in the geomembrane would result in additional decreases in thickness of the GCL beside the wrinkle, and potentially, increases beneath the wrinkle. Either with or without a wrinkle, if the GCL was subject to nonuniform loading such as from coarse gravel particles overlying the geomembrane, then local deformations could develop in the GCL. The magnitude of these deformations is expected to depend on the properties of the GCL (water content, the type of cover and carrier geotextiles, needlepunching and thermal treatment), the materials above and below the liner, the type of protection layer and the magnitude of applied stresses (Dickinson and Brachman, 2006).

The test apparatus consists of a cylindrical steel vessel with an internal diameter of 590 mm and height of 500 mm. Vertical pressures are simulated by applying fluid pressure to a flexible rubber bladder that is sealed around its perimeter between the body and lid of the apparatus. The apparatus is capable of applying vertical pressures as large as 3100 kPa. Lateral stresses are developed by limiting the outward deflection of the apparatus, producing essentially zero-lateral strain conditions (Brachman and Gudina, 2002).

The GCL used in this study consisted of woven carrier geotextile, sodium bentonite with mass of 4721 g/m², and a nonwoven cover geotextile. The GCL was needle-punched and the fibres were thermally fused to the carrier geotextile.

The wrinkle in the geomembrane decreased in height and width when subject to applied pressures, but the gap between the wrinkle and GCL remained even up to applied pressures of 1000 kPa. The magnitude of local GCL deformations increased with increasing initial water content.

As a result, the 150 mm thick sand protection layer reduced both the number and magnitude of the local indentations of the GCL where the 1200 and 2000 g/m² nonwoven needle-punched geotextile protection layers tested were not effective at reducing the magnitude of local indentations relative to no protection layer above the geomembrane. Thus, a 150 mm thick sand layer over a GCL would be effective in order to limit the indentations of the GCL when compared to nonwoven, needle-punched geotextiles with masses up to 2000 g/m².

Both shear strength and hydraulic conductivity of sodium and calcium bentonites were investigated (Gleason et al., 1997). The permeant liquids used in this study were tap water and distilled water containing 1.5 M calcium chloride (CaCl₂). Hydraulic conductivities of thin layers of both sodium and calcium bentonites were obtained by triaxial permeability tests according to ASTM D5084 and the results are listed in table 2.3.

Hydraulic conductivity to tap water was the same for both granular and powdered sodium bentonite, but an order of magnitude higher for calcium bentonite at a 35 kPa confining stress. But when the thin layer of bentonites were directly permeated with 1.5 M

CaCl_2 , highest hydraulic conductivity was obtained for granular sodium bentonite where lowest hydraulic conductivity was obtained for powdered sodium bentonite. These results show that permeant liquid plays an important role on the hydraulic conductivity of calcium and sodium bentonites.

Table 2.3. Hydraulic conductivities for thin bentonite layers at a compressive stress of 35 kPa (Gleason et al., 1997)

Material tested (1)	Hydraulic Conductivity (cm/s)		
	Water (2)	Direct permea- tion with 1.5 M CaCl_2 (3)	Permeated with water, then 1.5 M CaCl_2 (4)
Calcium bentonite	6×10^{-9}	3×10^{-8}	7×10^{-9}
Sodium bentonite (granular)	6×10^{-10}	6×10^{-7}	Not tested
Sodium bentonite (powdered)	6×10^{-10}	9×10^{-9}	Not tested

Low shear strength of hydrated bentonite is often an engineering design problem when a GCL is used as a component of a cover system or a landfill liner. Consolidated-drained direct shear tests were performed on thin layers of bentonites by distilled water as the saturation liquid. The bentonite samples were hydrated approximately 48 hours and then put into a 64-mm-diameter direct shear box. The samples were consolidated to the desired normal stress and were sheared until failure occurred.

Mohr-Coulomb envelopes for the consolidated-drained direct shear tests for both sodium and calcium bentonite layers were shown in figure 2.36. Cohesion (c) and internal friction angle (ϕ) values obtained at the end of the direct shear tests were 5.8 kPa and 21° for the calcium bentonite and 6 kPa and 10° for the sodium bentonite as seen in figure 2.36. Because the internal friction angle (ϕ) of calcium bentonite is higher than that of sodium bentonite, calcium bentonite has a shear strength approximately twice than the shear strength of sodium bentonite. Although calcium bentonite has higher hydraulic conductivity than sodium bentonite when water is used as the hydration and permeation liquid, calcium bentonite has an advantage for applications in which shear strength is crucial (Gleason et al., 1997).

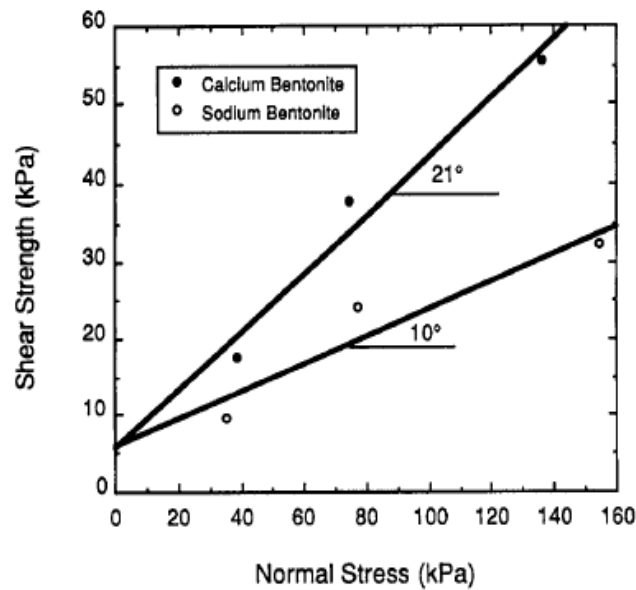


Figure 2.36. Results of Consolidated-Drained Direct Shear Tests on Sodium and Calcium Bentonite (Gleason et al., 1997)

2.5. Gas Permeability and Diffusion

Control of landfill gas has become a considerable problem for the protection of public health and safety. Gas emission is also one of the major concerns which threatens environment. Cover systems such as GCLs have to prevent oxygen from the atmosphere to come in contact with reactive materials such as sulphuric leachates in tailing dams which may generate acid.

2.5.1. Advective Gas Flow

When gas moves from a region of high pressure to a region of low pressure, the flow is called advective gas flow. It occurs when there is a difference of total pressure gradient. For landfills, pressure differentials are the main driving forces which cause gas migration. Natural fluctuations in atmospheric pressure is called barometric pumping and barometric pumping forms pressure differentials through cover systems (Bouazza, 2001). Decreases in barometric pressure causes gas to leave the landfill which increases the gas concentration near the surface layers. Increases in barometric pressure causes the atmospheric air to enter the landfill. Other possible formations for gas migration are changes in temperature and

leachate or groundwater table level. Gas permeability of GCLs depends on several factors such as water content, overburden pressure during hydration and manufacturing process (Vangpaisal and Bouazza, 2001).

Bouazza et al. (2002) performed permeability tests on three types of GCLs. GCL1 and GCL2 were formed by powdered sodium bentonite sandwiched between one nonwoven and one woven geotextiles where GCL3 was formed by granular sodium bentonite sandwiched between one nonwoven and one woven geotextiles. According to the results as seen in figures 2.37 and 2.38, permittivity increased when volumetric water content for all of the three GCL types under two different hydration conditions was decreased (confined under 20 kPa during hydration and no confining pressure was applied during hydration which means free swell hydration). But at the same volumetric water content, GCL1 and GCL2 had lower permittivities than GCL3. This result was because of the granular form of sodium bentonite in GCL3. Particularly, at lower volumetric water contents, hydrated granular bentonite was stiffer and much more clearly visible as soft grain than hydrated powdered bentonite (Bouazza, 2002). Because of these formations of hydrated granular bentonite, presence of larger inter-granular pore spaces helped to form preferential gas flow paths which caused an increase in gas permeability and permittivity of the GCL. The powdered bentonite in GCL1 and GCL2 had gel-like structure and softer than granular bentonite because of the reduction of inter-granular pore spaces in the powdered form.

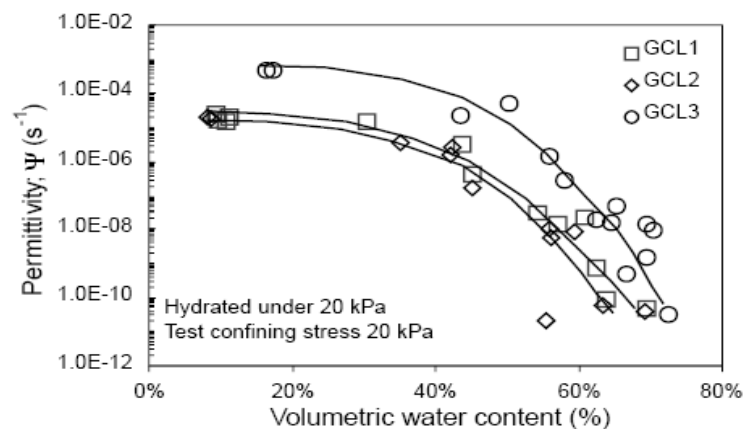


Figure 2.37. Variation of gas permittivity with volumetric water content for confined hydration (Vangpaisal and Bouazza, 2001)

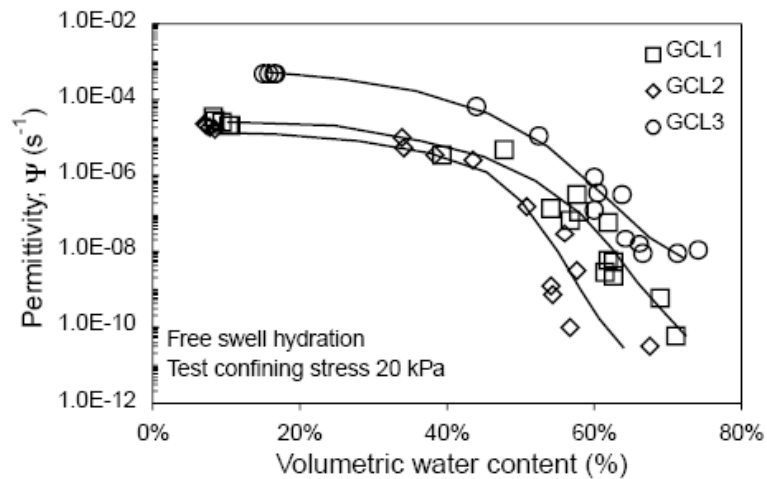


Figure 2.38. Variation of gas permittivity with volumetric water content for free swell hydration (Vangpaisal and Bouazza, 2001)

2.5.2. Diffusive Gas Flow

When a mass of gas is more concentrated in an area, then it tends to diffuse into a less concentrated area. Movement of molecules controls the diffusion of gas and the behavior of pressure gradient of a gas causes gas diffusion. Diffusive gas flow has to be taken into account when dealing with municipal waste facilities or capping of contaminated soils. Sulphidic mine tailing dams and uranium tailing dams are two main examples for cover applications in order to prevent oxidation of the underlying waste. Oxygen diffusion has to be limited by covering the soil with a barrier like GCL.

Oxygen diffusion may be limited by soil layers with high degree of saturation because the liquid-phase diffusion coefficient of oxygen is considerably lower than the gas-phase diffusion coefficient of oxygen. Thus, oxygen diffusion decreases with increasing the degree of saturation.

Gas diffusion usually occurs through the air filled pores of a soil where only a small amount of the gas diffusion occurs in dissolved form through the water filled pores of a soil.

Aubertin et al. (2000) expressed the porous media diffusion coefficient (D_{pg}) as:

$$D_{pg} = \theta_a D_\theta + \theta_w H D_R \quad (2.4)$$

Where D_θ and D_R are the air phase and water phase diffusion coefficients in the porous media, respectively. H is the modified Henry's law coefficient which is equal to 0.03 for oxygen at room temperature. θ_a and θ_w are volumetric air content and volumetric water content, respectively and expressed as:

$$\theta_a = n(1-S_r) \quad (2.5)$$

$$\theta_w = nS_r \quad (2.6)$$

Where n is porosity and S_r is degree of saturation.

2.6. Internal Erosion

2.6.1. Internal Erosion in Dams and Embankments

Many of the piping failures occur rapidly, in 6-12 hours, between the first observation of a concentrated leak and breach (failure) of the dam (Foster et al., 2000). These results are important for the management of dam safety.

The process of internal erosion and piping was divided into four phases by Foster and Fell (1999, 2000). Initiation of erosion, continuation of erosion, progression to form a pipe, and formation of a breach. This is shown in figure 2.39 for piping through the embankment initiated by a concentrated leak. Similar processes apply for piping through the foundation, and from the embankment to the foundation.

If there are filters or transition zones, they control the continuation phase of the process. If the filters are designed and constructed according to the filter criteria, the internal erosion process will almost certainly not continue. If the filter or transition zone particle size distribution is coarser than required for the no-erosion filters designed using

these criteria, erosion may continue. Depending on the grading of the filters and soil, some excessive or continuing erosion may occur (Foster and Fell, 2001).

There are three factors which affect the progression of piping through the embankment or foundation (Foster and Fell 1999, 2000). These factors are the ability of the soil to support a roof of the pipe, enlargement of the hole, limitation of the flow by crack filling from filters upstream of the core, or upstream zones.

Breaching failures such as piping through the embankment and piping from the embankment to foundation occur due to gross enlargement of the pipe hole, crest settlement, or sinkhole on the crest leading to overtopping, unravelling of the downstream slope and instability of the downstream slope.

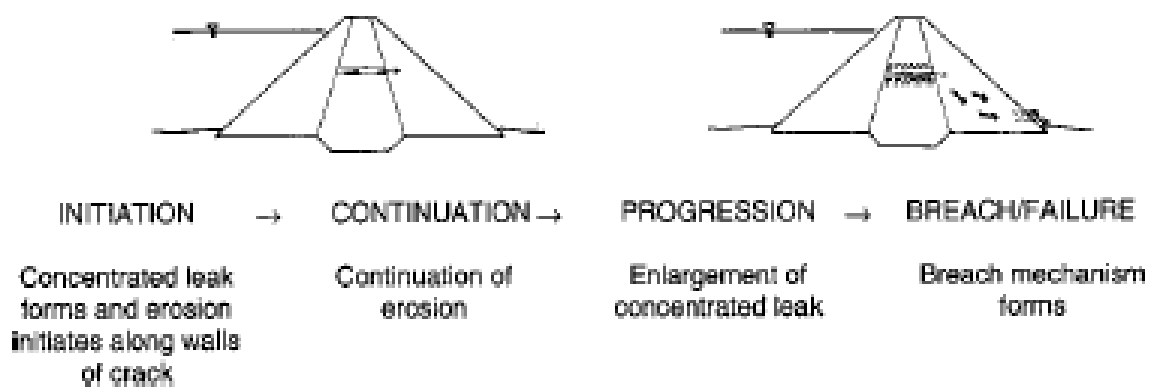


Figure 2.39. Model for development of failure by internal erosion and piping
(Foster and Fell, 1999,2000)

Most of the dams which have poor internal erosion and seepage control are constructed mainly of earthfill and the time for potential development of piping is short. For these dams, continuous monitoring of seepage or surveillance would be needed to detect the piping in time to give warning of possible failure, and to give time to attempt intervention to prevent the failure. In table 2.4, qualitative terms for the development of piping are given. Time is taken as weeks, hours and days for the development of piping (Fell et al., 2003).

Table 2.4. Qualitative terms for times of development of internal erosion, piping and breach (Fell et al., 2003)

Qualitative term	Equivalent time
Slow (S)	Weeks or months, even years
Medium (M)	Days or weeks
Rapid (R)	Hours (> 12 h) or days
Very rapid (VR)	< 3 h

2.6.2. Bentonite Thinning and Internal Erosion in GCLs

GCLs can be easily damaged during handling and installation. But most of the time, the damage is only a small defect which can be sealed by the swelling of the sodium bentonite. After formation of small penetrations or defects, hydraulic conductivity of a GCL slightly increases which does not cause a crucial permeability problem (Shan and Daniel, 1991; Mazzieri and Pasqualini, 2000). Approximately 15 days are enough to heal the defected part totally with a hole up to 30 mm in diameter in a GCL (Didier et al., 2000). Self-healing capacity of a GCL is depended on the hydraulic head on the GCL and when the head is more than 1 m, failure of the self-healed part of the GCL occurred easily under 10 kPa confinement. Although self-healing capacity of sodium bentonite in a GCL is high, ion exchange may slow down and sometimes prevent this healing process. (Lin and Benson, 2000; Mazzieri and Pasqualini, 2000).

Mazzieri and Pasqualini (1997) performed permeability tests on an adhesive bonded GCL punctured by plant roots and the results showed that hydraulic conductivity increased drastically. However, Daniel (2000) proved that the reason for the increase in permeability was the plant root itself; but not the bentonite of the GCL that was penetrated by the root. Furthermore, Didier et al. (2000) tested permeability with different objects penetrated into GCL. The results showed that the seal formed around an object penetrated into a GCL caused hydraulic conductivity of the GCL not to increase.

The hydraulic performance of GCLs depends also on the distribution of bentonite mass per area within the material (Bouazza, 2002). Hydrated bentonite has a very low

shear strength. Stress concentrations and structural loads on a GCL may cause the bentonite to squeeze and reduction in thickness is observed. As a result, higher index flux and permittivity values are obtained at these locations. To overcome these problems including hydraulic conductivity and thickness, a suitable cover soil is placed over a GCL before it hydrates and subjected to loads. The presence of coarse-grained material, such as gravel may sometimes cause bentonite migration due to stress concentration (Bouazza, 2002). A wrinkle in an overlying geomembrane may also cause bentonite migration. The bentonite in the underlying GCL may migrate into the reduced stress area which had been formed in the geomembrane because of the wrinkle. The particle size of the subgrade has to be chosen carefully in order not to cause an increase in hydraulic conductivity due to bentonite migration. Internal erosion is the movement of fine particles due to a high hydraulic gradient. Stam (2000) detected a drastical leakage from a GCL supported lake. The leakage caused a crucial increase in permeability in the GCL. Bentonite extrusion was observed through the nonwoven geotextile of the GCL into a coarse sand subgrade to a depth of 15-20 cm.

Another problem including bentonite extrusion from a GCL is the usage of a GCL over a leachate collection layer such as a coarse-grained material or a geonet. When the fine bentonite particles move into the drainage layer, they may clog the drainage layer and the hydraulic transmissivity of the drainage layer decreases which may lead to the failure of the leachate collection system. Giroud and Soderman (2000) defined a limit acceptance criterion for bentonite migration from a GCL into a geonet drainage layer with a mass per area of 10 g/m^2 . At this limit, the drainage layer is not significantly affected. Another way of avoiding bentonite loss from geotextile-supported GCL is to use an additional geotextile filter between the GCL and the drainage layer (Estornell and Daniel, 1992).

Weber and Zornberg (2005) performed permeability tests in order to verify whether to use a GCL in dam lining systems is feasible or not. Permeability tests were conducted to quantify leakage rates through different types of geosynthetic liners under high hydraulic heads which represent dam conditions. According to the experimental program, four test series were conducted. In test series 1, only geomembranes without GCLs in direct contact with sand subgrade were tested. In test series 2, geomembranes placed over unhydrated GCLs in direct contact with the same sand subgrade; in test series 3, geomembranes placed

over GCLs hydrated under a normal stress of 20 kPa in direct contact with the same sand subgrade and in test series 4, geomembranes placed over GCLs hydrated under a normal stress of 2 kPa in direct contact with the same sand subgrade were tested, respectively.

In these permeability tests, the effects of hydraulic head, interface contact quality between geosynthetic materials and sand subgrade and the presence of a geomembrane on leakage rates were investigated.

A permeameter made of acrylic material was used to measure the leakage rates of different test series. As seen in figure 2.40, there are two sections in the permeameter. The sand subgrade was placed at the bottom section and water was filled in the top section which was functioned as a reservoir. The geomembrane and the GCL were placed between the two sections and were sealed with o-rings. Water inlet and water outlets which were used to transfer water through the samples are also seen in figure 2.40. Inflow and outflow volumes of water were measured during the tests. A pressure panel was used to control the hydraulic heads, ranging from 7 m to 42 m.

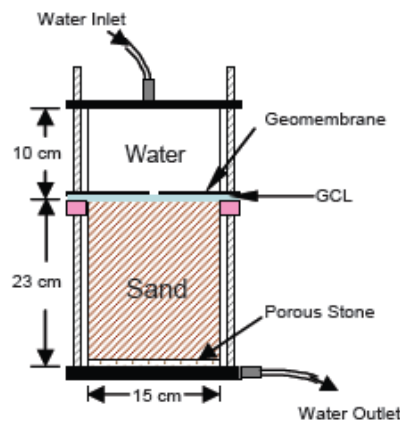


Figure 2.40. Permeameter cell used for the test series (Weber and Zornberg, 2005)

The geomembrane used in the experiments was a linear low-density polyethylene (LLDPE) with a thickness of 1 mm. The flexible nature of LLDPE allows the geomembrane to accommodate deformations of the system. A circular hole with a diameter of 1.6 mm was formed at the center of the geomembrane. The GCL used in the experiments was a Bentofix, which consists of sodium bentonite sandwiched between two

nonwoven geotextiles. The GCL has a hydraulic conductivity of approximately 10^{-11} m/s. Hydrated GCLs were soaked in water for at least 48 hours under a normal stress of 20 kPa. A series of tests was also conducted on a GCL hydrated under 2 kPa to evaluate the effect of hydration normal stresses on the hydraulic performance (Weber and Zornberg, 2005). No defects were imposed on the GCL. The sand subgrade used in the experiments was a medium to fine sand. The sand was densified in the permeameter cell using a shaking table to reach a relative density (D_R) of 75 per cent. The sand was saturated from the base of the cell before placing the hydraulic barrier system. The sand at this density has a saturated hydraulic conductivity of 8×10^{-7} m/s (Weber and Zornberg, 2005).

Leakage rates obtained for 4 different test series are listed in table 2.5. According to the results, leakage rates for the tests which included GCLs (test series 2, 3 and 4) were measured over three orders of magnitude lower than those for the tests which did not include GCLs (test series 1). These results showed that GCL placed over a sand subgrade provides considerable low permeabilities even under high hydraulic heads. Hydration of GCLs also caused hydraulic conductivity values to decrease approximately one order of magnitude. But the applied normal stress during hydration did not change the permeability and leakage rates. In all of the test series, bentonite migration into the sand subgrade which may cause a drastical increase in hydraulic conductivity and leakage rate did not occur.

Table 2.5. Average leakage rates measured for four different test series (Weber and Zornberg, 2005)

Baseline Test Series	Average Leakage Rates (m^3/s)
1	1.61×10^{-5}
2	1.36×10^{-8}
3	1.29×10^{-9}
4	1.28×10^{-9}

Steady-state flow was reached immediately in test series 1 where only geomembrane was placed over sand subgrade. Hydraulic heads ranging from 7 m to 35 m were applied to the samples and as the hydraulic head was increased, steady state leakage rates also increased. This result is because of the high permeability of the sand subgrade.

Giroud and Bonaparte (1989) recommend using Bernoulli's equation for flow through an orifice to estimate the flow through a defect in a geomembrane placed over a permeable soil. The orifice equation is as follows:

$$Q = Ca\sqrt{2gh} \quad (2.7)$$

Where Q is the flow rate, C is an empirical coefficient that accounts for the geometry of the orifice, a is the area of the orifice (in this case, the defect in the geomembrane), g is the acceleration due to gravity, and h is the hydraulic head. The measured leakage rates (steady-state rates reached for each head) for Test Series 1 were compared with Bernoulli's orifice equation, using different values for the empirical coefficient, C (Figure 2.41). Giroud and Bonaparte (1989) suggest a value of $C = 0.6$ for use with flow through defects in geomembranes. Instead, a coefficient value of $C = 0.4$ was found to yield flow rates that are very similar to those measured in Test Series 1. However, as shown in Figure 2.41, a coefficient of $C = 0.6$ gives leakage rates that are slightly larger than the measured value. The better comparison obtained using a lower C -value than the previously suggested value can be attributed to the high hydraulic heads in this study than those used by Giroud and Bonaparte (1989) (heads less than 3 m). The difference can also be attributed to the sharpness of the orifice edges, roughness of the defect interior and diameter of the defects. The comparison reveals that the equation for flow through an orifice can be used to estimate leakage for flow through a small defect in a geomembrane in good contact with sand. Although the good match depends on the selection of the proper flow coefficient (C), the basic trend of the orifice equation is consistent with the experimental data, indicating that the use of this equation and properly calibrated C -coefficients for high heads can be useful in predicting the leakage through the geomembrane for dam systems (Weber and Zornberg, 2005).

Fox et al. (2000) investigated the hydraulic performance of adhesive-bonded and needle-punched geotextile-supported GCLs under gravel cover soils. The hydraulic performance of geotextile-supported geosynthetic clay liners (GCLs) mostly depends on the quality, water content, and the distribution of bentonite mass per area within the product. Migration of bentonite within a GCL after installation is a concern because local reductions in bentonite mass per area may result in a higher fluid flux at those locations.

Hydraulic performance of the GCL may be compromised if the thickness or local mass per area of bentonite is substantially reduced under the soil particles. (Koerner, 1997).

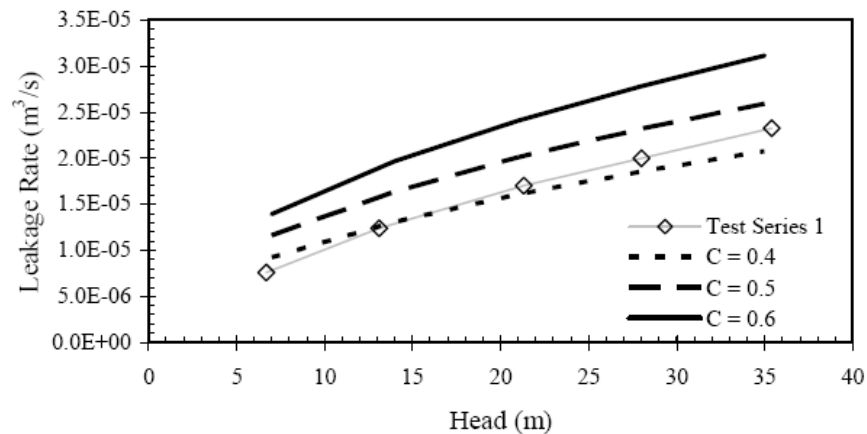


Figure 2.41. Leakage rate versus hydraulic head graphs for different Bernoulli's orifice coefficients (C) for test series 1 (Weber and Zornberg, 2005)

Hydraulic conductivity tests were conducted in flexible-wall permeameters for GCL specimens covered with uniformly graded fine, medium, and coarse gravel. After each test, local measurements of GCL thickness, water content, and mass per area were taken to quantify thickness variability and bentonite migration/consolidation behavior. Control tests were also performed to measure GCL hydraulic performance under conventional testing conditions (Fox et al., 2000).

Two different types of GCLs were used in this study. GCL-1 is an unreinforced adhesive-bonded GCL in which granular bentonite is held between two woven geotextiles, each having a mass per area of 109 g/m^2 . GCL-2 is a reinforced GCL in which granular bentonite is held between a woven geotextile having a mass per area of 109 g/m^2 and a nonwoven geotextile having a mass per area of 204 g/m^2 . Reinforcement is provided by the needle-punching process of polypropylene fibers from the nonwoven geotextile through the bentonite and the woven geotextile. Both of the GCLs have nominal minimum mass per area of 3700 g/m^2 at 0 per cent moisture content.

Uniformly graded fine, medium and coarse gravel were used as cover soils in this study. Table 2.6 lists the particle size range and the mean particle size (D_{50}) for each

cohesionless cover soil. The predominant particle shape for the cover soils was subrounded to subangular with few grains having sharp and angular structure.

Table 2.6. Gravel cover soils (Fox et al., 2000)

GRAVEL TYPE	PARTICLE SIZE RANGE (mm)	MEAN PARTICLE SIZE, D50 (mm)
Fine	12,7-19,1	15,9
Medium	19,1-25,4	22,3
Coarse	25,4-50,8	38,1

Hydraulic conductivity tests were conducted on circular GCL specimens having a diameter of 15 cm. Mainly, two types of hydraulic conductivity tests were performed on GCL samples. These tests are control and gravel hydraulic conductivity tests. In control hydraulic conductivity tests, circular GCL samples were placed between two porous stones in flexible-wall permeameters. Single-load control (SLC) hydraulic conductivity tests were performed in which the effective confining stress (σ'_c) was applied prior to hydration of the GCL specimens and held constant throughout permeation. Incremental-load control (ILC) hydraulic conductivity tests were performed in which hydraulic conductivity was measured for successive levels of effective confining stress. Similar to the SLC tests, the first stress level was applied prior to specimen hydration. Stress increments were applied rapidly (in about one minute) for the ILC tests. After each control test was completed, the specimen was removed from the permeameter and the average final thickness, water content, and mass per area were measured (Fox et al., 2000). Gravel hydraulic conductivity tests were performed to measure the permeability of GCLs covered with gravels of varying particle size. Schematic configuration of the test set-up is shown in figure 2.42. From top to bottom, an acrylic top cap, gravel cover soil, GCL sample, filter paper, porous stone and an acrylic base pedestal were placed. The height of the gravel soil was approximately 15 cm. Woven geotextile of GCL-2 was in contact with the cover soil. Latex membrane that covered the gravel over the GCL sample ruptured due to the high confining stress which pushed the membrane into the voids of the gravel column. This problem was mostly observed beneath the top cap. Two precautions were taken to prevent the membrane rupture. Fine gravel was placed beneath the top cap and the gravel column over the GCL sample was wrapped with a nonwoven geotextile having a mass per area of 420 g/m² to

protect the latex membrane (Figure 2.42). Fine gravel distributed the applied load from the top cap to the underlying coarse gravel column much more uniformly.

Single-load gravel (SLG) hydraulic conductivity tests, incremental-load gravel (ILG) hydraulic conductivity tests, and quick-load gravel (QLG) hydraulic conductivity tests were conducted on each GCL specimen. For SLG tests, confining stress was held constant during hydration and permeation. The ILG tests simulated quasi-static incremental loading conditions. The first stress level of 13.8 kPa was applied prior to hydration. Subsequent stress increments were applied after the hydraulic conductivity was measured at each stress level. For each stress increment, the confining stress was increased 6.9 kPa twice daily until the desired confining stress was reached. The QLG tests simulated rapid loading conditions, such as the passing of a vehicle. Specimens of each product were prepared using coarse gravel and hydrated under effective confining stress of 13.8 kPa.

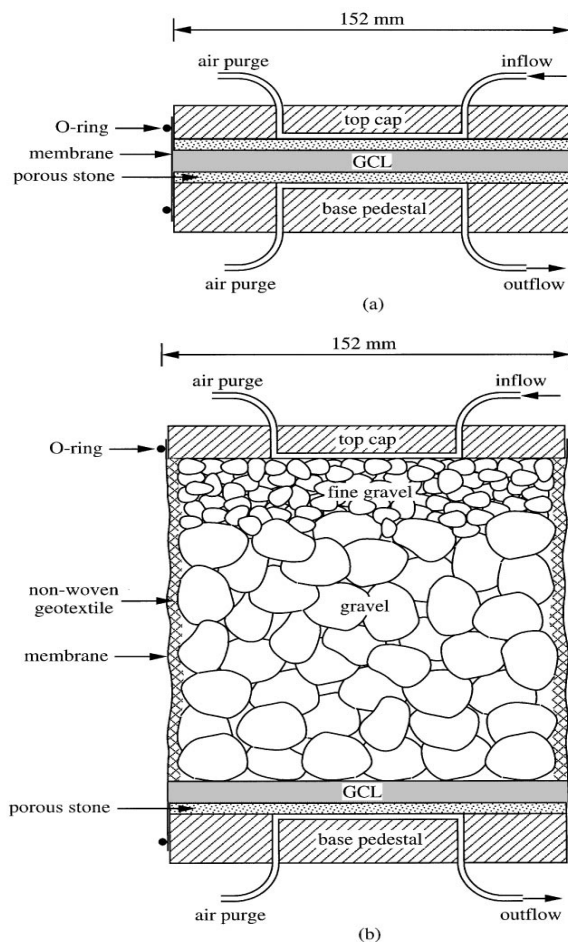


Figure 2.42. Configuration of test set-up a) Control hydraulic conductivity tests; b) Gravel hydraulic conductivity tests (Fox et al., 2000)

After the hydraulic conductivity was measured, the confining stress was quickly increased to 276 kPa and hydraulic conductivity was measured again (Fox et al., 2000). GCL-1 specimen covered with medium gravel in a triaxial permeability cell is shown in figure 2.43.

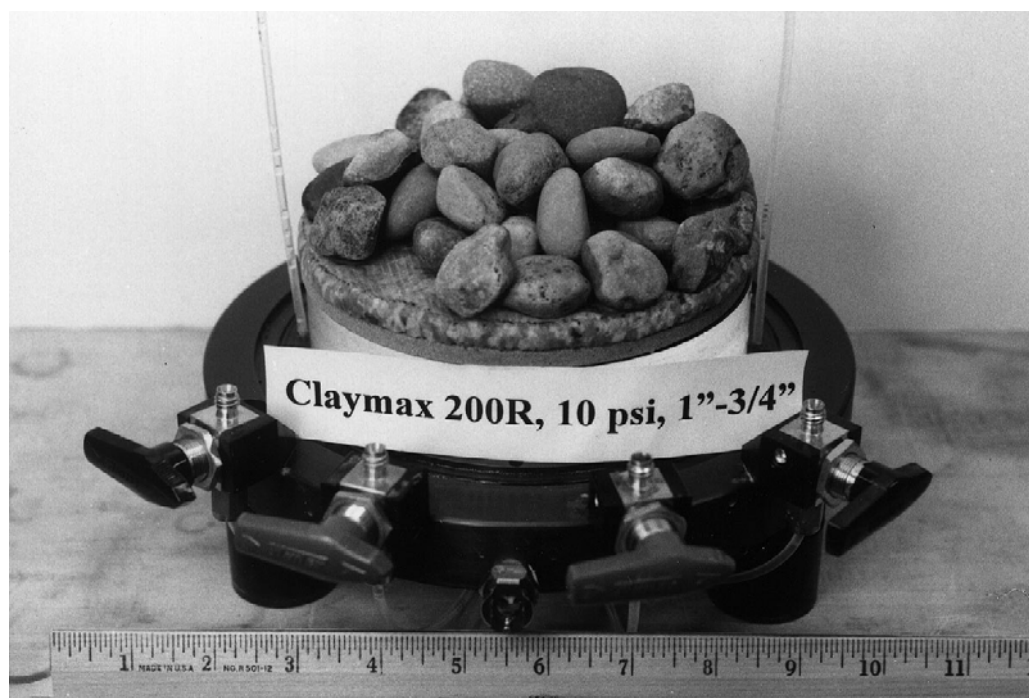


Figure 2.43. GCL-1 specimen covered with medium gravel during disassembly of a SLG test conducted at an effective confining stress of 69 kPa (1psi = 6.9 kPa, 1inch = 25.4 mm where the scale is in inches) (Fox et al., 2000)

Thickness, water content and bentonite mass per area of each GCL specimen were measured. Twelve measurements of water content and bentonite mass per area were obtained by using sampling tubes as seen in figure 2.44. Each cylindrical tube was made of stainless steel with a diameter of 13 mm and a height of 25 mm. Six “peak” and six “valley” measurements were taken where the topographically highest and lowest points on the surface of the bentonite were called “peaks” and “valleys” respectively. Measurements of GCL thickness, water content and mass per area show quantitative assessment of bentonite migration under cover soils with different particle diameters.

According to the results, permittivity and hydraulic conductivity values decreased with increasing confining stress for all of the GCL specimens (figures 2.45, 2.46 and 2.47).

Values for GCL-2 were smaller than those for GCL-1 at low stresses (13.8 kPa-138 kPa), which was likely due to the additional confinement provided by the needle-punched reinforcement for GCL-2. At high confining stresses (138-276 kPa), the effect of the reinforcement was reduced and the GCL specimens yielded similar permittivity and hydraulic conductivity values (Estornell and Daniel, 1992).



Figure 2.44. Sampling water content and bentonite mass per area of a GCL-1 specimen
(Fox et al., 2000)

Values of bentonite mass per area indicate that bentonite migration occurred for GCL specimens covered with gravel. The extent of bentonite migration increased with increasing cover soil particle size and rate of loading. Bentonite migration and variable stress conditions across the specimens produced differences in local water content and GCL thickness. The needle-punched GCL specimens tended to show less bentonite migration and thickness variability than the adhesive-boded GCL specimens as seen in figure 2.49 (Fox et al., 2000).

Average water content values were measured for 6 peaks and 6 valleys of GCL-1 specimens and the results are shown in figure 2.48. Higher water contents were obtained for the peaks and lower water contents were obtained for the valleys where the effective

confining stress (σ'_c) was higher than 13.8 kPa because the bentonite in the valleys carried the applied load from the cover soil particles.

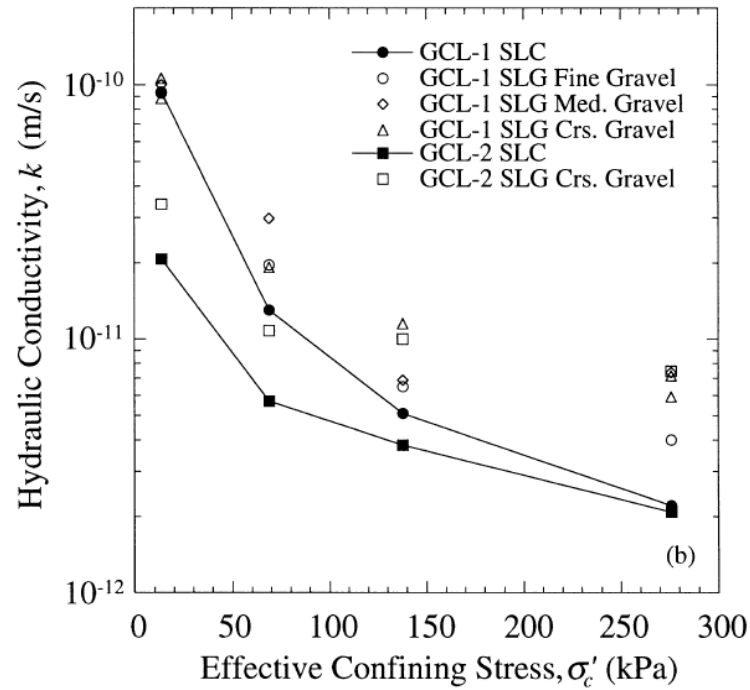


Figure 2.45. Hydraulic conductivity for SLC and SLG specimens (Fox et al., 2000)

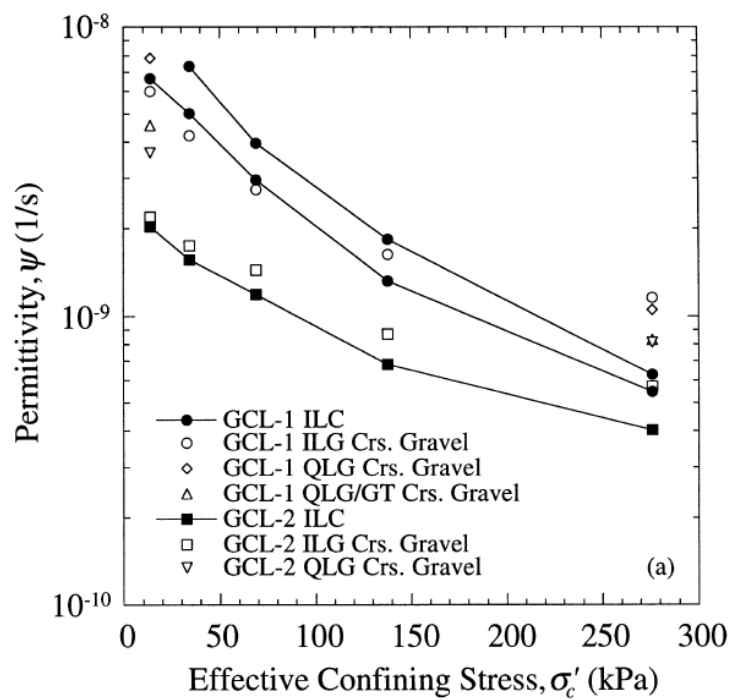


Figure 2.46. Permittivity for ILC, ILG and QLG specimens (Fox et al., 2000)

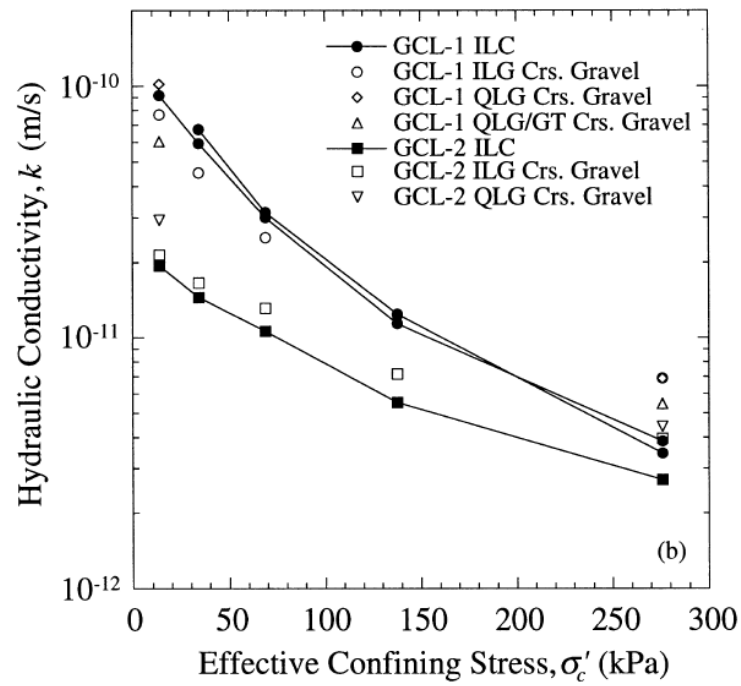


Figure 2.47. Hydraulic conductivity for ILC, ILG and QLG specimens (Fox et al., 2000)

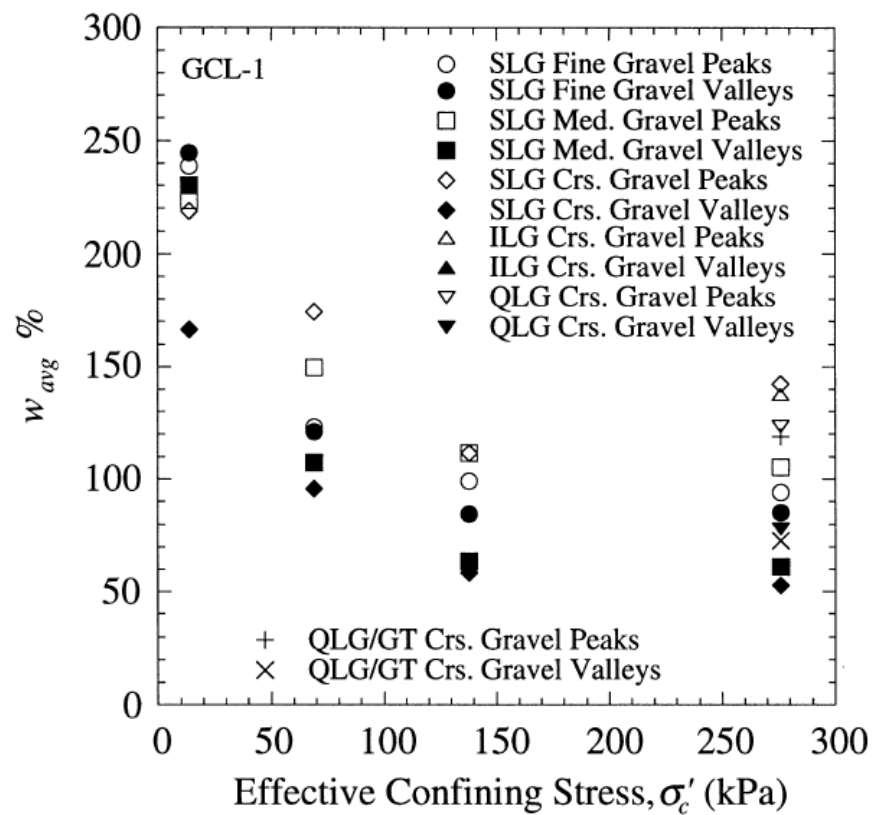


Figure 2.48. Average water contents for peaks and valleys of GCL-1 (Fox et al., 2000)

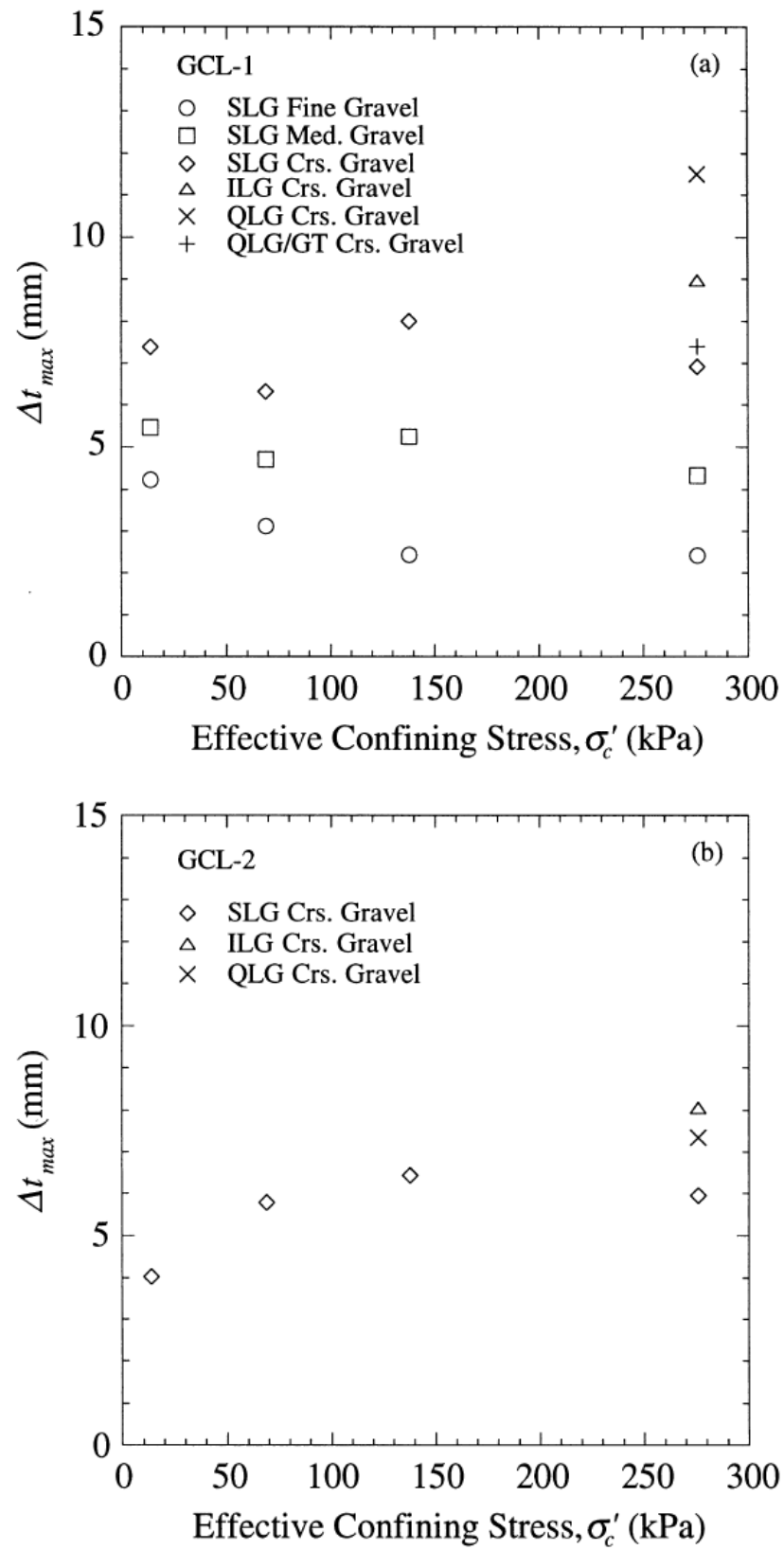


Figure 2.49. Maximum difference in GCL thickness of GCL-1 and GCL-2 (Fox et al., 2000)

Rowe and Orsini (2003) performed hydraulic conductivity tests under high hydraulic gradients on GCLs by using fixed-ring permeameter in order to evaluate the effect of GCL and subgrade type on internal erosion.

A fixed ring hydraulic conductivity apparatus with maintaining constant flow rate was used for the laboratory experiments. It had an inner diameter of 54 mm and a height of 70 mm. The GCL was sandwiched between an upper porous stone and a subgrade layer of sand, 6mm gravel, or geonet. Static confining stress (σ_c) was applied directly to the top of the specimen by springs placed between locator caps. Schematic view of the fixed-ring permeameter was seen in in figure 2.50.

Five different GCLs were tested over three different subgrades. These five GCLs were BWD (carrier geotextile was woven and bentonite was powdered), NWD (carrier geotextile was nonwoven and bentonite was granular), WD (carrier geotextile was woven and bentonite was granular), BSNWD (carrier geotextile was scrim-reinforced nonwoven and bentonite was powdered), SNWD (carrier geotextile was scrim-reinforced nonwoven and bentonite was granular). The scrim-reinforced geotextile was composed of two layers of geotextiles where a woven (scrim) and a nonwoven carrier geotextile were used together. Extra reinforcement in the bottom geotextile gives the GCL greater strength than the GCL without the scrim and this GCL performed better under hydraulic gradients up to 55 m of water.

The tests were performed in duplicate for all GCL types over three different subgrades. Results for the test with the BWD GCL and the geonet subgrade are shown in figures 2.51 and 2.52. At a flow rate of 4.49×10^{-5} ml/s, the BWD sample in Cell 2 had a hydraulic conductivity of 2.7×10^{-11} m/s at a maximum gradient of about 1000 (corresponding to a head of about 10 m water acting on the GCL) at 174–175 h. The hydraulic conductivity then slowly increased up to 330 h, at which point a sudden failure occurred and permeability increased to 9×10^{-10} m/s while the hydraulic gradient slowly decreased to a value of about 800 (8 m water) at 330 h and then suddenly dropped to a very low value while k increased to 1.7×10^{-9} m/s indicating that a failure had occurred (Rowe and Orsini, 2003).

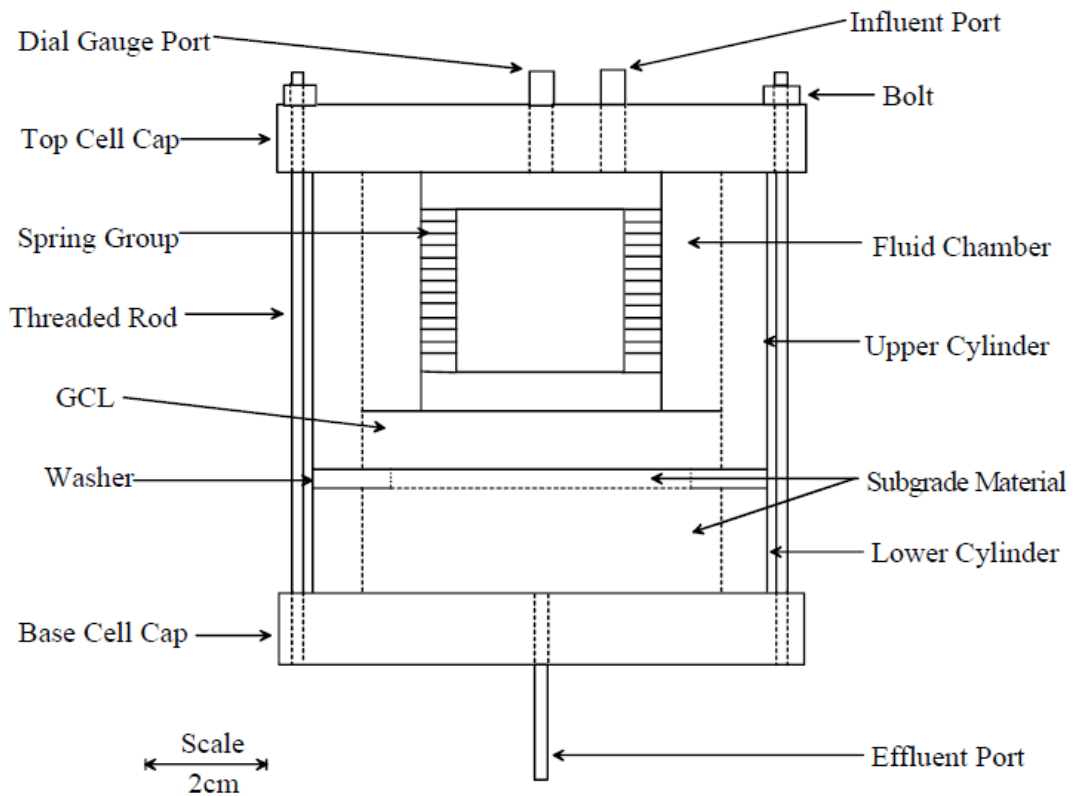


Figure 2.50. Schematic view of fixed-ring permeameter (Rowe and Orsini, 2003)

The sample in Cell 1 had a hydraulic conductivity of 1.8×10^{-11} m/s as shown in figure 2.51 and a hydraulic gradient of 1450 as shown in figure 2.52 at a flow rate of 4.49×10^{-5} ml/s. At 505 h, the flow rate was increased to 5.92×10^{-5} ml/s which yielded a hydraulic conductivity 1.7×10^{-11} m/s and a maximum hydraulic gradient of 2400 (24 m water). When the flow rate was increased at 775 h and permeability decreased to 1.6×10^{-11} m/s, the GCL sustained a gradient of about 2700 (27 m water) before failure occurred at 805 h and the hydraulic gradient dropped to about 50 (0.5 m water) while the hydraulic conductivity jumped to 1.3×10^{-9} m/s (Rowe and Orsini, 2003).

Hydraulic conductivity tests were performed on the other types of GCLs over geonet, sand and gravel subgrades, separately. According to the results of the tests, only BSNWD type of GCL (carrier geotextile was scrim-reinforced nonwoven and bentonite was powdered) did not experience internal erosion over geonet under hydraulic heads up to 55 m. But the other four types of GCLs showed internal erosion behavior where the hydraulic conductivities increased at least one order of magnitude and bentonite loss occurred at

hydraulic heads of 8-45 m. BSNWD type of GCL had a total carrier geotextile with mass per unit area of 350 g/m^2 .

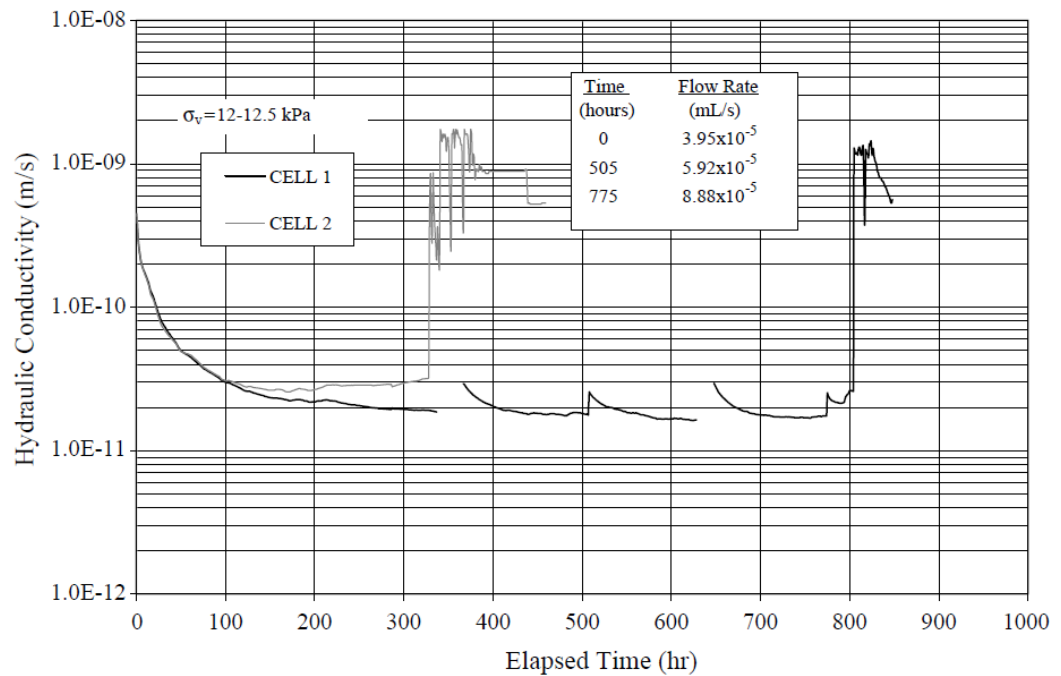


Figure 2.51. Hydraulic conductivity-time graph for BWD GCL over geonet subgrade (Rowe and Orsini, 2003)

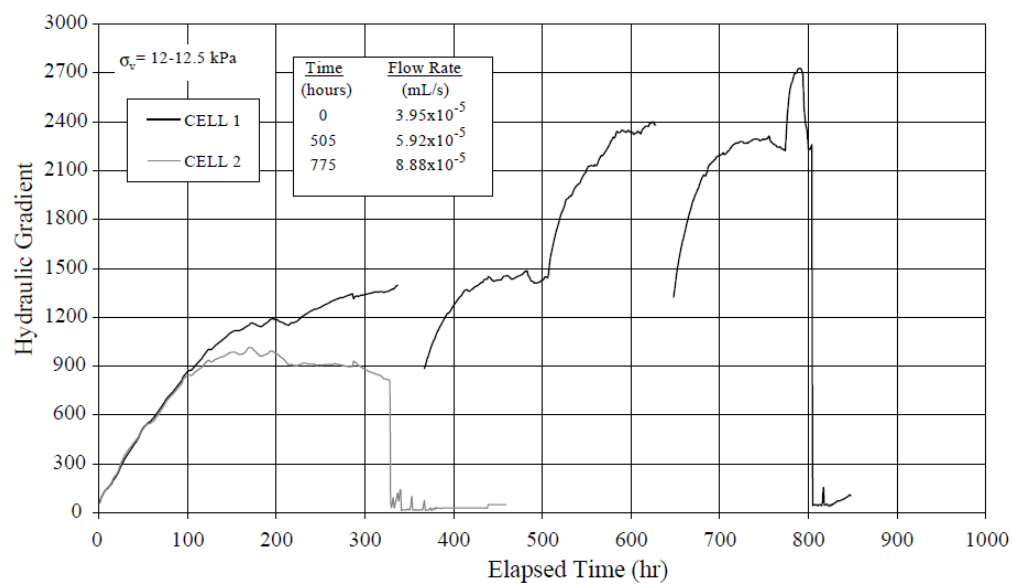


Figure 2.52. Hydraulic gradient-time graph for BWD GCL over geonet subgrade (Rowe and Orsini, 2003)

Three of the five GCL types (WD, NWD and BWD) experienced bentonite loss and internal erosion over 6 mm gravel under hydraulic heads ranging from 8 m to 90 m. But BSNWD and SNWD types of GCLs (scrim-reinforced GCLs) did not experience internal erosion over 6 mm gravel under hydraulic heads up to 60 m.

Sand subgrade showed the best performance where all of the GCL types did not suffer from any increase in hydraulic conductivity or loss of bentonite under hydraulic heads up to 80 m.

During the early periods of the experiments, decreases in permeability occurred because of the seepage drag stresses which caused decreases in void ratios.

Nonwoven carrier geotextiles performed better than woven carrier geotextiles when the GCLs were tested over gravel subgrade but there was not significant difference between the performances of nonwoven and woven carrier geotextiles when the GCLs were tested over geonet subgrade. The scrim-reinforced GCLs which had the greatest carrier geotextile mass per unit area withstood greater hydraulic gradients and they performed the best under high hydraulic heads against internal erosion.

Increases in the amount of bentonite loss caused increases in permeability and the GCLs with high hydraulic conductivities lost their hydraulic barrier capabilities. But in some cases, failure occurred with relatively little bentonite loss which means that failure was localized.

The effect of gravel subgrade on the hydraulic performance of two different types of GCLs was investigated by Shan and Chen (2003). GCL-A was composed of a needle-punched GCL with a nonwoven geotextile and a woven geotextile where the bentonite content was 3600 g/m^2 . GCL-B was composed of an adhesive-bonded GCL with a woven geotextile on the top and an open weave geotextile at the bottom where the bentonite content was also 3600 g/m^2 . The thickness was about 6 mm for both types of the GCLs when they were dry. Two different types of subgrade materials were used in the tests. One of them was crushed stone with diameter ranging from 25.4 mm to 50.8 mm. The shape of the stone was categorized as subangular-angular as seen in figure 2.53. The other subgrade

was gravel with diameter ranging from 50.8 mm to 76.2 mm. The shape of the gravel was categorized as subrounded-rounded as seen in figure 2.54.



Figure 2.53. Crushed stone with diameter ranging from 25.4 mm to 50.8 mm (Shan and Chen, 2003)

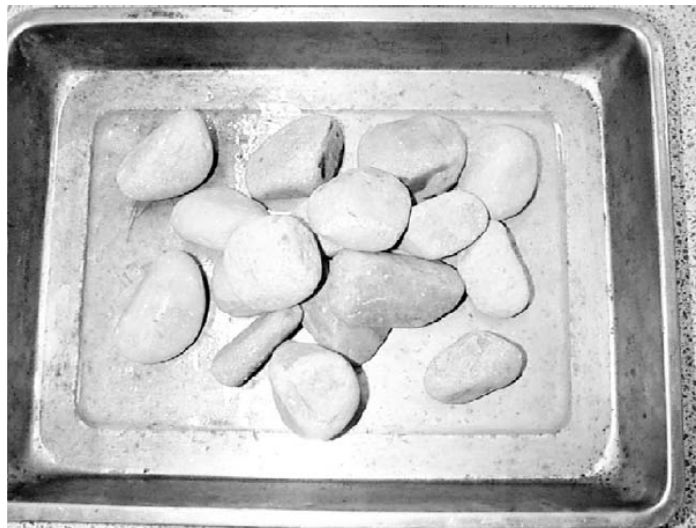


Figure 2.54. Gravel with diameter ranging from 50.8 mm to 76.2 mm (Shan and Chen, 2003)

The schematic diagram of the permeameter was shown in figure 2.55. The effective normal stress applied on the GCL samples was provided by static water pressure on the piston. The inner diameter of the permeameter was 300 mm. The height of both the upper

and lower half of the permeameter was 150 mm. The diameter and the height of the annular space in the ring were 360 and 9.0 mm, respectively. The annular space allowed the GCL specimen to be able to displace laterally. The nonwoven geotextile side of GCL-A and open weave geotextile side of GCL-B was placed against the subgrade. The whole test chamber was then assembled and the GCL specimens were allowed to hydrate under the predetermined effective stress (Shan and Chen, 2003).

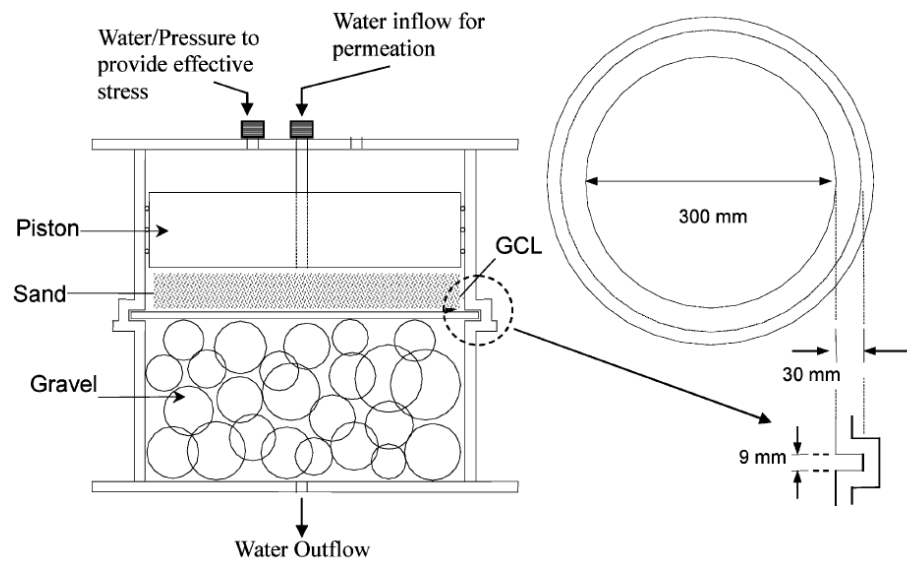


Figure 2.55. Schematic view of the permeameter (Shan and Chen, 2003)

Table 2.7. Subgrade materials and effective stresses used in the tests (Shan and Chen, 2003)

Test no.	Specimen	Subgrade material	Initial effective stress (kPa)	Effective stress sequence (kPa)
No. 1	GCL-A-1	Sand	13.8	13.8–34.5–69–138
No. 2	GCL-A-2	Crushed stone	13.8	13.8–69–138
No. 3	GCL-A-3	Crushed stone	34.5	34.5–69–138
No. 4	GCL-A-4	Gravel	34.5	34.5–69–138
No. 5	GCL-B-1	Sand	13.8	13.8–34.5–69–138
No. 6	GCL-B-2	Crushed stone	13.8	13.8–69–138
No. 7	GCL-B-3	Crushed stone	34.5	34.5–69–138
No. 8	GCL-B-4	Gravel	34.5	34.5–69–138

The initial effective stress under which GCL specimens were hydrated was 13.8 and 34.5 kPa as seen in table 2.7. Applied maximum effective stress was 138 kPa. This effective stress is representative of the overburden generated by 15–20 m high of

consolidated solid waste. The hydraulic head of water on the GCL specimen was approximately 0.69 m.

Permittivity, thickness and mass per unit area values were obtained after the termination of the experiments and the list of the results were shown in figure 2.56 and tables 2.8 and 2.9, respectively.

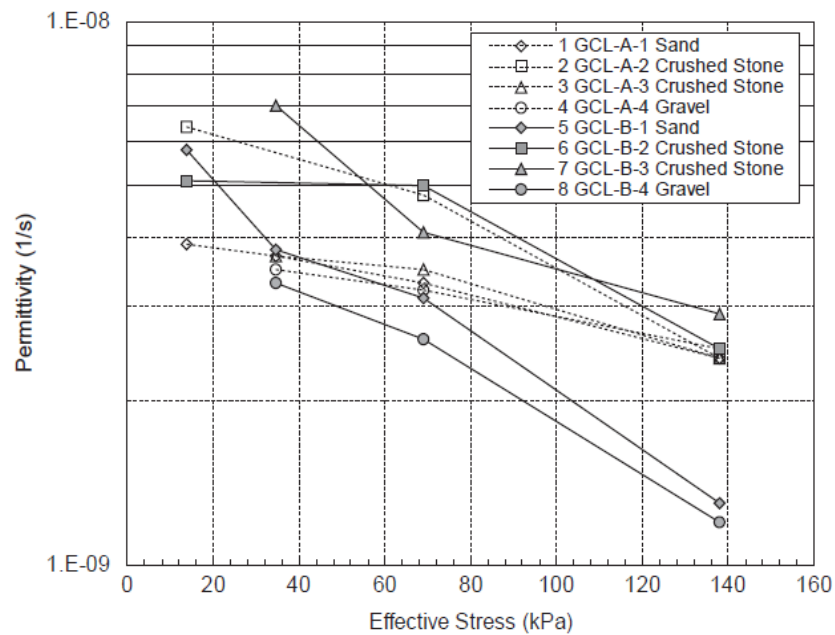


Figure 2.56. Permittivity-effective stress graph for GCL-A and GCL-B samples (Shan and Chen, 2003)

Table 2.8. Variation of thickness of GCL samples measured after permeation (Shan and Chen, 2003)

Test no.	Specimen	Subgrade	Maximum thickness (mm)	Minimum thickness (mm)	Maximum difference (mm)	Average thickness (mm)	Standard deviation (mm)	Standard deviation (%)
No. 1	GCL-A-1	Sand	11.7	9.8	1.9	10.0	0.43	4.3
No. 2	GCL-A-2	Crushed stone	20	5	15	10.1	3.39	33.56
No. 3	GCL-A-3	Crushed stone	17	5	12	10.25	2.34	22.83
No. 4	GCL-A-4	Gravel	20	3	17	9.85	3.20	32.49
No. 5	GCL-B-1	Sand	11.9	9.7	2.2	9.7	0.45	4.5
No. 6	GCL-B-2	Crushed stone	18	4	14	9.72	3.24	33.33
No. 7	GCL-B-3	Crushed stone	17	4	13	9.67	2.75	28.44
No. 8	GCL-B-4	Gravel	18	3	15	9.57	3.31	34.59

Table 2.9. Variation of mass per unit area of GCL samples measured after permeation (Shan and Chen, 2003)

Test no.	Specimen	Subgrade	Maximum value (g/cm ²)	Minimum value (g/cm ²)	Average (g/cm ²)	Standard deviation (g/cm ²)	Standard deviation (%)
No. 1	GCL-A-1	Sand	0.60	0.57	0.589	0.0016	2.8
No. 2	GCL-A-2	Crushed stone	0.69	0.53	0.587	0.0587	10.00
No. 3	GCL-A-3	Crushed stone	0.68	0.54	0.590	0.0523	8.86
No. 4	GCL-A-4	Gravel	0.68	0.54	0.591	0.0585	9.89
No. 5	GCL-B-1	Sand	0.45	0.43	0.440	0.0014	3.2
No. 6	GCL-B-2	Crushed stone	0.53	0.40	0.447	0.0448	10.02
No. 7	GCL-B-3	Crushed stone	0.48	0.37	0.425	0.0383	9.01
No. 8	GCL-B-4	Gravel	0.50	0.37	0.432	0.0479	11.09

Permittivity, Ψ (1/s), is obtained by dividing the permeability value of the GCL sample by the thickness of the GCL sample. According to the test results and figure 2.56, permittivity of both needle-punched GCL (GCL-A) and adhesive-bonded GCL (GCL-B) decreased as the effective stress increased. Effect of the size and shape of the subgrade material on permittivity and permeability became important when the effective stress was low enough. Larger particle size and more angular shape of the subgrade material and lower hydration effective stress caused the bentonite to distribute less uniformly. When the difference between maximum and minimum thickness and mass per unit area of a GCL sample was large enough, distribution of the bentonite through the GCL sample was not uniform.

Although the GCL sample with thinner geotextile and without needle-punched fibers had lower permittivity, the bentonite in the GCL sample with thicker geotextile and needle-punched fibers was distributed more uniformly. As a result, reinforced GCLs with needle-punched fibers (GCL-A) performed better on a gravel subgrade when compared to adhesive-bonded GCLs without reinforcement (GCL-B).

3. METHODOLOGY

In this thesis, four different types of geosynthetic clay liners (GCL-1, GCL-2, GCL-3 and GCL-4) were tested over bases with four different uniform circular voids having diameters of 2 cm, 1.5 cm, 1cm and 0.5 cm, respectively which represented coarse gravel subgrades. Flexible wall triaxial permeability tests were performed on the GCL samples under very high hydraulic heads up to 50 m in order to observe internal erosion. Tests were conducted both placing the nonwoven component and the woven component of the GCL samples on the base which represented coarse gravel subgrade.

By testing different types of GCL samples, effects of needlepunching, type of the geotextile and bentonite components of the GCL samples placed over the bases having uniform voids on internal erosion and bentonite migration were investigated.

Under different hydraulic heads, permeability, permittivity, index flux, mass per unit area, moisture content and thickness values of GCL samples were measured.

Below, the methodology for this thesis study is given in four main parts:

- Test Equipment
- Materials Tested
- Sample Preparation
- Testing Methods

3.1. Test Equipment

In this thesis, triaxial permeability tests were conducted using a standard flexible wall permeameter with a 100 mm diameter, permeameter cell. Test procedures as outlined in ASTM D 5084-03 and ASTM D 5887-09 were followed. The testing equipment was manufactured by Humboldt Mfg. Co.

According to ASTM D 5887-09, index flux which is the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a GCL specimen was measured. According to ASTM D 5084-03, hydraulic conductivity of a GCL specimen was measured. The test equipment used for and the test procedures followed by both of these tests are almost the same.

An air compressor which is connected to the flexible wall permeameter panels produces the air pressure. The air line is connected to the supply port of the panel by a plastic tube.



Figure 3.1. HM-4150 Flexpanels for Triaxial Permeability Tests

There are two flexpanels which allow to conduct two triaxial permeability tests at the same time as shown in figure 3.1. On each panel, there is a master control section. This

section interacts with the standard panel section. The digital panel on the master control section supplies a regulated voltage and reads the output of a 0-1000 kPa pressure transducer. The air pressure supply regulator is turned clockwise to increase the pressure. The vacuum regulator on the master control section has a connection for a vacuum pump. Vacuum supply regulator is used to adjust the working level of the vacuum pump. Deaired water tank control on the master control section is made up of two valves which controls the functions of the de-aired water tank. The top valve connects a regulated low level air pressure on the vacuum from the vacuum pump. The air pressure is used to help force the water from the de-aired water tank into the burettes on the standard panel. The vacuum is used when making de-aired water. The lower valve is used to drain the tank or fill it with water from a supply (Flexpanel HM-4150 User Guide, 2001). The de-aired water tank, as seen in figure 3.2 is connected to the flexpanels and the de-aired water supplier as shown in figure 3.3.



Figure 3.2. De-aired water tank

On each panel, there is a standard section which has three different main parts. These parts are cell pressure section which controls the applications for the whole triaxial permeability cell, base pressure which controls the applications for the base pedestal of the cell and the bottom part of the tested specimen and top pressure which controls the applications for the top cap of the cell and the top part of the tested specimen.

There are three pressure selection valves for cell pressure, base pressure and top pressure sections and pressure selection valve is used to select what is connected to the top of the adjacent burette assemble. In the off position, the top of the assemble is totally sealed off, in the pressure position, the pressure from the regulator below is connected, in the vent position, the assemble is vented to atmosphere and in the vacuum position, the regulated vacuum from the master panel or other vacuum connected to the service panel is connected to the assemble. This valve for all of the sections functions the same (Flexpanel HM-4150 User Guide, 2001).



Figure 3.3. De-aired water supplier

The vacuum is used to pull air out of the water in the burette assemble. The vent is used to apply atmospheric pressure to the top of the burette assemble. It is used when filling the burette assemble before opening the valve. The pressure regulator is supplied air pressure from the service panel and puts out a regulated pressure to the selection valve above. Burette tubes as seen in figure 3.1, are the inner glass tubes and external tubes as seen in figure 3.1, are the outer glass tubes for all of the cell, base and top pressure sections. Burette and external valves are connected to the bottom of the burette assemble; one connects to the inside and the other to the outer chamber. Fill and drain valves located at the bottom of the standard panel section, are used to fill and drain the burette and the external part. The burette and external valves need to be open to fill that portion of the burette assemble. The water to fill the burette assemble comes from the water port on the service panel. The burette assemble can not be filled unless the top is vented by turning the selection valve to vent. The top does not have to be vented to drain the burette assemble (Flexpanel HM-4150 User Guide, 2001).

A schematic diagram of the flexible wall triaxial permeameter cell is shown in figure 3.4 (ASTM D 5887-09, 2010). A GCL specimen is placed between two porous stones. The burette assemble for cell pressure is represented by the cell reservoir, the burette assemble for influent pressure is represented by the headwater reservoir and the burette assemble for the effluent pressure is represented by the tailwater reservoir in figure 3.4. Pressure supply is the air compressor in this study.

An impermeable, rigid top cap and base pedestal as seen in figure 3.5, are used to support the specimen and provide for transmission of water to and from specimen. The diameter and width of the top cap and base pedestal are equal to the diameter and width of the specimen. The base pedestal prevents leakage, lateral motion and tilting. The surface of the base pedestal and top cap that contacts the membrane to form a seal is smooth and free of scratches (ASTM D 5887-09, 2010).

Flexible membrane used to encase the GCL specimen provides reliable protection against leakage. The porous stones as shown in figure 3.6, are made of silicon carbide and they have plane and smooth surfaces without cracks, nonuniformities.

To prevent intrusion of material into the pores of the porous stones, one sheet of filter paper as shown in figure 3.7, is placed between top and bottom porous stones and the GCL specimen.

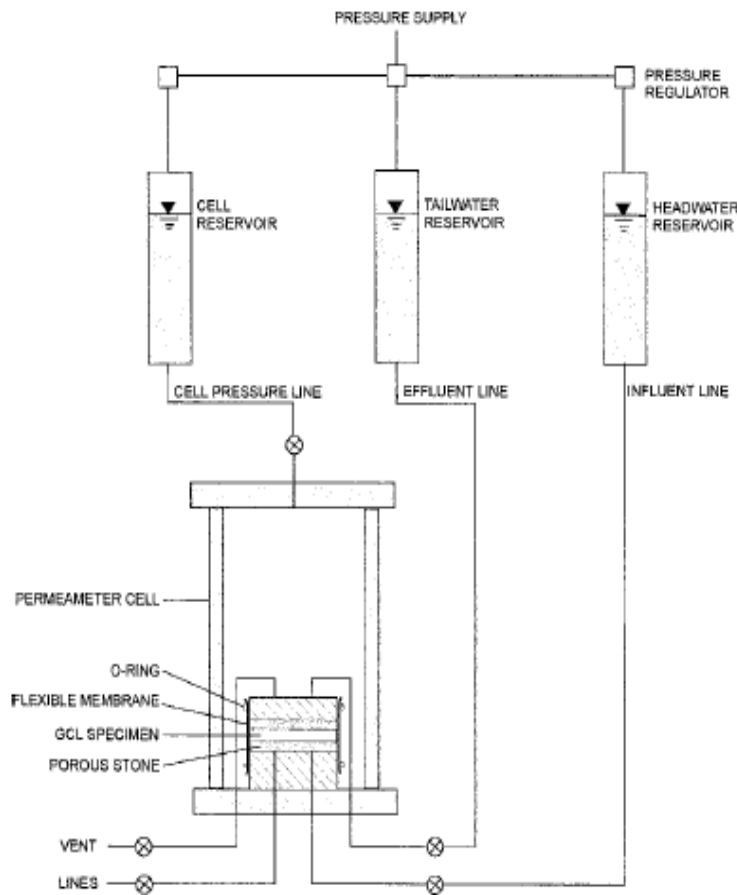


Figure 3.4. Permeameter cell and test setup (ASTM D 5887-09, 2010)

Filter papers were used where there was not bentonite migration or internal erosion risk even under high hydraulic heads. When a GCL specimen was tested between two porous stones and without a subgrade even under high hydraulic heads, it is not possible for the bentonite to be collected on the filter paper and to clog the water transfer from the top to the bottom of the GCL specimen.

However, when a base with uniform voids symbolizing a coarse gravelly subgrade was placed beneath a GCL specimen, it is observed that the migrated bentonite from the GCL specimen was collected on the filter paper and clogged the water transfer. Such a problem prevents the correct calculation of hydraulic conductivity of the GCL specimen.

In order to overcome this problem, a 100 per cent UV stabilized polypropylene needlepunched nonwoven geotextile named 120 NW (Thrace Plasticism Co.) and seen in figure 3.8 was placed between the base beneath the GCL specimen and the bottom porous stone. Mechanical and hydraulic properties of 120 NW are given in table 3.1.



Figure 3.5. Base pedestal of the permeameter cell



Figure 3.6. Porous stone used in the permeameter cell

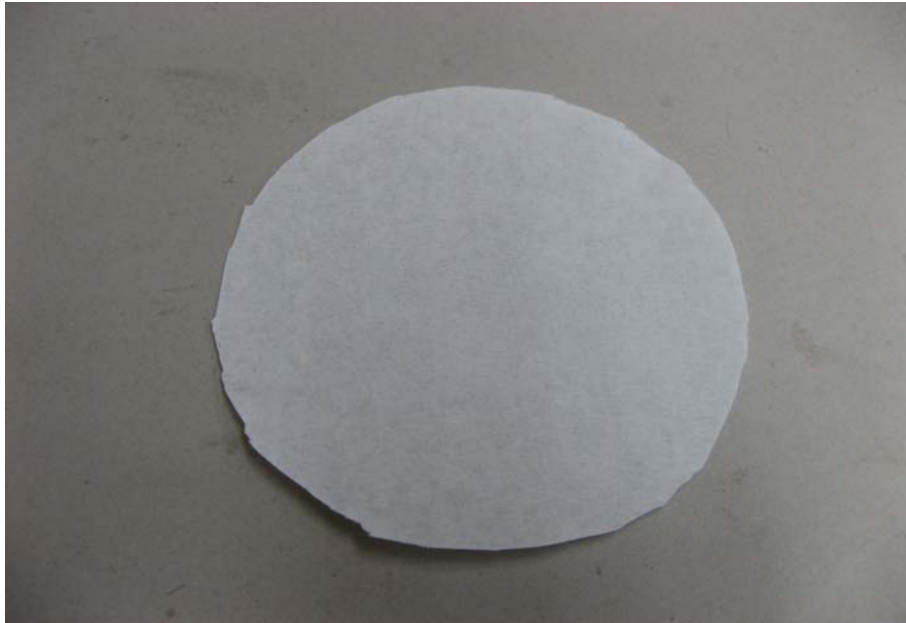


Figure 3.7. Filter paper used between porous stones and the GCL specimen



Figure 3.8. Nonwoven geotextile 120 NW used instead of filter paper

The pores of 120 NW permit water to pass through the effluent burette when bentonite migration from a GCL specimen occurred. This time, migrated bentonite did not collect on the nonwoven geotextile; instead, the migrated bentonite particles transferred with water to the effluent burette and hydraulic conductivity and index flux of the GCL

specimen were calculated correctly. Because 120 NW is more flexible than the filter paper, bentonite particles and water can pass beneath 120 NW without clogging the system.

Table 3.1. Properties of Nonwoven Geotextile 120 NW (Thrace Plastics Co.)

PROPERTY	TEST METHOD	VALUE
Thickness	EN 964-1	1.1 mm
Mass per unit area	EN 965	120 g/m ²
Tensile Strength	EN 10319	9 kN/m
Tensile Elongation	EN 10319	50%
Resistance to Static Puncture	EN ISO 12236	1800 N
Apparent Opening Size	EN ISO 12956	0.08 mm
Permeability	EN ISO 11058	11 cm/s
Water Flow Rate	EN ISO 11058	6600 l/min/m ²

3.1.1. Bases Used Beneath the GCL Samples

During flexible wall triaxial permeability tests, geosynthetic clay liners were placed over cylindrical bases made of plexiglass which represented gravel subgrades. Irregular subgrades such as gravel subgrade should not be used beneath GCL in flexible wall triaxial cell because sidewall leakage could occur through the sides of the GCL where the GCL was confined with latex membrane or the latex membrane could be damaged due to the extrusion of a gravel grain into the membrane under high hydraulic heads.

In order to simulate the permeable base, GCLs were placed over cylindrical bases made of plexiglass having holes with different diameters on them. Plexiglass is a kind of material that resists high confining pressures or hydraulic heads.

The void among the circular gravel grains is evaluated as a circular void as shown in figure 3.9. The possible diameters of the uniformly graded gravel subgrades are calculated by using trigonometric calculations according to figure 3.9. In table 3.2, different r values

calculated by using different t values in equation 3.1 are shown. In reality, the void is not circular but by approximation, the area of the void can be taken as a circle.

$$\begin{aligned}
 (2r)^2 + (2r)^2 &= (2r + 2t)^2 \\
 8r^2 &= 4r^2 + 8rt + 4t^2 \\
 4r^2 - 8rt - 4t^2 &= 0 \\
 r^2 - 2rt - t^2 &= 0
 \end{aligned}
 \tag{3.1}$$

Where:

r = radius of the uniform gravel grain

t = radius of the void among the gravel grains

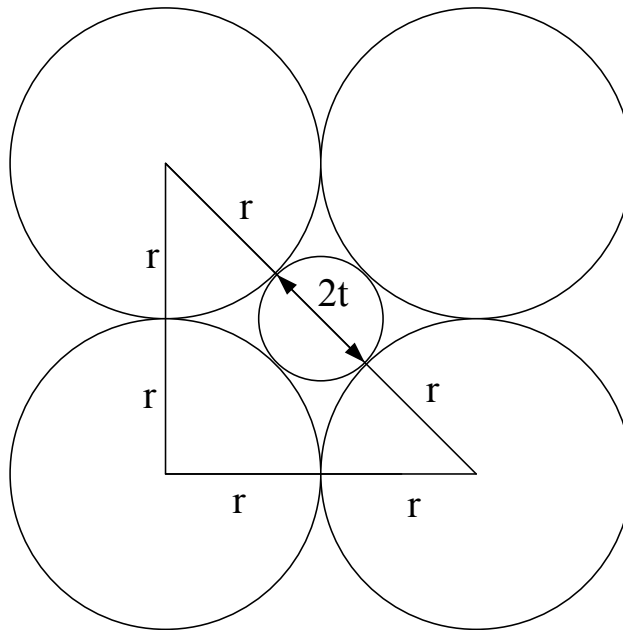


Figure 3.9. Schematic view of the uniform gravel grains

A simple formula (ASTM D 774-07) that is shown in equation 3.2 is also derived to calculate the uniform gravel grain diameters by taking into account the void diameters. In table 3.3, different d values calculated by using different d_v values in equation 3.2 are shown. According to equation 3.2, approximately the same gravel diameters are calculated as those obtained from the trigonometric calculations shown in equation 3.1. Furthermore, r values calculated by using equation 3.1 and shown in table 3.2 are almost the same as d values calculated by using equation 3.2 and shown in table 3.3.

Table 3.2. r values obtained by using t values in equation 3.1

t	r
0,25	0,60
0,50	1,21
0,75	1,81
1	2,41

$$d_v = 0.4d \quad (3.2)$$

Where:

d = diameter of the uniform gravel grain

d_v = diameter of the void among the gravel grains

Table 3.3. d values obtained by using d_v values in equation 3.2

d_v	d
0,25	0,63
0,50	1,25
0,75	1,88
1	2,50

As a result of the trigonometric calculations shown below, the uniform gravel grain diameter is calculated as approximately 5 cm where the void diameter is 2 cm, 3.75 cm where the void diameter is 1.5 cm, 2.5 cm where the void diameter is 1 cm and 1.25 cm where the void diameter is 0.5 cm. The plan views of the plexiglass bases with measurements are also shown in figures 3.10, 3.11 and 3.12.

The cylindrical plexiglass bases have the same diameter as the GCL specimen has. The diameter and height of the plexiglass bases are 10 cm and 1 cm, respectively. Four different bases were used with different circular, uniform holes on them. These uniform holes represented the voids among the gravel grains. Each of the four bases have circular, uniform holes with a diameter of 2 cm, 1.5 cm, 1 cm and 0.5 cm, respectively as shown in

figures 3.13, 3.14, 3.15 and 3.16. The centre of the circular voids on a base was placed approximately 1.5-2 cm away from the outer perimeter of the base as shown in figures 3.10, 3.11 and 3.12 in order not to cause side leakage and wrong hydraulic conductivity calculation.

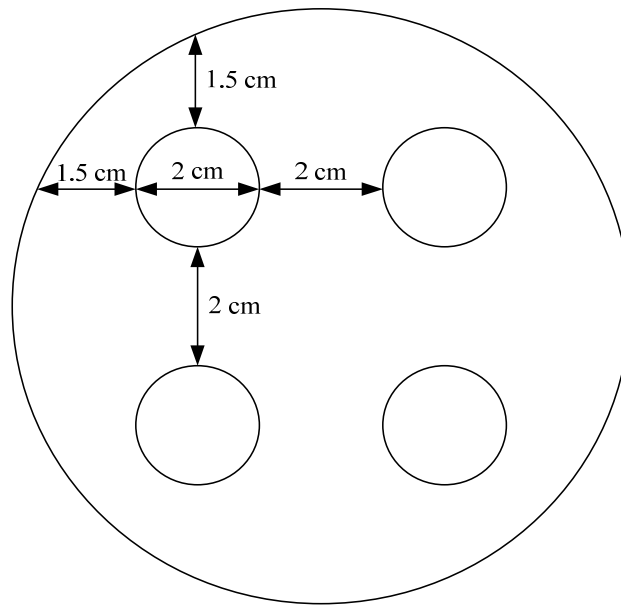


Figure 3.10. Plan view of the base which has uniform circular voids of 2 cm in diameter

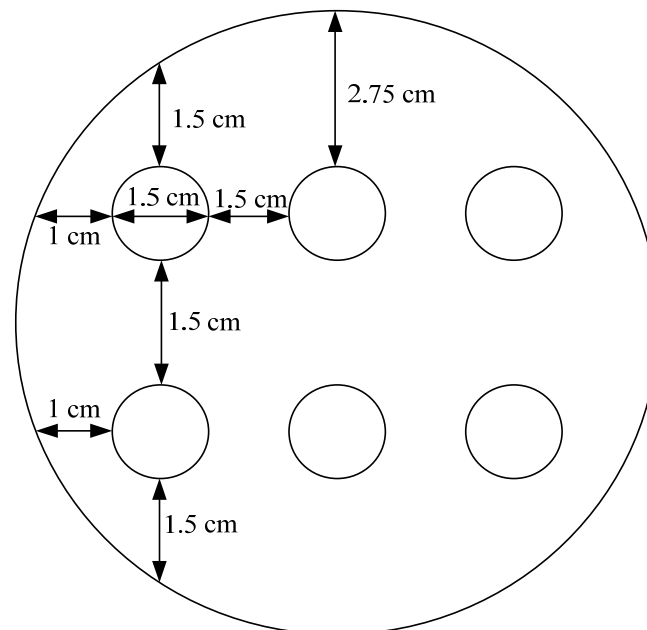


Figure 3.11. Plan view of the base which has uniform circular voids of 1.5 cm in diameter

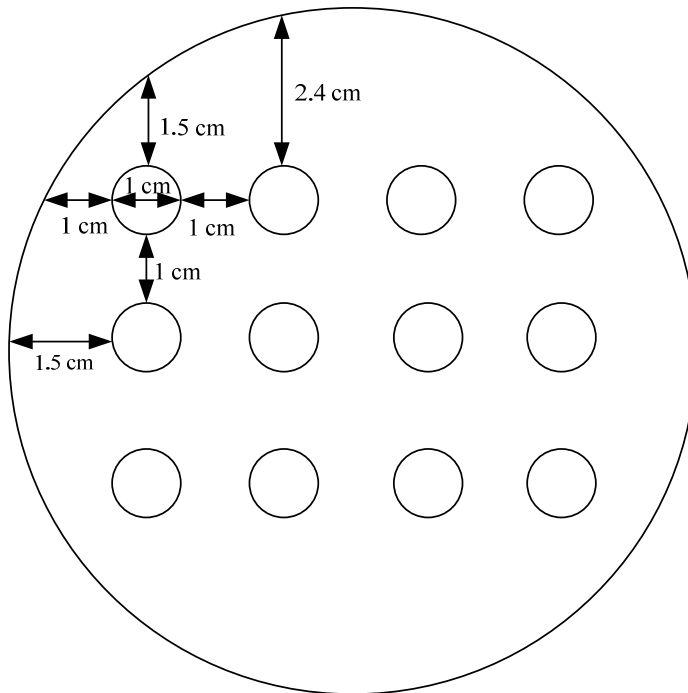


Figure 3.12. Plan view of the base which has uniform circular voids of 1 cm in diameter



Figure 3.13. Plexiglass base having uniform holes of 2 cm in diameter representing gravel base having uniformly graded gravel grains of 5 cm in diameter



Figure 3.14. Plexiglass base having uniform holes of 1.5 cm in diameter representing gravel base having uniformly graded gravel grains of 3.75 cm in diameter



Figure 3.15. Plexiglass base having uniform holes of 1 cm in diameter representing gravel base having uniformly graded gravel grains of 2.5 cm in diameter



Figure 3.16. Plexiglass base having uniform holes of 0.5 cm in diameter representing gravel base having uniformly graded gravel grains of 1.25 cm in diameter

3.2. Materials Tested

3.2.1. Geosynthetic Clay Liners

3.2.1.1. GCL-1. GCL-1 (Bentomat SS100) was a needlepunched GCL manufactured by needlepunching fibers from a nonwoven geotextile (N1) through the sodium bentonite (SB) to a woven geotextile (W1) while GCL-2, GCL-3 and GCL-4 were manufactured without needlepunching process. The most important aim of testing GCL-1 was to investigate the effect of needlepunching on internal erosion.

The needlepunched geosynthetic clay liner used in this study is designated as GCL-1. GCL-1 is a reinforced GCL (Bentomat SS100) consisting of a layer of natural, granular sodium bentonite between a woven slit-film polypropylene geotextile (105 g/m^2) and a nonwoven needlepunched polypropylene geotextile (203 g/m^2). To provide reinforcement, polypropylene fibers from the nonwoven geotextile are needlepunched through the bentonite and the woven geotextile (Colloid Environmental Technologies Company–CETCO, 2008). A roll of GCL-1 (Bentomat SS100) is shown in figures 3.17 and 3.18

where the woven geotextile component of GCL-1 is at the top in figure 3.17 and the nonwoven geotextile component of GCL-1 is at the top in figure 3.18.

The thickness of GCL-1 was measured as 6 mm when it was dry. The bentonite content in GCL-1 was measured as 6.1 kg/m^2 at a water content of the bentonite in dry GCL-1 of 12 per cent. The properties of Bentomat SS100 are listed in table 3.4. GCL permeability and index flux values in table 3.4 were obtained when the tests were performed by using de-aired distilled water at 551 kPa cell pressure, 531 kPa headwater pressure and 517 kPa tailwater pressure.

Even if the minimum required values for mass per unit area and swell index of bentonite are 4.8 kg/m^2 and 24 ml/2g as shown in table 3.4, mass per unit area and swell index of bentonite were measured as 6.1 kg/m^2 and 28 ml/2g respectively in the laboratory.



Figure 3.17. Woven geotextile component of Bentomat SS100 (GCL-1)

Flexible wall triaxial permeability tests were conducted on GCL-1 samples where both the woven and the nonwoven geotextiles were in contact with the base. The uniform void diameter of the bases were 2 cm, 1.5 cm and 1 cm. Two permeability tests without

using the bases were also performed. In these tests, porous stone was used instead of the base beneath a GCL sample.



Figure 3.18. Nonwoven geotextile component of Bentomat SS100 (GCL-1)

Table 3.4. Properties of Bentomat SS100 (CETCO, 2007)

MATERIAL PROPERTY	TEST METHOD	REQUIRED VALUES
Bentonite Swell Index	ASTM D 5890	24 ml/2g min
Bentonite Mass per Unit Area	ASTM D 5993	4.8 kg/m ² min
Bentonite Fluid Loss	ASTM D 5891	18 ml max.
GCL Peel Strength	ASTM D 6496	65 N
GCL Grab Strength	ASTM D 4632	400 N
GCL Grab Elongation	ASTM D 4632	20%
GCL Tensile Strength	EN ISO 10319	8 kN/m
GCL Tensile Elongation	EN ISO 10319	15%
GCL Index Flux	ASTM D 5887	2×10^{-9} - 2×10^{-10} m ³ /m ² /s
GCL Permeability	ASTM D 5887	1×10^{-11} - 1×10^{-12} m/s

The designations of the GCL-1 samples tested in this study were shown below:

- GCL-1 NW: GCL-1 sample tested between two porous stones where the nonwoven geotextile component was at the bottom
- GCL-1 W: GCL-1 sample tested between two porous stones where the woven geotextile component was at the bottom
- GCL-1-NW-D2: GCL-1 sample tested over the base that had uniform voids of 2 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-1-W-D2: GCL-1 sample tested over the base that had uniform voids of 2 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-1-NW-D1.5: GCL-1 sample tested over the base that had uniform voids of 1.5 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-1-W-D1.5: GCL-1 sample tested over the base that had uniform voids of 1.5 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-1-NW-D1: GCL-1 sample tested over the base that had uniform voids of 1 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-1-W-D1: GCL-1 sample tested over the base that had uniform voids of 1 cm in diameter, where the woven geotextile component was in contact with the base

3.2.1.2. GCL-2. GCL-2 was manufactured in the laboratory by using the same sodium bentonite (SB) sandwiched between the same woven (W1) and nonwoven geotextiles (N1) as the tested needlepunched GCL (GCL-1) was composed of. But GCL-2 was produced without needlepunching the geotextiles. The geotextiles were separately connected to the sodium bentonite. The results of the tests where GCL-2 samples were used were compared

with the results of the tests where GCL-1 samples were used in order to compare the effect of needlepunching on internal erosion.

Flexible wall triaxial permeability tests were conducted on GCL-2 samples where both the woven and the nonwoven geotextiles were in contact with the base. The uniform void diameter of the bases were 2 cm, 1.5 cm, 1 cm and 0.5 cm. Two permeability tests without using the bases were also performed. In these tests, porous stone was used instead of the base beneath a GCL sample.

The designations of the GCL-2 samples tested in this study were shown below:

- GCL-2 NW: GCL-2 sample tested between two porous stones where the nonwoven geotextile component was at the bottom
- GCL-2 W: GCL-2 sample tested between two porous stones where the woven geotextile component was at the bottom
- GCL-2-NW-D2: GCL-2 sample tested over the base that had uniform voids of 2 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-2-W-D2: GCL-2 sample tested over the base that had uniform voids of 2 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-2-NW-D1.5: GCL-2 sample tested over the base that had uniform voids of 1.5 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-2-W-D1.5: GCL-2 sample tested over the base that had uniform voids of 1.5 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-2-NW-D1: GCL-2 sample tested over the base that had uniform voids of 1 cm in diameter, where the nonwoven geotextile component was in contact with the base

- GCL-2-W-D1: GCL-2 sample tested over the base that had uniform voids of 1 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-2-NW-D0.5: GCL-2 sample tested over the base that had uniform voids of 0.5 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-2-W-D0.5: GCL-2 sample tested over the base that had uniform voids of 0.5 cm in diameter, where the woven geotextile component was in contact with the base

3.2.1.3. GCL-3. GCL-3 was also manufactured in the laboratory by using calcium bentonite (CB) sandwiched between the same woven (W1) and nonwoven geotextiles (N1) as the tested needlepunched GCL (GCL-1) was composed of. GCL-3 was not produced by needlepunching. The most important aim of testing GCL-3 was to investigate the effect of the type of the bentonite component of a GCL sample on internal erosion.

Flexible wall triaxial permeability tests were conducted on GCL-3 samples where both the woven and the nonwoven geotextiles were in contact with the base. The uniform void diameter of the bases were 2 cm, 1.5 cm, 1 cm and 0.5 cm. Two permeability tests without using the bases were also performed. In these tests, porous stone was used instead of the base beneath a GCL sample.

The designations of the GCL-3 samples tested in this study were shown below:

- GCL-3 NW: GCL-3 sample tested between two porous stones where the nonwoven geotextile component was at the bottom
- GCL-3 W: GCL-3 sample tested between two porous stones where the woven geotextile component was at the bottom
- GCL-3-NW-D2: GCL-3 sample tested over the base that had uniform voids of 2 cm in diameter, where the nonwoven geotextile component was in contact with the base

- GCL-3-W-D2: GCL-3 sample tested over the base that had uniform voids of 2 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-3-NW-D1.5: GCL-3 sample tested over the base that had uniform voids of 1.5 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-3-W-D1.5: GCL-3 sample tested over the base that had uniform voids of 1.5 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-3-NW-D1: GCL-3 sample tested over the base that had uniform voids of 1 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-3-W-D1: GCL-3 sample tested over the base that had uniform voids of 1 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-3 NW-0.5: GCL-3 sample tested over the base that had uniform voids of 0.5 cm in diameter, where the nonwoven geotextile component was in contact with the base
- GCL-3-W-D0.5: GCL-3 sample tested over the base that had uniform voids of 0.5 cm in diameter, where the woven geotextile component was in contact with the base

3.2.1.4. GCL-4. GCL-4 was produced by using the same sodium bentonite (SB) sandwiched between another type of woven (W2) and the same nonwoven geotextile (N1) as used in GCL-1, GCL-2 and GCL-3 without needlepunching. The most important aim of testing GCL-4 was to investigate the effect of the type of the woven geotextile component of a GCL sample on internal erosion.

Flexible wall triaxial permeability tests were conducted on GCL-4 samples where only the woven geotextiles were in contact with the base. The uniform void diameter of the bases were 2 cm, 1.5 cm, 1 cm.

The designations of the GCL-2 samples tested in this study were shown below:

- GCL-4-W-D2: GCL-4 sample tested over the base that had uniform voids of 2 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-4-W-D1.5: GCL-4 sample tested over the base that had uniform voids of 1.5 cm in diameter, where the woven geotextile component was in contact with the base
- GCL-4-W-D1: GCL-4 sample tested over the base that had uniform voids of 1 cm in diameter, where the woven geotextile component was in contact with the base

3.2.2. Geotextile Components of the Tested GCL Samples

3.2.2.1. Nonwoven Geotextile (N1). The nonwoven geotextile component of GCL-1 is also used separately in GCL-2, GCL-3 and GCL-4. However, the polypropylene fibers from the nonwoven geotextile are not needlepunched through the bentonite and the woven geotextile in GCL-2, GCL-3 and GCL-4. The nonwoven geotextile is designated as N1 in this study.

N1 is a polypropylene, staple fiber, needlepunched nonwoven geotextile as shown in figure 3.19. N1 is resistant to damage from construction stresses. The fibers of N1 are needled to form a stable network which retains dimensional stability relative to each other. N1 is also resistant to ultraviolet degradation and to biological and chemical environmental effects normally occur in soils (Propex Geosynthetics, 2006). The engineering properties of N1 are listed in table 3.5.

The nonwoven geotextile (N1) has 203 g/m^2 mass per unit area and 2 mm thickness. Grab tensile strength of N1 is measured as 756 N. Hydraulic properties of N1 are also given in table 3.3. According to table 3.3, N1 has apparent opening size of 0.212 mm with permittivity and permeability values of 1.5 s^{-1} and 0.38 cm/s, respectively.

Table 3.5. Properties of Nonwoven Geotextile N1 (Propex Geosynthetics, 2006)

PROPERTY	TEST METHOD	VALUE
Mass per unit area	ASTM D 5261	203 g/m ²
Thickness	ASTM D 5199	2.0 mm
Tensile Strength (Grab)	ASTM D 4632	756 N
Elongation	ASTM D 4632	50%
Puncture	ASTM D 4833	490 N
Mullen Burst	ASTM D 3786	2275 kPa
Trapezoidal Tear	ASTM D 4533	312 N
UV Resistance	ASTM D 4355	70%
Apparent Opening Size	ASTM D 4751	0.212 mm
Permittivity	ASTM D 4491	1.5 s ⁻¹
Permeability	ASTM D 4491	0.38 cm/s
Water Flow Rate	ASTM D 4491	4480 l/min/m ²



Figure 3.19. Polypropylene, staple fiber, needlepunched nonwoven geotextile (N1)

3.2.2.2. Woven Geotextile (W1). The woven geotextile component of GCL-1 is also used separately in GCL-2 and GCL-3. GCL-2 is composed of sodium bentonite sandwiched between N1 and W1 and GCL-3 is composed of calcium bentonite sandwiched between

N1 and W1. Both of these GCLs are not needlepunched and the geotextile components are bonded to the bentonite with the help of cohesiveness of the bentonite. The woven geotextile in GCL-2 and GCL-3 is designated as W1.

W1 is a woven slit-film geotextile where the silt films are woven together in order to provide dimensional stability relative to each other as seen in figure 3.20. W1 is also resistant to ultraviolet degradation and to biological and chemical environmental effects normally occur in soils (SI Geosolutions, 2000). The engineering properties of W1 are listed in table 3.6.

The woven geotextile (W1) has a mass per unit area of 108 g/m^2 that is approximately half of the mass per unit area of the nonwoven geotextile (N1). The grab tensile strength is higher for N1 than that for W1. Higher mullen burst, trapezoidal tear and puncture force values for N1 than those for W1 also explains the better mechanical behavior of N1 than that of W1. 50 per cent of grab elongation for N1 is relatively higher than that for W1 which also explains the more rigid texture of W1 than N1.

Even if the woven geotextile (W1) has an apparent opening size of 0.425 mm that is approximately twice of the apparent opening size of the nonwoven geotextile (N1), W1 has relatively lower permittivity and water flow rate values than those obtained for N1. According to the hydraulic properties of these woven and nonwoven geotextiles, W1 has larger pores but the whole nonwoven geotextile (N1) permits much more water to pass through itself than the whole woven geotextile (W1) permits. Thus, hydraulic conductivity of N1 is higher than that of W1 when the whole geotextile with openings (pores) is taken into consideration.

3.2.2.3. Woven Geotextile (W2). Another type of woven geotextile was also used in this study in order to investigate the effect of the engineering properties of the geotextile component of a geosynthetic clay liner on bentonite migration and internal erosion when the GCL is placed over a gravelly base. A polypropylene woven geotextile that is designated as W2 (figure 3.21) in this study is used as the woven geotextile component of GCL-4 where sodium bentonite is sandwiched between W2 and N1 without needlepunching. W2 is a type of woven geotextile that is preferred especially for soil

separation and stabilization. W2 is resistant to highly acid and alkaline environments, oxidation, microbiological degradation and chemical ageing (Thrace Plastics, 2008). The engineering properties of W2 are listed in table 3.7.

Table 3.6. Properties of Woven Geotextile W1 (SI Geosolutions, 2000)

PROPERTY	TEST METHOD	VALUE
Mass per unit area	ASTM D 5261	108 g/m ²
Thickness	ASTM D 5199	0.4 mm
Tensile Strength (Grab)	ASTM D 4632	600 N
Grab Elongation	ASTM D 4632	15%
Wide Width Tensile Strength	ASTM D 4595	12.2 kN/m
Wide Width Elongation	ASTM D 4595	10%
Puncture	ASTM D 4833	310 N
Mullen Burst	ASTM D 3786	1826 kPa
Trapezoidal Tear	ASTM D 4533	200 N
UV Resistance	ASTM D 4355	90%
Apparent Opening Size	ASTM D 4751	0.425 mm
Permittivity	ASTM D 4491	0.08 s ⁻¹
Water Flow Rate	ASTM D 4491	240 l/min/m ²

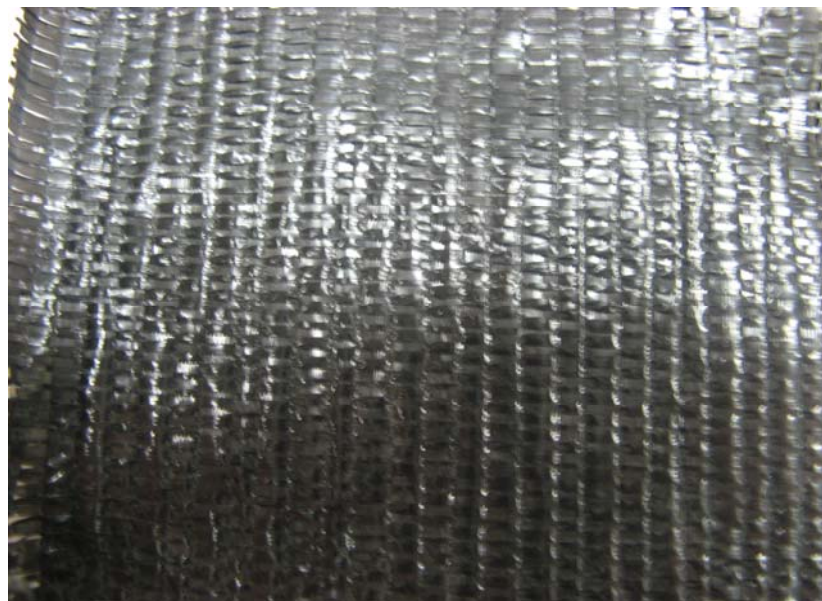


Figure 3.20. Slit-film woven geotextile (W1)

W2 has a mass per unit area of 210 g/m^2 that is twice of the mass per unit area of W1. So, W2 is much heavier than W1. The mechanical properties are better for W2 than those for W1. Tensile strength of W2 is 44 kN/m and is relatively higher than that of W1. Tensile elongations are 10 per cent 15 per cent for W1 and W2, respectively. These values are relatively lower than the tensile elongation of N1. Higher elongation causes higher flexibility. So, woven geotextiles are more rigid than nonwoven geotextiles. Tensile modulus of W2 is also very high. High tensile strength and tensile modulus show that W2 is much more durable than W1 against mechanical effects such as construction stresses. Apparent opening size of W2 is 0.380 mm . This value is not drastically different from the apparent opening size of W1.

Table 3.7. Properties of Woven Geotextile W2 (Thrace Plastics, 2008)

PROPERTY	TEST METHOD	VALUE
Mass per unit area	EN 9864	210 g/m^2
Thickness	EN 9863-1	0.77 mm
Tensile Strength	EN 10319	44 kN/m
Elongation	EN 10319	15%
Resistance to Static Puncture	EN ISO 12236	5600 N
UV Resistance	EN 12224	80%
Apparent Opening Size	EN ISO 12956	0.38 mm



Figure 3.21. Polypropylene woven geotextile (W2)

3.2.3. Bentonite Component of the Tested GCL Samples

3.2.3.1. Sodium Bentonite (SB). Bentonite used in the needlepunched GCL (GCL-1), GCL-2 and GCL-4 is a natural, granular, high-swelling Wyoming sodium bentonite and commercially known as Volclay CG-50. Granular sodium bentonite used in this study is designated as SB and is recommended for lining and sealing applications involving moist soils (CETCO, 2009). Granular particles of the sodium bentonite (SB) can be easily detected from figure 3.22.



Figure 3.22. Granular sodium bentonite used in GCL-1 (SB)

Sodium bentonite is a hydrous silicate of alumina primarily consisting of the clay mineral montmorillonite which swells several times its own volume when wetted. The granular sodium bentonite (SB) used in this study has 62.2 per cent SiO_2 and 19.1 per cent Al_2O_3 in it. It also has a high amount of sodium montmorillonite amount as 92 per cent. The chemical and mineralogical composition of SB are shown in tables 3.8 and 3.9.

The sodium bentonite (SB) has a high swelling capacity with a swell index of 28 ml/2g. The swell index test result is shown in figure 3.23. SB has also high liquid limit (344 per cent) and high plasticity index (308 per cent) values which shows that the sodium bentonite (SB) is a highly plastic clay. The geotechnical properties of SB are shown in table 3.10.

Table 3.8. Chemical composition of sodium bentonite (SB)

CHEMICAL COMPOUND	%
SiO ₂	62.2
Al ₂ O ₃	19.1
Fe ₂ O ₃	3.8
CaO	1.7
Na ₂ O	2.7
MgO	2.4
K ₂ O	1.3

Table 3.9. Mineralogical composition of sodium bentonite (SB)

MINERAL	%
Sodium Montmorillonite	92
Quartz	4
Feldspar	3
Biotite	1



Figure 3.23. Swell Index test result for sodium bentonite (SB) in a graduated cylinder

Table 3.10. Geotechnical properties of sodium bentonite used in GCL-1 (SB)

PROPERTY	VALUE
Dry Bulk Density	1.04 kg/m ³
Specific Gravity	2.68
Particle Size	Maximum 5% retained on #10 mesh sieve (2 mm) Maximum 15% passed through #200 mesh sieve (0.074 mm)
Moisture Content	12% as shipped
Swell Index	28 ml/2g
Liquid Limit	344%
Plastic Limit	36%
Plasticity Index	308%
Cohesion	9 kN/m ²
Internal Friction Angle	12°

3.2.3.2. Calcium Bentonite (CB). Bentonite used in GCL-3 (geosynthetic clay liner composed of calcium bentonite sandwiched between nonwoven (N1) and woven (W1) geotextiles without the nonwoven geotextile needlepunched through the bentonite and the woven geotextile) is powdered calcium bentonite manufactured by Karakaya Bentonit from Ankara, Turkey and designated as CB in this study. Dispersed structure of the powdered calcium bentonite (CB) is seen in figure 3.24.

Chemical composition of CB is shown in table 3.11. SiO₂ amount is approximately 3 per cent higher than that of SB, Al₂O₃ amount is about 1.5 per cent lower than that of SB. CB has also 0.5 per cent of TiO₂ in it where SB does not have any amount of TiO₂. Calcium montmorillonite content of CB is 85 per cent.

Calcium bentonite is usually not preferred to be used in geosynthetic clay liners because of its lower swelling capacity and higher hydraulic conductivity than sodium bentonite. But calcium bentonite has generally higher internal friction angle and shear strength than sodium bentonite as indicated in literature. In this study, bentonite migration and internal erosion of the bentonite in geosynthetic clay liners were investigated under

high hydraulic heads and the effect of bentonite type on bentonite migration and internal erosion was also taken into account by using both sodium and calcium bentonite in geosynthetic clay liners.



Figure 3.24. Powdered calcium bentonite used in GCL-3 (CB)

Table 3.11. Chemical composition of calcium bentonite (CB)

CHEMICAL COMPOUND	%
SiO ₂	65.4
Al ₂ O ₃	17.5
Fe ₂ O ₃	2.1
CaO	1.7
Na ₂ O	0.2
MgO	3.9
K ₂ O	0.4
TiO ₂	0.5

Calcium bentonite used in GCL-3 (CB) has a swelling index of 20 ml/2g as seen in figure 3.25. 20 ml/2g of swell capacity is lower than that of the sodium bentonite (SB) and even lower than the minimum required value for the bentonite used in geosynthetic clay

liners which is 24 ml/2g (CETCO, 2009). Liquid limit and plasticity index values of CB are 141 per cent and 100 per cent, respectively. These values are relatively lower than those obtained for SB. The geotechnical properties of CB are shown in table 3.12.

Table 3.12. Geotechnical properties of calcium bentonite used in GCL-3 (CB)

PROPERTY	VALUE
Specific Gravity	2.66
Moisture Content	10% as shipped
Swell Index	20 ml/2g
Liquid Limit	141%
Plastic Limit	41%
Plasticity Index	100%



Figure 3.25. Swell Index test result for calcium bentonite (CB) in a graduated cylinder

3.3. Sample Preparation

3.3.1. GCL-1

To perform flexible wall triaxial permeability test, the diameter of a GCL specimen has to be 100 mm as outlined in ASTM D 5887-09 and ASTM D 5084-03. The diameter of the base pedestal, top cap, porous stones, filter papers and bases is also 100 mm.

First, a porous stone having 100 mm diameter as a template was put on the GCL roll where the woven geotextile side of the GCL roll was on the top. Then, the intersection points of the GCL roll with the porous stone were soaked with deionized water. Afterwards, the porous stone was removed from the GCL roll. The GCL specimen which would be taken from the GCL roll is shown in figure 3.26 with its soaked perimeter. Then, the GCL specimen was taken from the GCL roll by cutting the GCL specimen with a utility knife. During cutting process, the bentonite around the edges of the GCL specimen was soaked with deionized water in order to make it easier to cut the GCL specimen with the utility knife. However, it is essential to take the GCL specimen with little or no loss of bentonite.



Figure 3.26. GCL specimen with its soaked perimeter during cutting process

After cutting the GCL sample and taking it from the GCL roll, the bentonite around the GCL specimen was soaked with deionized water again and the bentonite was allowed to hydrate for 2 to 5 minutes. The geotextile fibers from the upper and lower geotextile backings must not be interconnected, otherwise wrong hydraulic conductivity values might be measured. Transfer of water through the geotextile fibers which are located on the edges of the GCL specimen leads to side leakage and high permeability. To prevent this effect, the edges of the geotextile backings were slightly trimmed by using scissors. A GCL specimen was cut from a GCL roll and is shown in figures 3.27 and 3.28 where the woven and nonwoven geotextiles are on the top, respectively.



Figure 3.27. GCL-1 specimen where the woven geotextile is on the top



Figure 3.28. GCL-1 specimen where the nonwoven geotextile is on the top

3.3.2. GCL-2, GCL-3 and GCL-4

GCL-2, GCL-3 and GCL-4 are geosynthetic clay liners manufactured without needlepunching the nonwoven geotextile through the bentonite and the woven geotextile. These GCLs were formed by bonding nonwoven and woven geotextiles to the bentonite, separately.

Sample preparation for GCL-2, GCL-3 and GCL-4 was slightly different from that for GCL-1. This time, woven and nonwoven geotextiles were cut from geotextile rolls by scissors. Porous stone having 100 mm diameter was used as template again.

Sodium bentonite was used for GCL-2 and GCL-4. The same amount of bentonite was taken to use for GCL-2 and GCL-4 as the amount of bentonite used in GCL-1. This amount was calculated according to the mass per unit area of the bentonite in GCL-1 which was 6100 g/m^2 . A GCL specimen had a diameter and surface area of 10 cm and 78.5 cm^2 , respectively. According to the mass per unit area of GCL-1, measured as 6100 g/m^2 , approximately 47.9 g of bentonite had to be used in a GCL specimen in this thesis.

47.9 g of granular sodium bentonite was placed on a nonwoven geotextile having 100 mm diameter as shown in figure 3.29. Then, the bentonite was soaked with deionized water homogenously as seen in figure 3.30. Afterwards, a woven geotextile having 100 mm diameter was placed over the soaked bentonite. Finally, GCL-2 and GCL-4 specimens were obtained by bonding the woven and nonwoven geotextiles to the bentonite by cohesiveness of the soaked bentonite. The edges of the bentonite were soaked again in order to allow the bentonite to hydrate for 2 to 5 minutes. Geotextile fibers from both woven and nonwoven geotextiles were cut again in order to prevent wrong hydraulic conductivity calculations because of side leakage through the edges of the GCL specimen. A photograph of a GCL-4 specimen is shown in figure 3.31 where sodium bentonite was sandwiched between N1 and W2 geotextiles.

Powdered calcium bentonite was sandwiched between W1 and N1 geotextiles for GCL-3. The only difference between the sample preparation of GCL-3 and GCL-2 or GCL-4 is the soaking procedure of the bentonite.

Calcium bentonite used in this study was powdered. The powdered structure of the bentonite makes it difficult to soak the bentonite. Granular sodium bentonite became wet homogenously but powdered sodium bentonite was not soaked easily when deionized water was added to it when the bentonite was placed over a nonwoven geotextile. It was not possible to bond the woven geotextile to the wetted calcium bentonite. Loss of bentonite also occurred from the nonwoven geotextile after soaking the bentonite.



Figure 3.29. Granular bentonite placed over a nonwoven geotextile



Figure 3.30. Soaked bentonite on a nonwoven geotextile



Figure 3.31. GCL-4 specimen where sodium bentonite is sandwiched between woven geotextile (W2) and nonwoven geotextile (N1)

In order to bond both geotextiles to the powdered calcium bentonite, 47.9 g of calcium bentonite as shipped was placed in an aluminium container. Then, deionized water was sprayed to the bentonite homogenously. When the dispersed calcium bentonite platelets began to flocculate, water spraying process was terminated. Then, the soaked bentonite was placed on a nonwoven geotextile having 100 mm diameter as shown in figure 3.32. Afterwards, a woven geotextile having 100 mm diameter was bonded to the bentonite and the same procedures as followed for the sample preparation of GCL-1, GCL-2 and GCL-4 were carried out for GCL-3 specimen. A GCL-3 specimen with calcium bentonite sandwiched between woven geotextile (W1) and nonwoven geotextile (N1) was shown in figure 3.33 after sample preparation.



Figure 3.32. Soaked calcium bentonite placed on a nonwoven geotextile



Figure 3.33. GCL-3 specimen where calcium bentonite is sandwiched between woven geotextile (W1) and nonwoven geotextile (N1)

3.4. Testing Methods

3.4.1. Tests Conducted for Determining Geotechnical Properties of Bentonite

3.4.1.1. Swell Index Tests. Swell index of clay mineral component of geosynthetic clay liners is determined by the standard test method as outlined in ASTM D 5890-06 (2006). There are two different types of bentonites used as clay components of the GCLs in this study. One of the bentonites is granular sodium bentonite (SB) used in GCL-1, GCL-2 and GCL-4 and the other bentonite is powdered calcium bentonite (CB) used in GCL-3.

According to ASTM D 5890-06 (2006), 2 g of oven-dried bentonite sample, 100 per cent of passing a 100 mesh U.S. standard sieve was collected in a can. A 100 ml graduated cylinder was filled up to 90 ml with deionized water. Not more than 0.1 g of the 2 g oven-dried bentonite sample was dusted in the graduated cylinder with a volumetric spoon. A minimum period of 10 minutes passed in order to allow the bentonite to wet, hydrate and settle to the bottom of the graduated cylinder. This process was repeated until the entire 2 g of the bentonite sample had been added to the water in the graduated cylinder. Then, the graduated cylinder was gently tipped at a 45° angle while deionized water was added to rinse any adhering bentonite particles from the sides of the cylinder into the water and the

water level was increased up to the 100 ml mark. After a minimum of 16 hours hydration period, the volume level on the top of the settled bentonite was measured from the graduated cylinder. This value is the swell index value of the bentonite as ml/2g.

After the swell index tests were conducted as outlined in ASTM D 5890-06 (2006), swell index values of the sodium bentonite (SB) and calcium bentonite (CB) used in this study were measured as 28 ml/2g and 20 ml/2g, respectively.

The results of the swell index tests show that SB has higher swelling capacity than CB. Higher swelling index of a bentonite is preferred for the bentonite used in GCLs in terms of lower hydraulic conductivity.

3.4.1.2. Atterberg Limit Tests. Atterberg limits of the bentonite used in the GCL samples such as liquid limit, plastic limit and plasticity index are determined by the standard method as outlined in ASTM D 4318-10 (2010).

Atterberg limit tests were conducted on both SB and CB bentonites used in this study. Multipoint liquid limit test was performed in order to determine the liquid limit of both sodium bentonite and calcium bentonite.

According to ASTM D 4318-10 (2010), about 200 g of oven-dried bentonite 100 per cent of passing a 40 mesh U.S. standard sieve ($0.425\mu\text{m}$) was wetted with deionized water. Then, an amount of the bentonite that closed approximately half of the inner surface of the Cassagrande liquid limit device was placed in the device smoothly. After that, a groove was formed in the soil by using a flat grooving tool. Then, the number of drops, approximately twice in a second, required to close about 1.3 cm of the groove was recorded. Then, a slice of soil was taken from the closed groove with a spatula in order to determine the water content. When more bentonite was added to the mixture of the soil with water, the number of drops to close the groove becomes higher. The test was conducted three times and three different drops were obtained with three different water contents. From the graphs shown in figures 3.34 and 3.35, the liquid limits are the water contents correspond to 25 drops.

Table 3.13. Liquid limit test results for the sodium bentonite (SB)

No. of blows	13	26	34
Water content (%)	397	354	306

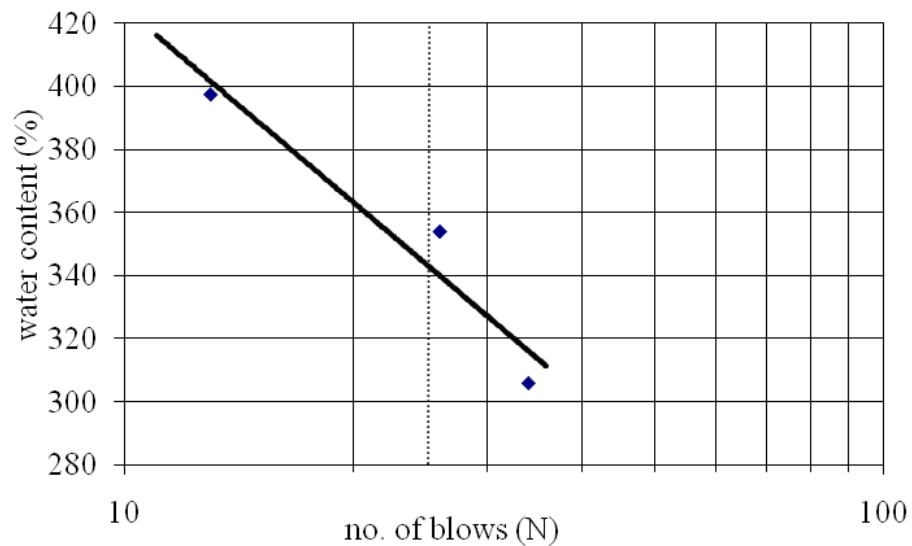


Figure 3.34 Liquid limit determination for the sodium bentonite (SB) from the graph

Table 3.14. Liquid limit test results for the calcium bentonite (CB)

No. of blows	19	28	33
Water content (%)	181	123	101

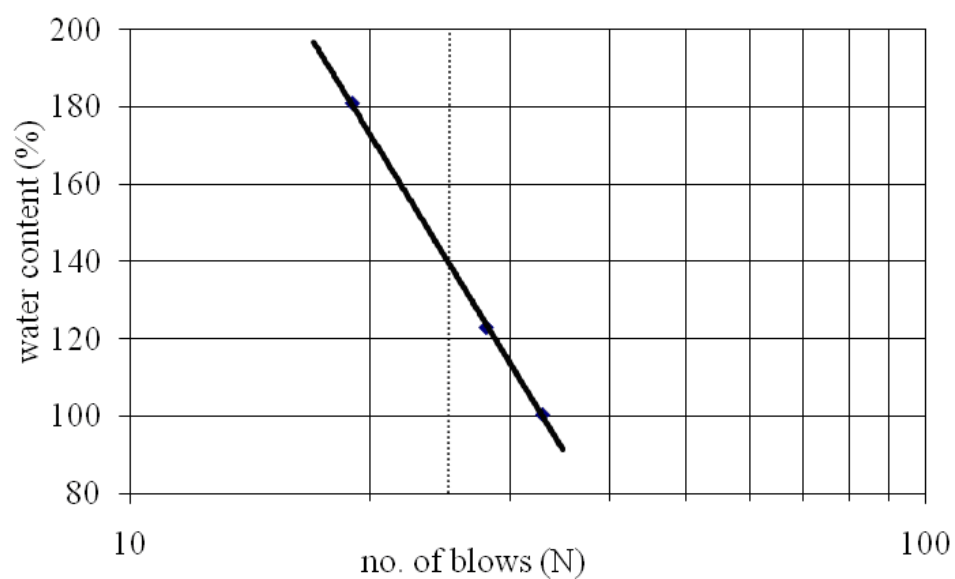


Figure 3.35. Liquid limit determination for the calcium bentonite (CB) from the graph

After conducting liquid limit test, about 20 g of the soil from the material prepared for the liquid limit test was taken. The water content of the soil was reduced to a consistency at which it could be rolled without sticking to the hands by spreading or mixing continuously on a glass plate (ASTM D 5890-06, 2006).

Then, a 1.5-2 g portion was taken from the soil. The soil was rolled between the palm and the glass plate into a thread of uniform diameter. The thread was further deformed on each stroke so that its diameter reached approximately 3.2 mm. Then, the threads were taken into a can in order to determine the plastic limit water content (ASTM D 5890-06, 2006).

Table 3.15. Plastic limit test results for the sodium bentonite (SB)

Water content (%)	39	33

Table 3.16. Plastic limit test results for the calcium bentonite (CB)

Water content (%)	38	43

Table 3.17. Atterberg limits for the sodium bentonite (SB)

LIQUID LIMIT	344
PLASTIC LIMIT	36
PLASTICITY INDEX	308

Table 3.18. Atterberg limits for the calcium bentonite (CB)

LIQUID LIMIT	141
PLASTIC LIMIT	41
PLASTICITY INDEX	100

According to the figures 3.34 and 3.35 and tables 3.13, 3.14, 3.15, 3.16, 3.17 and 3.18 showing the results of the atterberg limit tests, plasticity index for both types of bentonites was obtained by subtracting plastic limit from liquid limit. As a result, sodium bentonite (SB) had higher liquid limit and plasticity index values than calcium bentonite

(CB). Plasticity index was 308 per cent for SB and 101 per cent for CB. The results show that SB had much higher plasticity than CB.

3.4.1.3. Specific Gravity Tests. Specific gravity is the ratio of the mass of a unit volume of a soil solids to the mass of the same volume of gas-free distilled water at 20°C (ASTM D 854-10, 2010). Specific gravities of both sodium and calcium bentonites used in this study were also determined according to the standard test method as outlined in ASTM D 854-10 (2010).

About 50 g of the bentonite was poured into a 500 ml flask and about two-thirds of the flask was filled with deionized water. Then, the flask was attached to a vacuum pump about ten minutes. During this time, the flask was shaken and turned in order to fasten the deairing process. After that, the flask was filled with deionized water up to the 500 ml level. Then, the flask with the bentonite and water was weighed without air in the mixture and the bentonite in it was poured into a dish. The bentonite in the dish was oven-dried.

The same procedures were repeated for only deionized water in the flask without the bentonite. The water was deaired with the vacuum pump, too. Weight of the de-aired water in the 500 ml flask was measured (ASTM D 854-10, 2010).

Another 50 g of the same bentonite was taken and tested again. The same procedures were followed. Flusk with de-aired water and soil was weighed and the soil was poured into a dish and the bentonite in the dish was oven-dried again. Flusk with de-iaired water was also weighed (ASTM D 854-10, 2010).

Finally, two specific gravity (G_s) values were obtained for the same bentonite. The arithmetical average of these two values was taken as the specific gravity (G_s) for that bentonite as seen in tables 3.19 and 3.20. Temperature correction coefficients that were used to calculate the specific gravities were also shown in table 3.21.

According to the specific gravity test results, the specific gravity (G_s) of granular sodium bentonite (SB) used in GCL-1, GCL-2 and GCL-4 was obtained as 2.68 and the

specific gravity (G_s) of powdered calcium bentonite (CB) used in GCL-3 was obtained as 2.66.

Table 3.19. Specific Gravity (G_s) determination for sodium bentonite (SB)

$G_s = \alpha M_s / M_w$	2,67	2,69
Average G_s	2,68	

Table 3.20. Specific Gravity (G_s) determination for calcium bentonite (CB)

$G_s = \alpha M_s / M_w$	2,66	2,66
Average G_s	2,66	

Table 3.21. Temperature correction coefficients for different temperatures

T (°C)	α	ρ_w (g/cm ³)
16	1,0007	0,99897
18	1,0004	0,99862
20	1,0000	0,99823
22	0,9996	0,99780
24	0,9991	0,99732
26	0,9986	0,99681

3.4.2. Flexible Wall Triaxial Permeability Tests

3.4.2.1. Setting Up Triaxial Sample. After sample preparation, flexible wall triaxial permeability tests were conducted according to ASTM D 5887-09 and ASTM D 5084-03. Hydraulic conductivity and index flux values of GCL samples were determined under high hydraulic heads up to 50 m.

Nonwoven geotextile (120 NW) was used instead of filter paper and porous stone beneath a base in permeability tests where a GCL sample was tested over a base. However, filter paper and porous stone were used beneath a GCL sample instead of nonwoven geotextile (120 NW) in permeability tests where a GCL sample was not tested over a base. In these permeability tests, GCL samples were tested between two porous stones. Configuration of test specimens for both types of permeability tests were shown in figures 3.36 and 3.37.

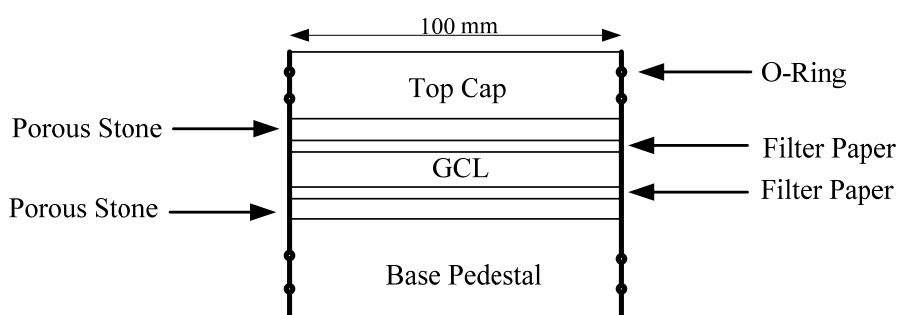


Figure 3.36. Configuration of test specimen for permeability test where a base is not placed beneath the GCL sample

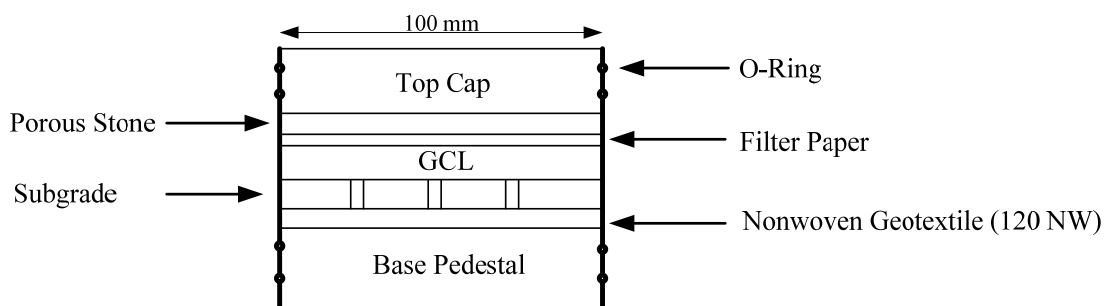


Figure 3.37. Configuration of test specimen for permeability test where a base is placed beneath the GCL sample

Before setting up a GCL sample in the triaxial cell, water was allowed to flow through the top and bottom tubes to flush air out of the lines. The flushing process was complete when no additional bubbles came from the base and there were no apparent bubbles in the tube connecting the cell to the panel (Flexpanel HM-4150 User Guide, 2001). The burette assemblies for cell pressure, influent pressure and effluent pressure were also filled with deaired water.

A thin coat of silicon high-vacuum grease was applied to the sides of the base pedestal in order to prevent water leakage through the sides of the base. First, a soaked porous stone and a soaked filter paper having 100 mm diameter were placed on the base pedestal for permeability tests where a GCL sample was not tested over a base. Instead of a porous stone and a filter paper, a base made of plexiglass, with circular uniform voids as shown in figure 3.38 was placed over a nonwoven geotextile (120 NW) on the base pedestal where a GCL sample was tested over a base. Silicon high-vacuum grease was also applied to the sides of the base.

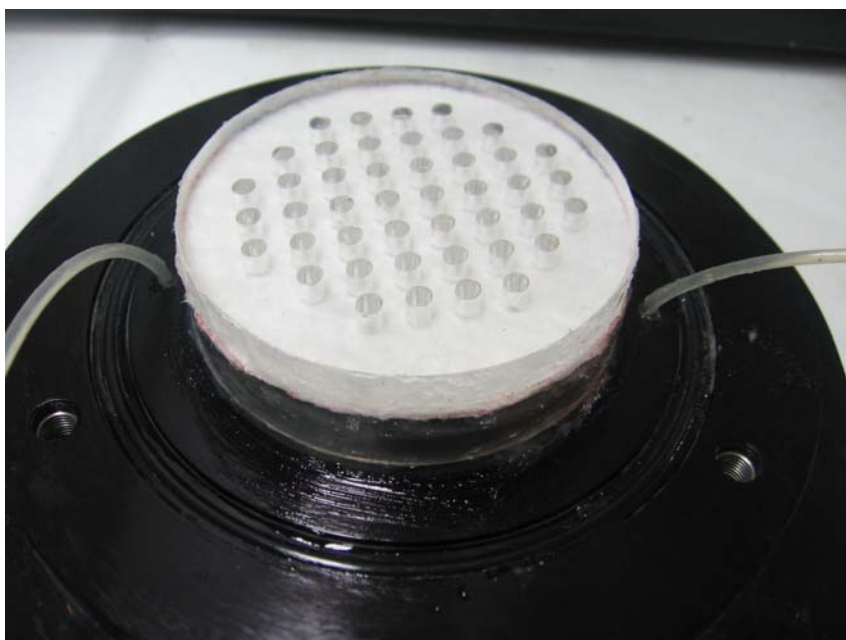


Figure 3.38. Base having 0.5 cm circular voids placed over a nonwoven geotextile (120 NW) on the base pedestal

Then, a GCL sample was placed over the base or the filter paper. Afterwards, a soaked filter paper was put on top of the GCL sample and then a soaked porous stone as shown in figure 3.39. Silicon high-vacuum grease was also applied to the sides of the top cap in order to prevent water leakage. Then, the top cap was placed over the upper porous stone as shown in figures 3.40 and 3.41.

Finally, a flexible latex membrane was placed around the test specimen where the base pedestal was at the bottom and the top cap was at the top, including the GCL sample as seen in figures 3.40 and 3.41. A vacuum regulator was connected to the membrane

holder and the membrane was placed around the GCL sample while the vacuum regulator was working in order to deair the contact points between the test specimen and the membrane. Then, O-rings were placed on each end cap to seal the membrane.

Then, the flow tubes were attached to the top cap. The permeameter cell was sealed and closed as shown in figure 3.42. The triaxial cell was filled with deionized, deaired water before saturation stage.

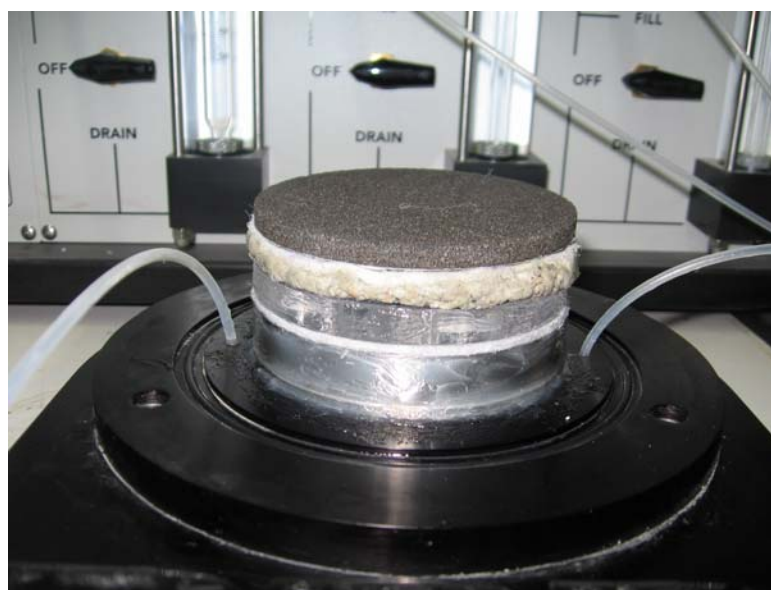


Figure 3.39. Porous stone and filter paper placed over a GCL sample

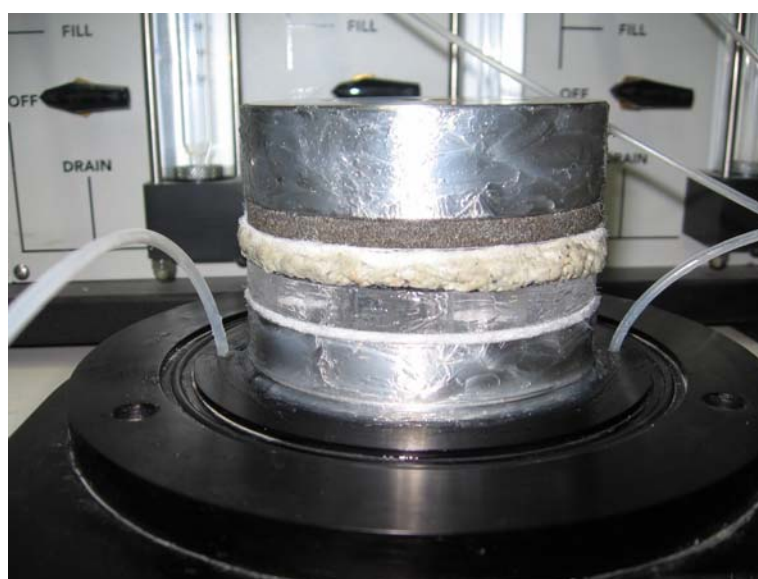


Figure 3.40. Top cap placed over a GCL sample where the GCL was tested over a base

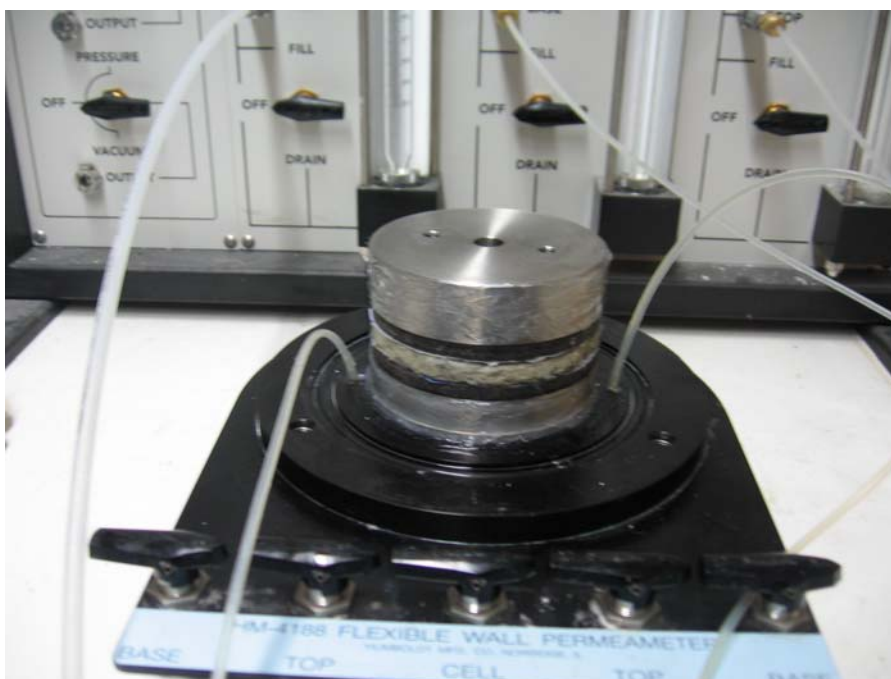


Figure 3.41. Top cap placed over a GCL sample where the GCL was tested between two porous stones without a base



Figure 3.42. GCL sample covered with latex membrane and O-rings in flexible wall triaxial permeameter cell

3.4.2.2. Saturation and Consolidation Stages. In this thesis, constant head triaxial permeability tests were performed in flexible wall permeameters. The level of hydraulic head was kept constant during the permeation stage of the test. If there had not been a drastical increase in permeability of the GCL sample which means that bentonite migration from the GCL or internal erosion had not occurred, the level of hydraulic head would have been increased and the same procedure was followed till internal erosion occurred or till 50 m hydraulic head was maintained.

Before starting saturation stage for the constant head triaxial permeability tests, initial cell pressure was applied into the permeameter cell. This cell pressure was a small confining pressure of approximately 35 kPa and was given equally through three dimensions to the GCL sample. Then, a backpressure less than the confining pressure (7-14 kPa) was applied to both the influent and effluent systems and water was flushed through the flow system (ASTM D 5084-03, 2010). After all air had been removed from the flow lines, the control valves on the permeameter cell were closed.

To saturate a GCL sample, back pressuring is usually necessary. Permeation of the GCL sample was chosen from top to bottom in order to evaluate the internal erosion phenomenon when the GCL sample was placed over a coarse base. During saturation of the GCL sample, first, the cell pressure was increased to 70 kPa and the backpressure was increased to 35 kPa. 35 kPa of difference between the cell pressure and the backpressure kept constant until the end of the saturation stage. Then, the cell pressure and the backpressure were increased simultaneously in increments of 70 kPa in 1 hour intervals until a final cell pressure of 550 kPa and a backpressure of 515 kPa were obtained (ASTM D 5887-09, 2010). The cell pressure of 550 kPa and backpressure of 515 kPa were maintained for a period of approximately 40 hours to allow hydration, saturation and consolidation of the GCL sample to occur (ASTM D 5887-09, 2010). The desired effective stress of 35 kPa was maintained by the difference between the cell pressure and backpressure. When the cell pressure was increased to 550 kPa, that was the level necessary to develop the desired effective stress, consolidation of the GCL sample was initiated. Drainage was allowed from the base of the GCL sample. Outflow volumes were recorded by using the effluent burette assemble. When the water flow through the GCL

specimen to the effluent burette assembly ceased, it was confirmed that the consolidation stage was also completed (Flexpanel HM-4150 User Guide, 2001).

3.4.2.3. Permeation Stage. Permeation was initiated by raising the pressure at the top of the specimen which was applied by increasing the influent pressure. As a result, downward flow was produced through the GCL sample with a pressure difference of 15 kPa. Influent pressure was raised to 530 kPa where the effluent pressure was 515 kPa (ASTM D 5887-09, 2010).

As outlined in ASTM D 5887-09 and ASTM D 5084-03, 15 kPa of head difference between the top and bottom of a GCL sample which is equal to approximately 1.53 m of hydraulic head on the GCL sample, is necessary to measure the hydraulic conductivity and index flux values of a GCL sample by using a flexible wall permeameter.

During permeation stage, cell pressure, influent pressure and effluent pressure values were 550 kPa, 530 kPa and 515 kPa, respectively. The criteria for measuring the hydraulic conductivity and index flux are listed as follows as outlined in ASTM D 5887-09:

- Rate of inflow is determined by measuring the water level in influent burette and rate of outflow is determined by measuring the water level in effluent burette with an accuracy of 10 per cent.
- At least three values of flow rate have to be measured over a minimum time period of 8 hours.
- The ratio of rate of inflow to the rate of outflow has to be between 0.75 and 1.25 for the last three consecutive flow measurements.
- The last three consecutive flow rates shall be neither less than 0.75 times nor greater than 1.25 times the average flow rate.
- The index flux and hydraulic conductivity values are computed by averaging the last three consecutive computed values.

In this thesis, 1.53 m of hydraulic head was not enough to cause bentonite migration or internal erosion from a GCL sample when the GCL sample was placed over a base with voids. In order to investigate and observe bentonite migration or internal erosion, hydraulic head on the GCL sample was increased up to 50 m during permeation.

Internal erosion is a time-dependant phenomenon (Fell et al., 2003). Internal erosion sometimes occurs suddenly after a couple of hours or days when a high load is applied on top of a dam or a GCL and sometimes occurs slowly after months or even years. In this study, the effects of different parameters such as geotextile and bentonite types of a GCL and coarseness of the base placed beneath a GCL on internal erosion were evaluated. Considering the reasons which would prolong the test durations, it was decided to perform a triaxial permeability test under the tested hydraulic head up to 12 days. It was also determined to apply the hydraulic head in 5 m increments.

During the permeation stage, 1.53 m of hydraulic head was applied first as outlined in ASTM D 5887-09 and ASTM D 5084-03. When the flow became steady and the flow measurements were taken correctly, the head was increased to 5 m by 1 m increments in every 10 minutes.

During 1.53 m of hydraulic head that is equal to about 15 kPa, first, the valves on the permeameter were closed. Then, the effluent pressure was decreased from 515 kPa to 508.57 kPa while 530 kPa of influent pressure was kept constant. The difference between 515 kPa and 510.4 kPa is 4.6 kPa which is the pressure equals to approximately 0.47 m of hydraulic head. Totally, the difference between influent and effluent pressures became 19.6 kPa that is equal to approximately 2 m of hydraulic head. After the head was increased to 2 m, the permeation under 2 m of head was maintained approximately 10 minutes by opening the valves on the permeameter. Then, the valves on the permeameter were closed and the effluent pressure was decreased to 500.6 kPa while 530 kPa of influent pressure was kept constant. The difference between influent and effluent pressures was approximately equal to the hydraulic head of 3 m. After opening the valves and waiting for about 10 minutes, the effluent pressure was decreased by 9.81 kPa again to obtain 4 m of hydraulic head. This process continued until the desired hydraulic head of 5 m was obtained.

1 m of hydraulic head increments in 10 minutes time periods from 1.53 m to 5 m were applied because the increase in the hydraulic head had to be in a slower way. If the head was increased from 1.53 m to 5 m or from 5 m to 10 m suddenly without any head increments or time periods, misleading permeability values could be obtained.

In reality, when a GCL is placed over a coarse subgrade in a tailing dam, the collected water in the dam causes the hydraulic head on the GCL. When the water level increases by raining, for instance, the hydraulic head will increase in a slower way, like the application of 1 m hydraulic heads in every 10 minute-time intervals in this study. Sudden increase in hydraulic head is out of the scope for this study.

When the head became 5 m, the permeation was maintained for approximately 12 days. If internal erosion had occurred and sudden increase in permeability of the GCL sample had been observed during this time period, the flow would have continued until considerable amount of bentonite had been migrated from the GCL or the voids of the base pedestal had been clogged. If internal erosion had not occurred during 12 days, the hydraulic head would have increased from 5 m to 10 m in 1 m of head increments in 10 minutes of time periods as done before.

If internal erosion had occurred, hydraulic head would not have been increased, however, if internal erosion had not occurred, hydraulic head would have been increased to 15 m, then after 12 days to 20 m and this process would have been followed up to 50 m of hydraulic head. When increasing hydraulic head, every time, both the cell and influent pressures were kept constant while the effluent pressure was decreased to the desired value.

To obtain 50 m of hydraulic head, the cell pressure, influent pressure and effluent pressure were taken as 550 kPa, 530 kPa and 39.5 kPa, respectively. The difference between influent and effluent pressure was 490.5 kPa which is equal to approximately 50 m of hydraulic head of water on the GCL sample. Under 50 m of hydraulic head, a GCL sample was tested 12 days again. If internal erosion had not occurred and drastical increase in permeability had not been observed during 12 days time period, the triaxial permeability test was terminated.

After completion of the permeation stage, the applied confining (cell), influent and effluent pressures were reduced to zero in a manner that did not generate significant volume change of the GCL sample (ASTM D 5084-03, 2010). Reduction of these pressures were done by step by step. In every 10 minutes, all of the pressures were decreased by approximately 34.5 kPa. The effluent pressure was decreased down to 1-5 kPa and remained constant until the cell and influent pressures were also decreased to that level. When all of these pressures were totally released, the permeameter cell was disassembled and the GCL sample was removed carefully.

The thickness of a GCL sample was measured by using a caliper. Water content and mass per unit area values for the bentonite of the GCL sample were obtained by using sampling tubes. As a result, hydraulic conductivity, permittivity and index flux values of the GCL sample were calculated.

3.4.2.4. Calculations for Flexible Wall Triaxial Permeability Tests

Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) are the three main parameters that were obtained after the termination of flexible wall triaxial permeability tests.

Coefficient of permeability (k) is the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of porous medium under a unit hydraulic gradient and standard temperature conditions (20°C) (ASTM D 5887-09, 2010). Coefficient of permeability (k), also known as hydraulic conductivity of GCL samples was calculated as follows:

$$k = \frac{\Delta Q \cdot L}{A \cdot h \cdot \Delta t} \quad (3.3)$$

Where:

k = coefficient of permeability of the GCL sample (cm/s)

ΔQ = average of inflow and outflow quantities for a given time interval (cm³)

L = length of the GCL sample (cm)

A = cross-sectional area of the GCL sample (cm^2)

Δt = interval of time over which the flow ΔQ occurs (s)

t_1 = time at the start of permeation (s)

t_2 = time at the end of permeation (s)

h = hydraulic head on the GCL sample (cm)

Length of a GCL sample (L) is the thickness of the sample measured by a caliper after the termination of a triaxial permeability test. The average thickness without taking the maximum and minimum thickness values was obtained by ten thickness measurements taken randomly from the GCL sample. Flexible wall triaxial permeability test cell does not include a device to measure the thickness of a GCL sample during a test. The thickness of the GCL sample could only be measured after the termination of the test. When calculating the coefficient of permeability of a GCL sample (k), the thickness of the sample (L) was always taken as the value obtained at the end of a test. Even if the thickness of the sample (L) changed throughout a permeability test, very low thickness values of the GCL samples made it almost realistic to use the final thickness value for the whole stages of the test.

The diameter of a GCL sample was 10 cm and the cross-sectional area of the GCL sample (A) was calculated as 78.5 cm^2 for all of the triaxial permeability tests. For the tests when the base with voids was placed beneath a GCL sample, the cross-sectional area (A) was also taken as 78.5 cm^2 even if there were only circular voids on the base. The water permeated through a GCL sample from top to bottom, then it permeated to the base pedestal through the circular holes on the base. However, the whole cross-sectional area of the GCL sample transferred the water to the base pedestal and the coefficient of permeability (k) of the GCL sample was calculated by taking the cross-sectional area of the whole GCL sample into account.

Hydraulic head (h) was not the same during a triaxial permeability test. The hydraulic head (h) on a GCL sample just before the termination of the test was taken into consideration. Coefficient of permeability (k) was corrected to that for 20°C by multiplying k by the ratio of the viscosity of water at test temperature to the viscosity of water at 20°C as follows (ASTM D 5084-03 and ASTM D 5887-09, 2010):

$$k_{20} = R_T k \quad (3.4)$$

Where:

k_{20} = coefficient of permeability corrected at 20°C (cm/s)

R_T = ratio of viscosity of water at test temperature to the viscosity of water at 20°C

Viscosity values of water at different temperatures are listed in table 3.22.

Table 3.22. Properties of distilled water (Bowles, 1992)

Temp., °C	Unit weight of water, g/cm ³	Viscosity of water, poise*
4	1.00000	0.01567
16	0.99897	0.01111
17	0.99880	0.01083
18	0.99862	0.01056
19	0.99844	0.01030
20	0.99823	0.01005
21	0.99802	0.00981
22	0.99780	0.00958
23	0.99757	0.00936
24	0.99733	0.00914
25	0.99708	0.00894
26	0.99682	0.00874
27	0.99655	0.00855
28	0.99627	0.00836
29	0.99598	0.00818
30	0.99568	0.00801

$$*\text{Poise} = \frac{\text{dyne} \cdot \text{s}}{\text{cm}^2} = \frac{\text{g}}{\text{cm} \cdot \text{s}}$$

Permittivity (Ψ) is also another hydraulic conductivity parameter calculated from the triaxial permeability test results. Permittivity (Ψ) is the ratio of the coefficient of permeability of a GCL sample (k) to the average thickness (t) of the GCL sample measured after the termination of a permeability test. The use of Ψ is more advantageous than the use of k for thin, compressible geosynthetic products such as GCLs because the thickness of the GCL sample does not need to be measured (Koerner, 1998). Permittivity (Ψ) of the GCL samples was calculated as follows (ASTM D 5084-03, 2010):

$$\Psi = \frac{k}{\Delta t} \quad (3.5)$$

Where:

Ψ = permittivity of the GCL sample (1/s)

Index flux (q_i) is another important hydraulic conductivity parameter that was measured for each GCL sample. Index flux (q_i) is the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a GCL specimen (ASTM D 5887-09, 2010) and was calculated as follows:

$$q_i = \frac{\Delta Q}{A \Delta t} \quad (3.6)$$

Where:

q_i = index flux of the GCL sample (m^3/m^2)/s

3.4.3. Mass per Unit Area and Moisture Content Tests

3.4.3.1. Testing Method. After performing flexible wall triaxial permeability tests, mass per unit area of the bentonite in a GCL sample was determined as outlined in ASTM D 5993-99 (2009). The moisture content of the bentonite was also measured by subtracting the dry mass of the bentonite from the initial mass of the bentonite. Mass per unit area and moisture content determination tests were not conducted on the whole portion of a GCL sample. They were conducted on eight smaller portions of the GCL sample.

Mass per unit area tests were conducted on only GCL-2, GCL-3 and GCL-4. GCL-1 is a needlepunched type of geosynthetic clay liner and it is not possible to peel away the geotextiles by hand from a GCL-1 sample. The fibers that were needlepunched from the nonwoven geotextile through the bentonite and the woven geotextile prevent the top geotextile to be peeled away from GCL-1 easily.

However, moisture content measurements of a GCL-1 is possible. Eight smaller samples were taken from a GCL-1 sample by cutting the smaller samples with scissors and after oven drying, moisture contents were obtained for the smaller GCL samples. Four of these smaller samples were taken from crests on a GCL sample. Crests are topographically highest points on the surface of the GCL sample. The formation of crest points was due to the contact of a GCL sample with the voids of a coarse base beneath the GCL sample. Under higher hydraulic water heads, higher crest points were obtained on the surface of the GCL sample because higher pressure pushed the GCL sample more into the voids of the coarse base. The other four smaller samples were taken from the surface of a GCL sample where the GCL sample was in contact with the solid parts of a coarse base. These samples were taken from flat parts of the GCL sample. It is crucial not to take these smaller samples from the outer perimeter of the GCL sample. Because the exposed surfaces of the bentonite on the outer perimeter are open to atmosphere which may lead wrong moisture content values. The moisture contents obtained after oven drying were measurements not from the bentonite of a GCL-1 sample; from the whole GCL-1 sample, including both bentonite and geotextile components.

It is possible to peel away the top geotextile from the GCL sample for GCL-2, GCL-3 and GCL-3. These GCL types were not manufactured by needlepunching the nonwoven geotextile to the woven geotextile; they were manufactured by bonding woven and nonwoven geotextiles to the bentonite. After peeling away the top geotextile, eight bentonite samples were taken with a sampling tube as seen in figure 3.43. Each sampling tube was made of thin-walled steel cylinder with 7.5 mm diameter and 23 mm height as shown in figure 3.44.

Four topographically highest points on the surface of the bentonite where a GCL sample faced the voids of the base were identified as “crests” and four flat points where a GCL sample faced the solid base were identified as “flats”. Then, a sampling tube was pushed into the bentonite and then, twisted and removed to obtain small samples of bentonite at “crest” and “flat” locations as shown in figure 3.45 according to the method described by Fox et. al (1998).



Figure 3.43. Sampling mass per unit area and moisture content of a GCL-2 sample after termination of a flexible wall triaxial permeability test



Figure 3.44. Sampling tube made of thin-walled steel cylinder having 7.5 mm diameter and 23 mm height for mass per unit area and moisture content determination of the bentonite



Figure 3.45. A sampling tube with bentonite inside placed in a can

3.4.3.2. Calculations. Mass per unit area of the bentonite component of each GCL-2, GCL-3 and GCL-4 samples was calculated as outlined in ASTM D 5993-99 (2009) as follows:

$$m_b = \frac{M_b}{A_{st}} \quad (3.7)$$

$$M_b = M_{b, st, c} - M_{st, c} \quad (3.8)$$

Where:

m_b = mass per unit area of the dried bentonite component of the GCL sample (g/cm^2)

M_b = dried mass of the bentonite component of the GCL sample (g)

A_{st} = surface area of the sampling tube (cm^2) that is 0.44 cm^2 with a diameter of 0.75 cm

$M_{b, st, c}$ = dried mass of the bentonite component of the GCL sample + mass of the sampling tube + mass of the metallic can (g)

$M_{st, c}$ = mass of the sampling tube + mass of the metallic can (g)

Moisture content of the bentonite component of each GCL-2, GCL-3 and GCL-4 samples was calculated as outlined in ASTM D 5993-99 (2009) as follows:

$$w_b = \frac{M_w}{M_b} \times 100 \quad (3.9)$$

$$M_w = M_{wb} - M_b \quad (3.10)$$

$$M_{wb} = M_{wb, st, c} - M_{st, c} \quad (3.11)$$

Where:

w_b = initial moisture content of the bentonite component of the GCL sample (%)

M_w = mass of the water in the bentonite component of the GCL sample (g)

M_{wb} = initial wet mass of the bentonite component of the GCL sample (g)

$M_{wb, st, c}$ = initial wet mass of the bentonite component of the GCL sample + mass of the sampling tube + mass of the metallic can (g)

Moisture content of each GCL-2, GCL-3 and GCL-4 samples was calculated as outlined in ASTM D 5993-99 (2009) as follows:

$$w_{GCL} = \frac{M_w}{M_{GCL}} \times 100 \quad (3.12)$$

$$M_w = M_{wGCL} - M_{GCL} \quad (3.13)$$

Where:

w_{GCL} = initial moisture content of the GCL sample (%)

M_w = mass of the water in the GCL sample (g)

M_{GCL} = dried mass of the GCL sample (g)

M_{wGCL} = initial wet mass of the GCL sample (g)

4. FLEXIBLE WALL TRIAXIAL PERMEABILITY TEST RESULTS

After the termination of flexible wall triaxial permeability tests, hydraulic conductivity parameters (coefficient of permeability, permittivity and index flux) of the GCL samples were measured. High increases in hydraulic conductivity parameters were evaluated and internal erosion was detected for some of the GCL samples tested under high hydraulic heads.

Thickness of the GCL samples, mass per unit area and water content of the bentonite components of the GCL samples were also measured after the termination of triaxial permeability tests. The results of these measurements were evaluated in order to detect and investigate bentonite migration and internal erosion.

All of the results were listed and evaluated by testing GCL-1, GCL-2, GCL-3 and GCL-4 specimens under hydraulic water heads ranging from approximately 1.5 m up to 50 m.

4.1. Hydraulic Conductivity Results

4.1.1. GCL-1 Test Results

GCL-1 NW: According to the test results as shown in figures 4.1 and 4.2, lower hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 283 hours. Coefficient of permeability (k) decreased from $2,69 \times 10^{-10}$ cm/s to $8,05 \times 10^{-11}$ cm/s during 283 hour-elapsed time. Permittivity (Ψ) and index flux (q_i) values also decreased as shown in figures 4.1 and 4.2, while 50 m of hydraulic water head was being applied to GCL-1 sample for 283 hours.

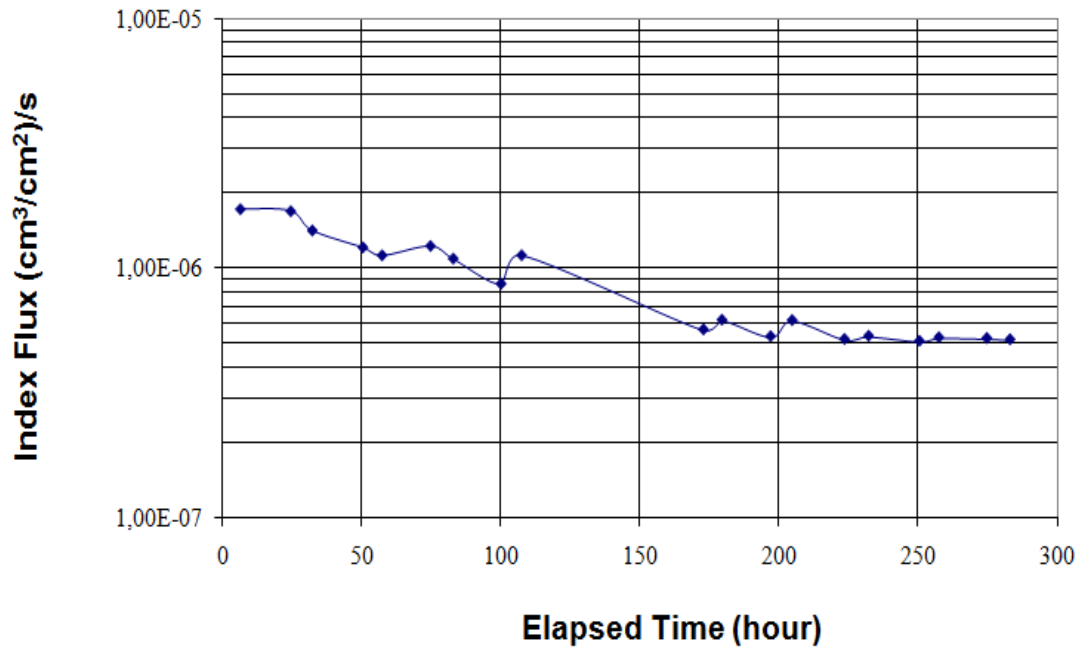


Figure 4.1. Index flux-elapsed time graph for GCL-1 NW (under 50 m of hydraulic head)

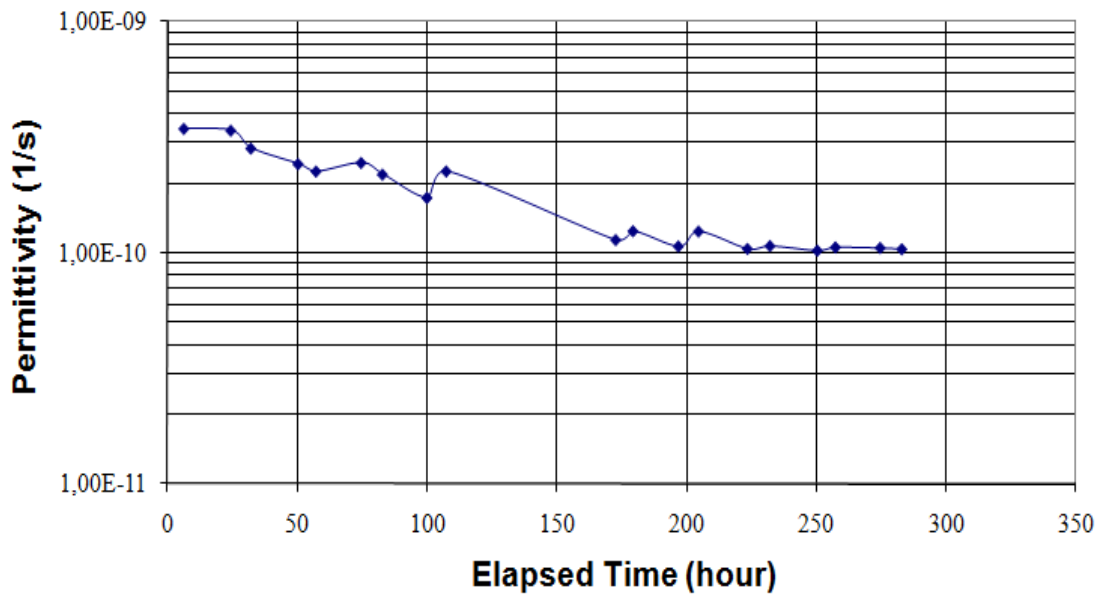


Figure 4.2. Permittivity-elapsed time graph for GCL-1 NW (under 50 m of hydraulic head)

GCL-1 W: According to the test results as shown in figures 4.3 and 4.4, lower hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 277 hours. Coefficient of permeability (k) decreased from $3,92 \times 10^{-10}$ cm/s to $9,26 \times 10^{-11}$ cm/s during 277 hour-

elapsed time. Permittivity (Ψ) and index flux (q_i) values also decreased by approximately half order of magnitude as shown in figures 4.3 and 4.4, while 50 m of hydraulic water head was being applied to GCL-1 sample for 277 hours.

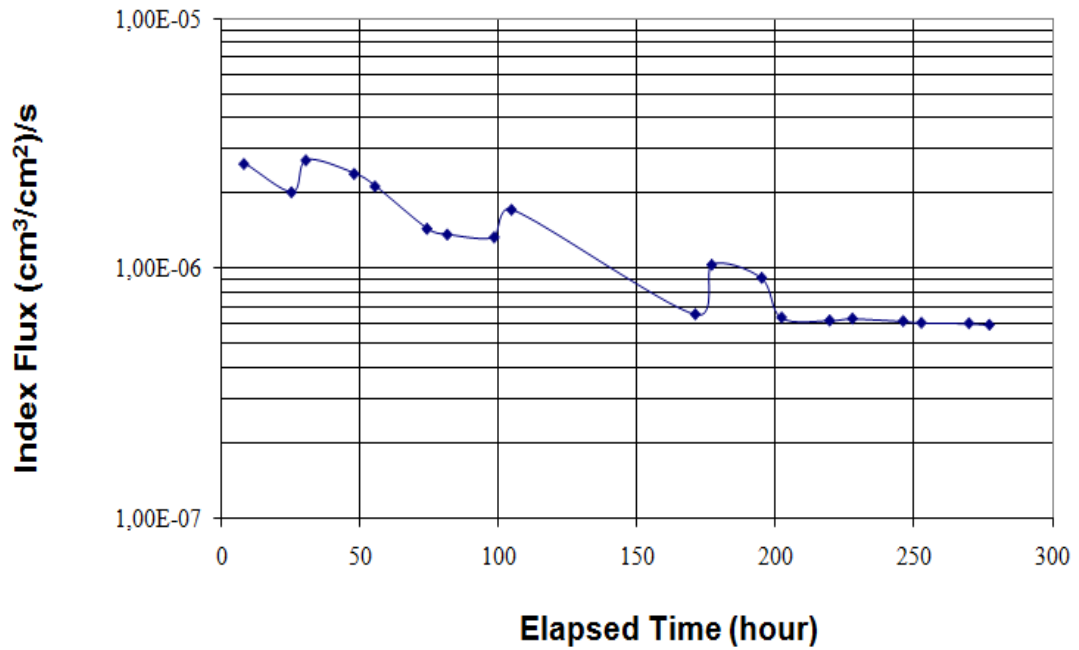


Figure 4.3. Index flux-elapsed time graph for GCL-1 W (under 50 m of hydraulic head)

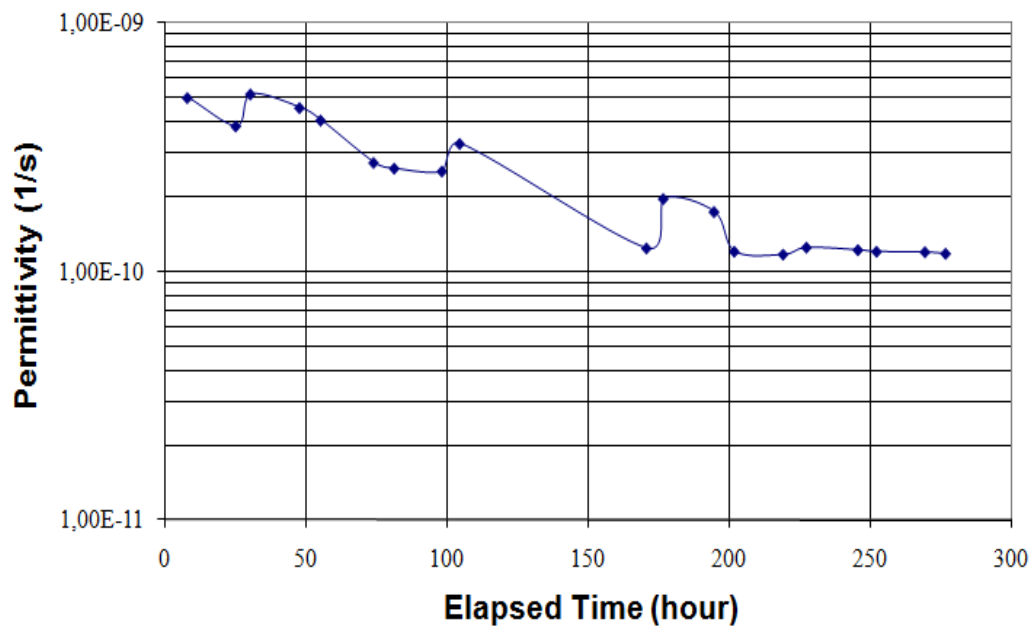


Figure 4.4. Permittivity-elapsed time graph for GCL-1 W (under 50 m of hydraulic head)

GCL-1-NW-D2: According to the test results as shown in figures 4.6 and 4.7, hydraulic conductivity parameters began to increase after about 175-190 hours from the start of the test under 35 m hydraulic head. This increase continued to approximately 220 elapsed time and then, a sudden and much higher increase in hydraulic conductivity was measured at about 1-2 hours. This sudden increase was higher than two and a half orders of magnitude for coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values.

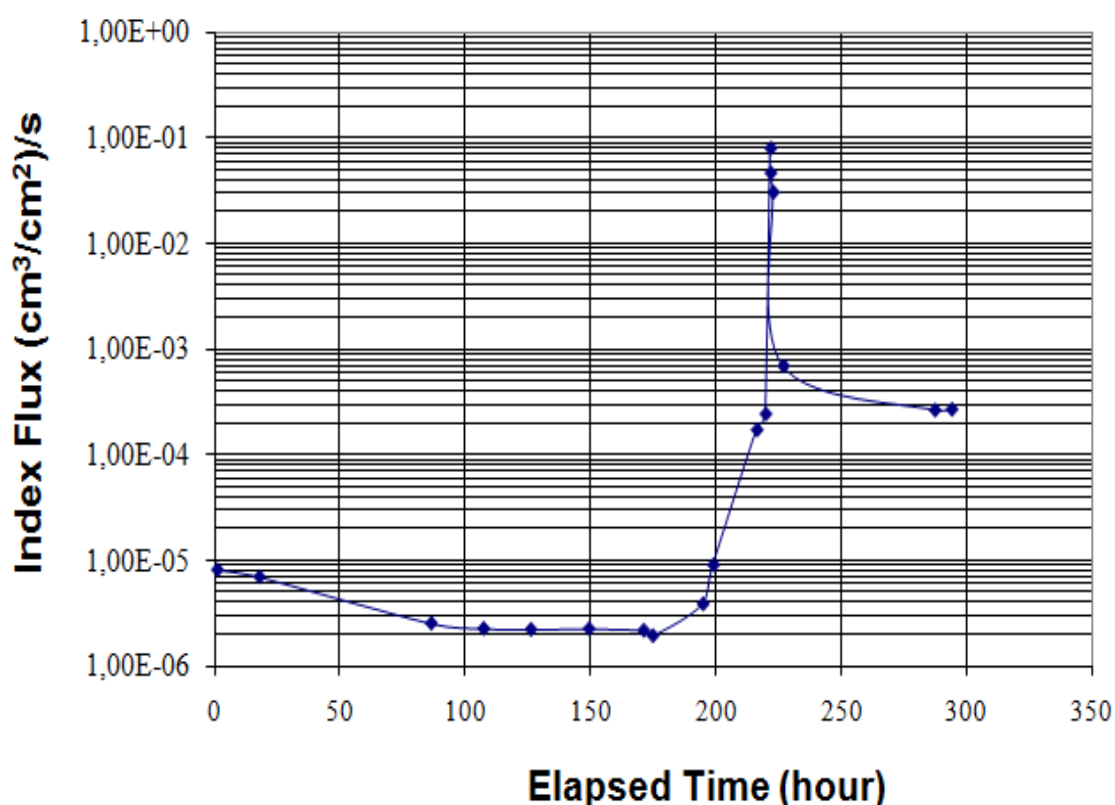


Figure 4.5. Index flux-elapsed time graph for GCL-1-NW-D2 (under 35 m of hydraulic head; elapsed time after the clogging of the test apparatus was taken into consideration)

From the start to the 222 hour-elapsed time, approximately four orders of magnitude of increase was measured for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from 2×10^{-9} cm/s to $1,99 \times 10^{-5}$ cm/s, permittivity (Ψ) increased from $2,3 \times 10^{-9}$ 1/s to $2,29 \times 10^{-5}$ 1/s and index flux (q_i) increased from $8,1 \times 10^{-6}$ cm³/cm²/s to 8×10^{-2} cm³/cm²/s.

However, a sudden decrease of about two orders of magnitude in hydraulic conductivity parameters were measured in a couple of hours. Then, these parameters

remained almost stable until the end of the test. This sudden decrease in hydraulic conductivity was due to the clogging of the voids of the base pedestal. The migrated bentonite from the GCL sample was observed to accumulate on the nonwoven geotextile (120 NW) that was used instead of filter paper beneath the base. At first, the migrated bentonite was transferred through the voids of 120 NW to the effluent burette assemble but there was a critical time when this transfer ceased and the cumulation of the bentonite particles beneath the base and on 120 NW began. After this cumulation, water transfer through the GCL sample was reduced due to this blocking. Both of the results were shown in figures 4.5 and 4.6. In figure 4.5, index flux (q_i) decreased after about 222 hours from the start and in figure 4.6, index flux (q_i) increased up to $8,0 \times 10^{-2} \text{ cm}^3/\text{cm}^2/\text{s}$ at about 222 hours from the start and the test was terminated at this stage with high increases in hydraulic conductivity parameters.

These lower hydraulic conductivity parameters were not true permeability values of the GCL in reality. Therefore, for the other permability tests reported in this thesis, the portion of the measurement after the maximum permeability value was measured was not shown in figures and was not given in tables. The results with the decreases in hydraulic conductivity parameters due to the clogging of the voids of the base pedestal did not represent the real situation and were not taken into consideration for the other permeability tests in this study.

As shown in figure 4.8, high amount of bentonite migration occurred from the openings of the crest zones on the nonwoven geotextile component of GCL-1-NW-D2 sample. The crests were formed where the GCL sample was pressed into the voids of the base under 35 m of hydraulic head. Most of the high increase in hydraulic conductivity was due to this bentonite loss. The nonwoven geotextile used in this thesis (N1) is more flexible than the woven geoetextile (W1) which caused N1 to withstand more against high hydraulic heads than W1.

In this thesis, most of the bentonite loss was due to the vertical bentonite extrusion through the openings of the lower geotextile which got larger under high hydraulic heads and through the damaged fibres and slit flim tapes on the geotextiles.

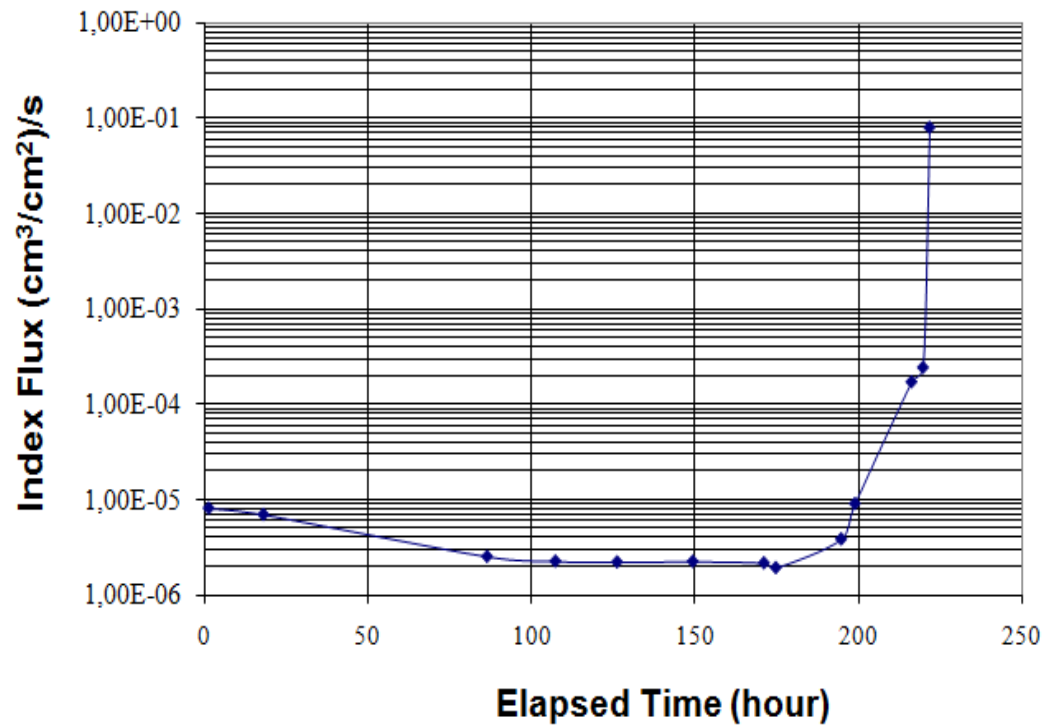


Figure 4.6. Index flux-elapsed time graph for GCL-1-NW-D2 (under 35 m of hydraulic head)

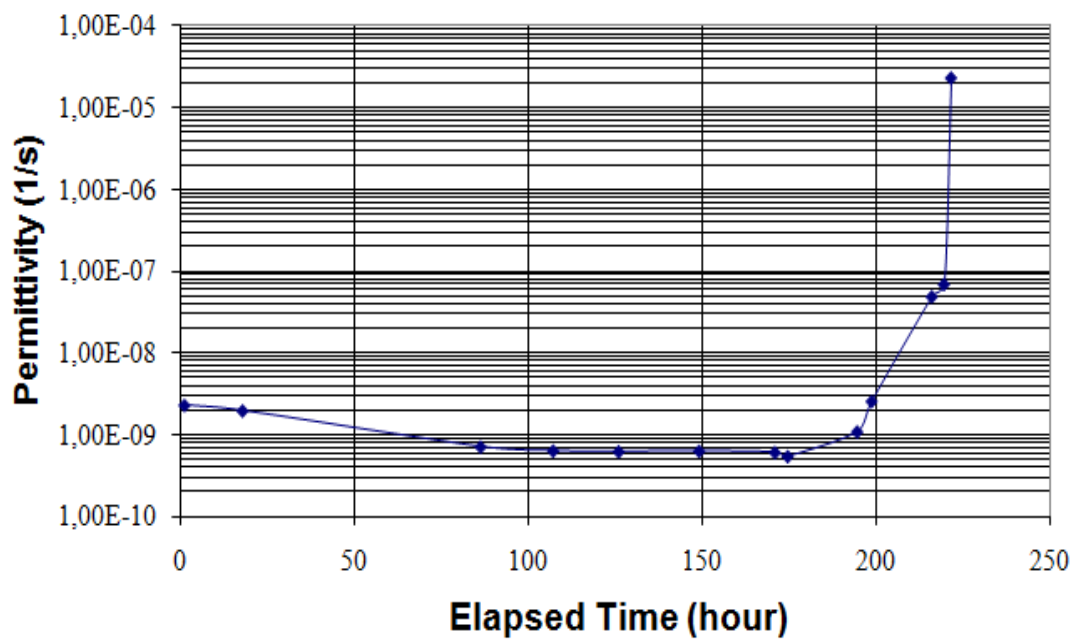


Figure 4.7. Permittivity-elapsed time graph for GCL-1-NW-D2 (under 35 m of hydraulic head)

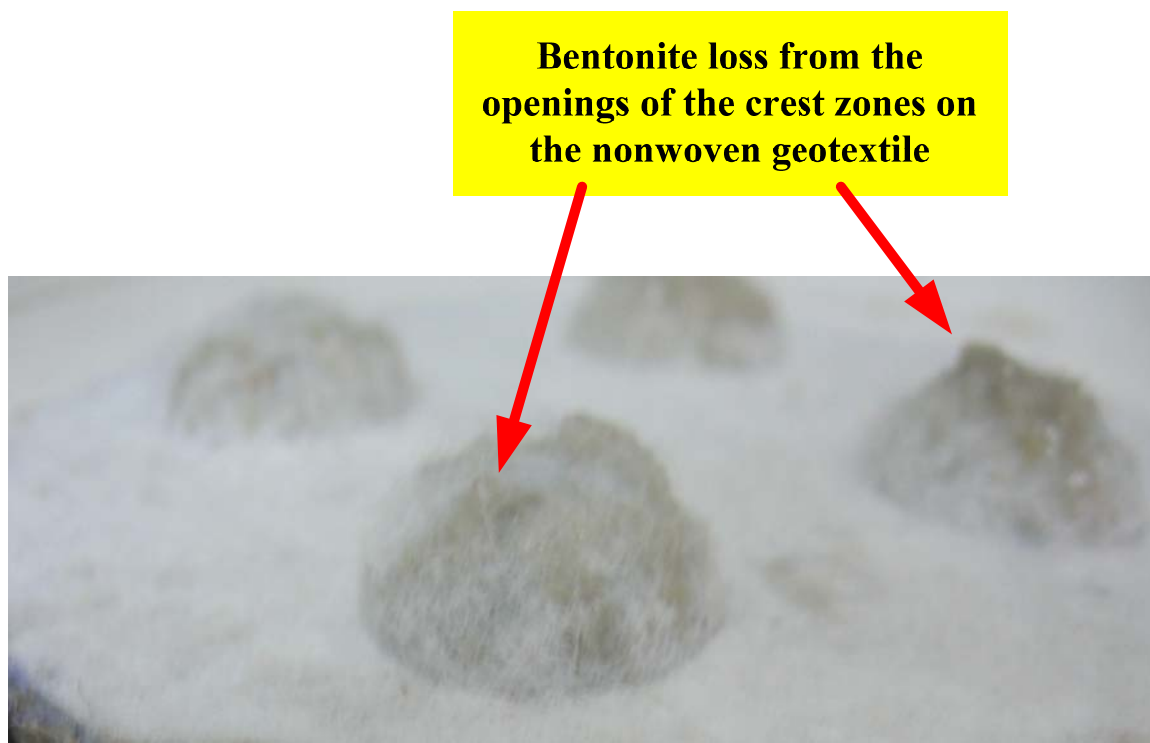


Figure 4.8. GCL-1-NW-D2 sample after the termination of the flexible wall triaxial permeability test

GCL-1-W-D2: According to the test results as shown in figures 4.9 and 4.10, hydraulic conductivity parameters began to increase after about 115-120 hours from the start of the test under 30 m hydraulic head. This increase slightly continued to approximately 220-230 elapsed time and then, a sudden and much higher increase in hydraulic conductivity occurred in about 20 hours. This sudden increase was higher than approximately three orders of magnitude for coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values.

From the start to the 247 hour-elapsed time, more than four orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $8,6 \times 10^{-10}$ cm/s to $1,9 \times 10^{-5}$ cm/s, permittivity (Ψ) increased from 1×10^{-9} 1/s to $2,3 \times 10^{-5}$ 1/s and index flux (q_i) increased from $3,2 \times 10^{-6}$ cm³/cm²/s to $6,8 \times 10^{-2}$ cm³/cm²/s.

In figure 4.9, index flux (q_i) increased up to $6,8 \times 10^{-2} \text{ cm}^3/\text{cm}^2/\text{s}$ at about 247 hours from the start and the test was terminated at this stage with high increases in hydraulic conductivity parameters.

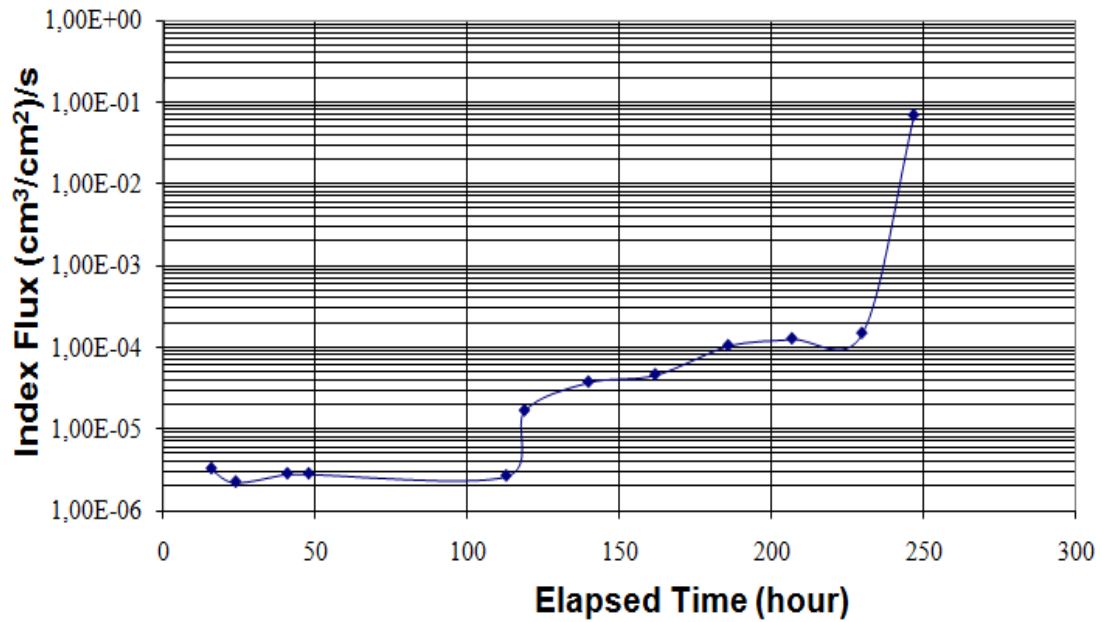


Figure 4.9. Index flux-elapsed time graph for GCL-1-W-D2 (under 30 m of hydraulic head)

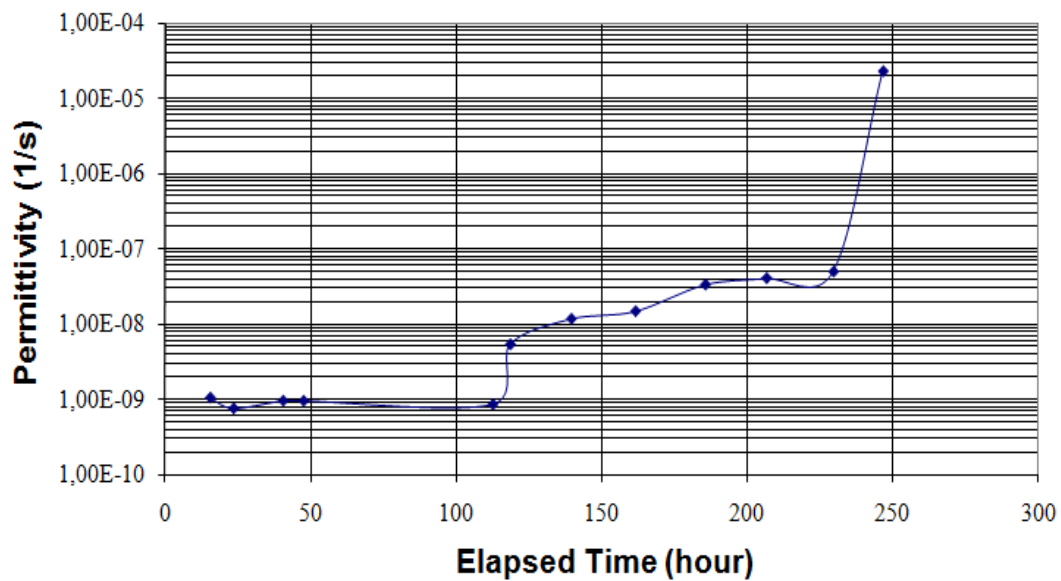


Figure 4.10. Permittivity-elapsed time graph for GCL-1-W-D2 (under 30 m of hydraulic head)



Figure 4.11. GCL-1-W-D2 sample after the termination of the flexible wall triaxial permeability test

As shown in figure 4.11, high amount of bentonite loss occurred from the openings of the crest zones on the woven geotextile component of GCL-1-W-D2. Most of the high increase in hydraulic conductivity was due to this bentonite loss. Some of the slit film tapes of the woven geotextile on the crest zones were damaged and needlepunched fibres were torn as shown in figure 4.11. Bentonite particles might have easily been removed out through these damaged zones.

W1 is more rigid than N1 and it was easier for W1 to be damaged and to let much more water pass through its openings than for N1. When the slit film tapes of a woven geotextile are damaged, loss of bentonite from the openings between the slit film tapes becomes easier and this may also create a preferential flow path when a sufficient amount of bentonite migrates out of the GCL sample.

GCL-1-NW-D1.5: According to the test results as shown in figures 4.12 and 4.13, low hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 288 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were $2,34 \times 10^{-10}$ cm/s, $3,04 \times 10^{-10}$ 1/s and $1,6 \times 10^{-6}$ cm³/cm²/s, respectively at the end of 288 hour-elapsed time. These results show that neither any high amount of bentonite migration from the

GCL-1-NW-D1.5 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 288 hours.

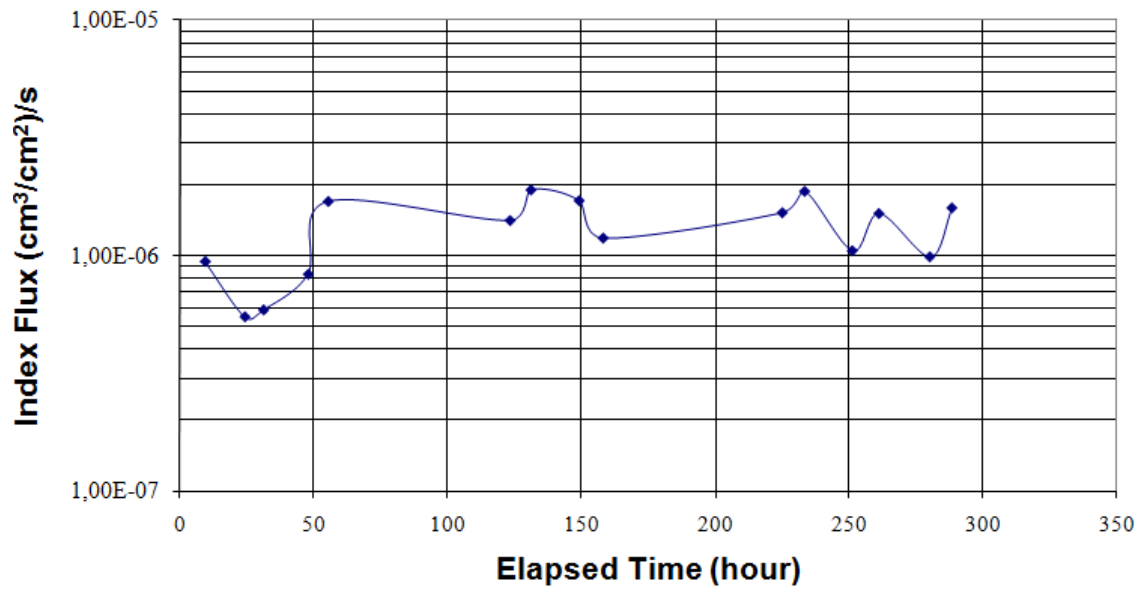


Figure 4.12. Index flux-elapsed time graph for GCL-1-NW-D1.5 (under 50 m of hydraulic head)

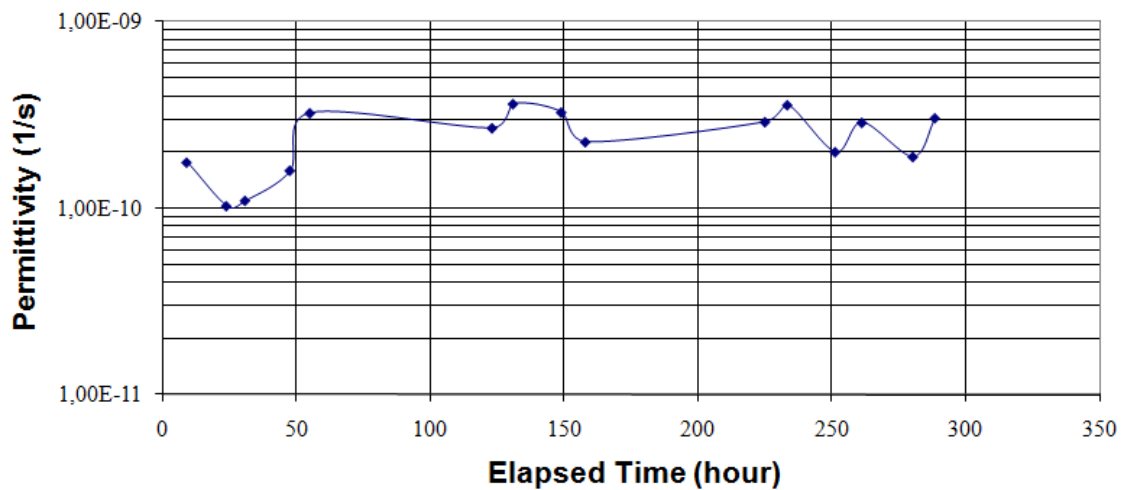


Figure 4.13. Permittivity-elapsed time graph for GCL-1-NW-D1.5 (under 50 m of hydraulic head)

Not any considerable amount of bentonite loss was observed from the openings of the crest zones on GCL-1-NW-D1.5 sample as shown in figure 4.14. Low hydraulic

conductivity values measured at the end of the permeability test also support this observation.



Figure 4.14. GCL-1-NW-D1.5 sample after the termination of the flexible wall triaxial permeability test

GCL-1-W-D1.5: According to the test results as shown in figures 4.15 and 4.16, hydraulic conductivity parameters began to increase after about 100-105 hours from the start of the test under 45 m hydraulic head. This increase continued to approximately 144 elapsed time and then, a sudden and much higher increase in the hydraulic conductivity parameters occurred in about 1-2 hours. This sudden increase was higher than two orders of magnitude for coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values.

From the start to the 144 hour-elapsed time, approximately four and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $7,3 \times 10^{-10}$ cm/s to $2,2 \times 10^{-5}$ cm/s, permittivity (Ψ) increased from $9,7 \times 10^{-10}$ 1/s to 3×10^{-5} 1/s and index flux (q_i) increased from $4,9 \times 10^{-6}$ cm³/cm²/s to $1,4 \times 10^{-1}$ cm³/cm²/s.

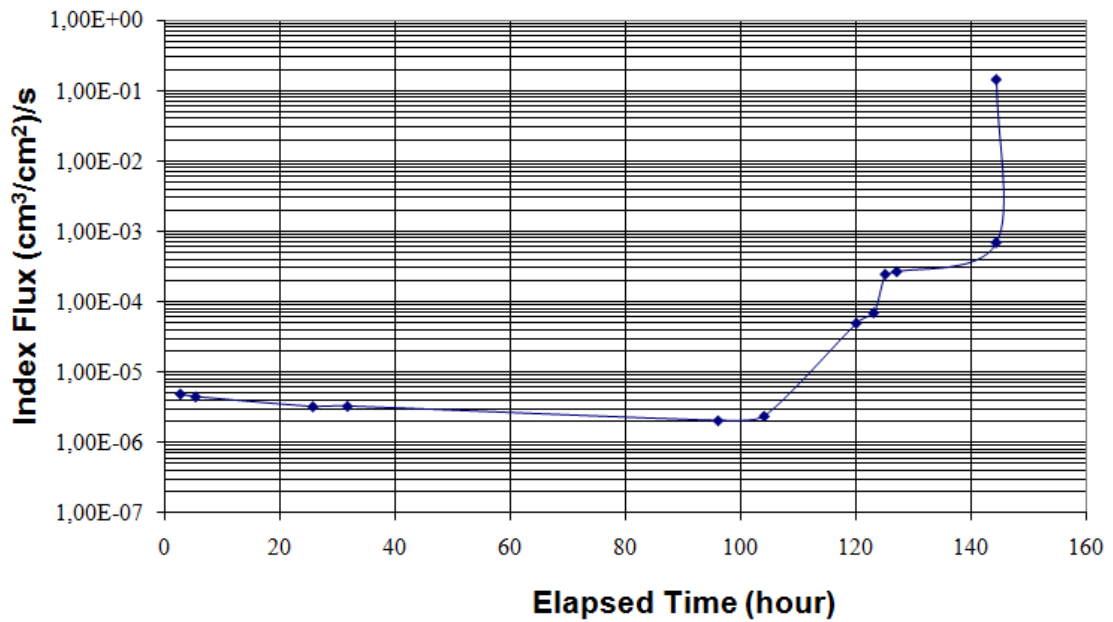


Figure 4.15. Index flux-elapsed time graph for GCL-1-W-D1.5 (under 45 m of hydraulic head)

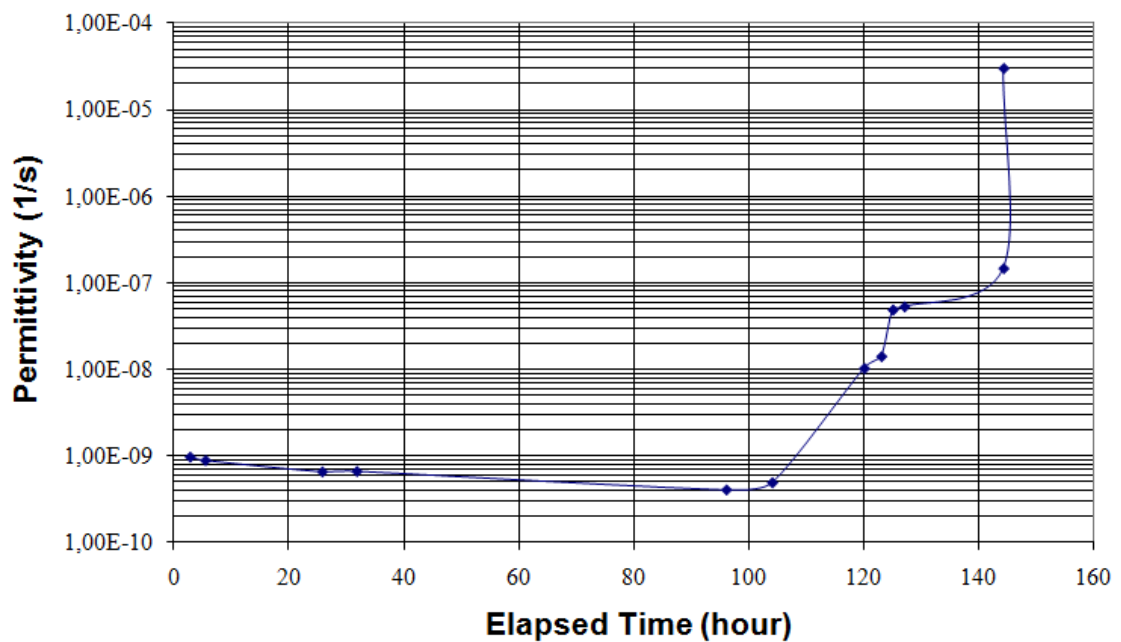


Figure 4.16. Permittivity-elapsed time graph for GCL-1-W-D1.5 (under 45 m of hydraulic head)

GCL-1-NW-D1: According to the test results as shown in figures 4.17 and 4.18, low hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 311 hours. Coefficient

of permeability (k), permittivity (Ψ) and index flux (q_i) values were $6,47 \times 10^{-11}$ cm/s, $9,95 \times 10^{-11}$ 1/s and $4,98 \times 10^{-7}$ cm³/cm²/s, respectively at the end of 311 hour-elapsed time.

These results show that neither any high amount of bentonite migration from the GCL-1-NW-D1 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 311 hours.

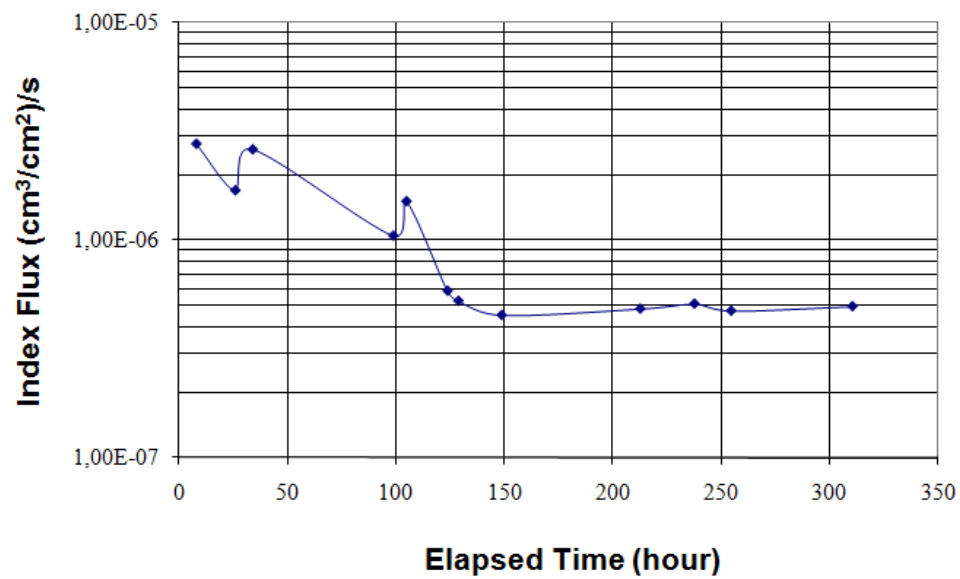


Figure 4.17. Index flux-elapsed time graph for GCL-1-NW-D1 (under 50 m of hydraulic head)

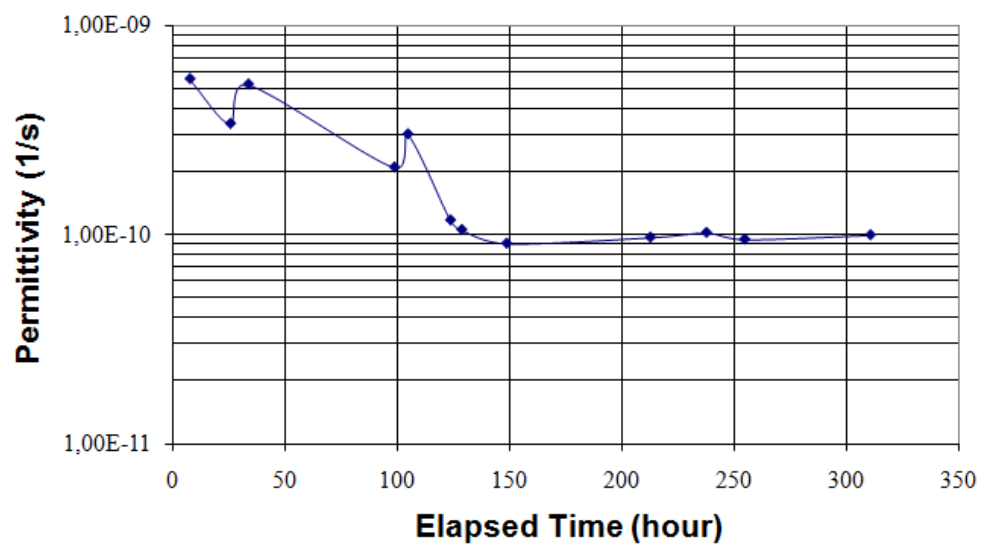


Figure 4.18. Permittivity-elapsed time graph for GCL-1-NW-D1 (under 50 m of hydraulic head)

GCL-1-W-D1: According to the test results as shown in figures 4.19 and 4.20, low hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 317 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were $8,99 \times 10^{-11}$ cm/s, $1,32 \times 10^{-10}$ 1/s and $6,61 \times 10^{-7}$ cm³/cm²/s, respectively at the end of 317 hour-elapsed time.

These results show that neither any high amount of bentonite migration from the GCL-1-W-D1 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 317 hours.

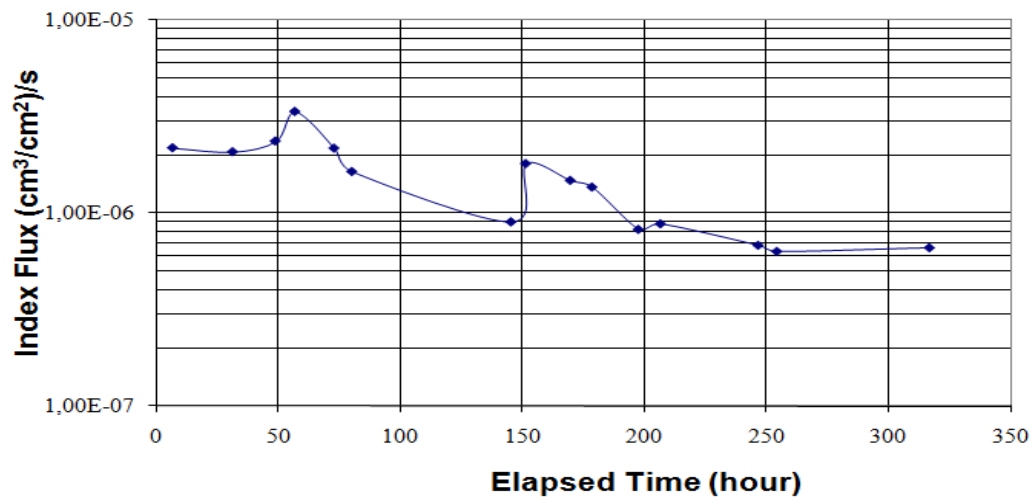


Figure 4.19. Index flux-elapsed time graph for GCL-1-W-D1 (under 50 m of hydraulic head)

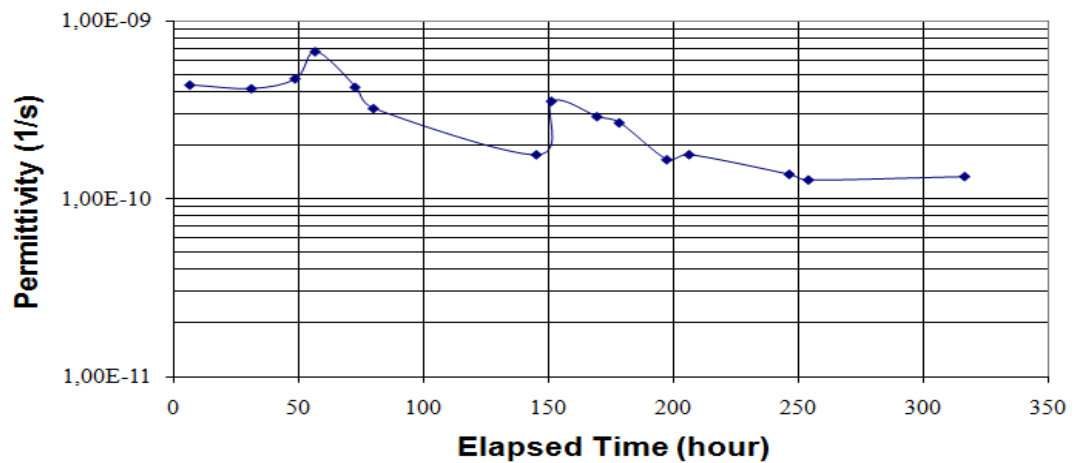


Figure 4.20. Permittivity-elapsed time graph for GCL-1-W-D1 (under 50 m of hydraulic head)

4.1.2. GCL-2 Test Results

GCL-2 NW: According to the test results as shown in figures 4.21 and 4.22, lower hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 289 hours. Coefficient of permeability (k) decreased from $2,58 \times 10^{-10}$ cm/s to $9,44 \times 10^{-11}$ cm/s during 289 hour-elapsed time. Permittivity (Ψ) and index flux (q_i) values also decreased as shown in figures 4.21 and 4.22, while 50 m of hydraulic water head was being applied to GCL-2 sample for 289 hours.

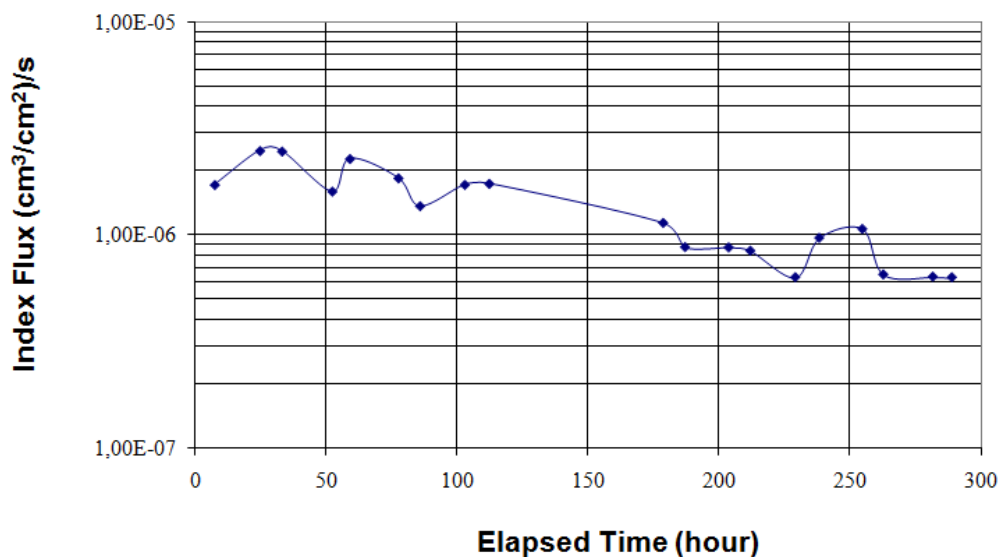


Figure 4.21. Index flux-elapsed time graph for GCL-2 NW (under 50 m of hydraulic head)

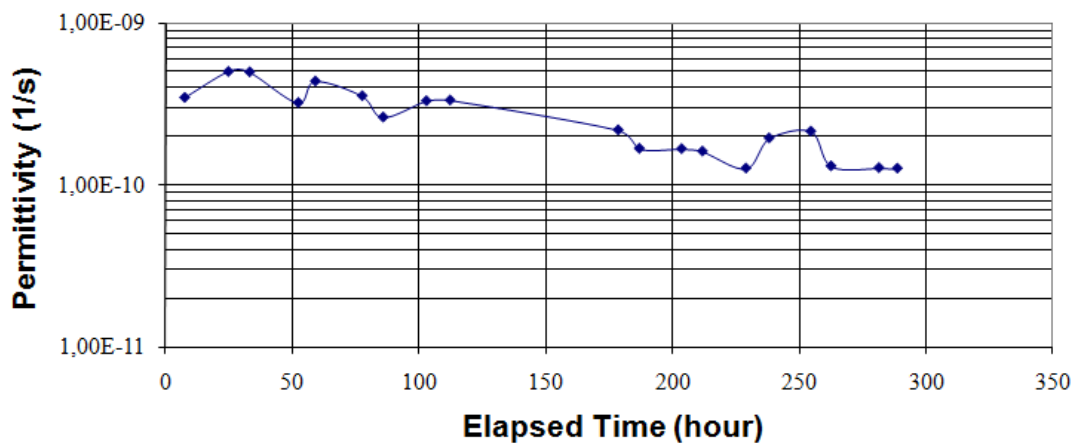


Figure 4.22. Permittivity-elapsed time graph for GCL-2 NW (under 50 m of hydraulic head)

GCL-2 W: According to the test results as shown in figures 4.23 and 4.24, lower hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 300 hours. Coefficient of permeability (k) decreased from $5,54 \times 10^{-10}$ cm/s to $1,69 \times 10^{-10}$ cm/s during 300 hour-elapsed time. Permittivity (Ψ) and index flux (q_i) values also decreased as shown in figures 4.23 and 4.24, while 50 m of hydraulic water head was being applied to GCL-2 sample for 300 hours.

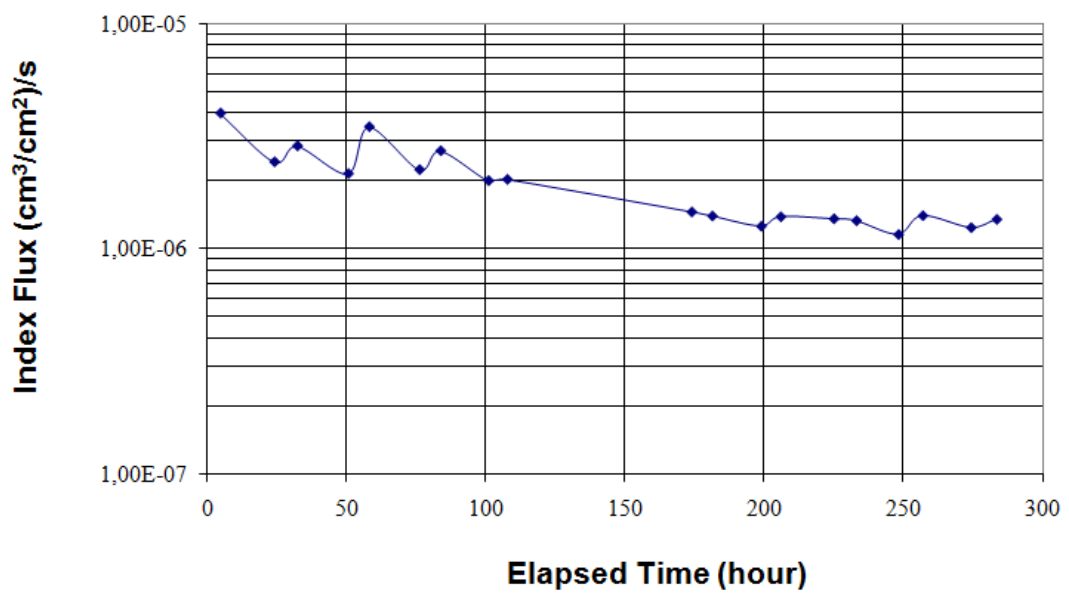


Figure 4.23. Index flux-elapsed time graph for GCL-2 W (under 50 m of hydraulic head)

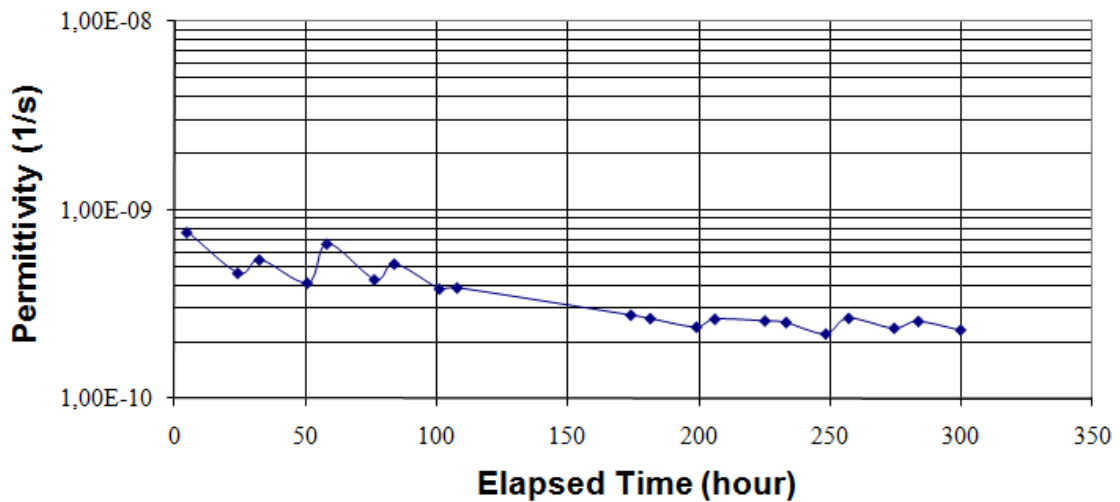


Figure 4.24. Permittivity-elapsed time graph for GCL-2 W (under 50 m of hydraulic head)

GCL-2-NW-D2: According to the test results as shown in figures 4.25 and 4.26, hydraulic conductivity parameters began to increase after about 220 hours from the start of the test under 20 m hydraulic head. This increase continued to 317 hours elapsed time. This sudden increase was approximately three orders of magnitude for coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values.

From the start to the 317 hour-elapsed time, more than three and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $2,0 \times 10^{-9}$ cm/s to $8,7 \times 10^{-6}$ cm/s, permittivity (Ψ) increased from $2,9 \times 10^{-9}$ 1/s to $1,3 \times 10^{-5}$ 1/s and index flux (q_i) increased from $6,6 \times 10^{-6}$ cm³/cm²/s to $4,6 \times 10^{-2}$ cm³/cm²/s.

GCL-2-W-D2: According to the test results as shown in figures 4.27 and 4.28, hydraulic conductivity parameters began to increase after about 165-170 hours from the start of the test under 10 m hydraulic head. This increase continued to 208 hours elapsed time.

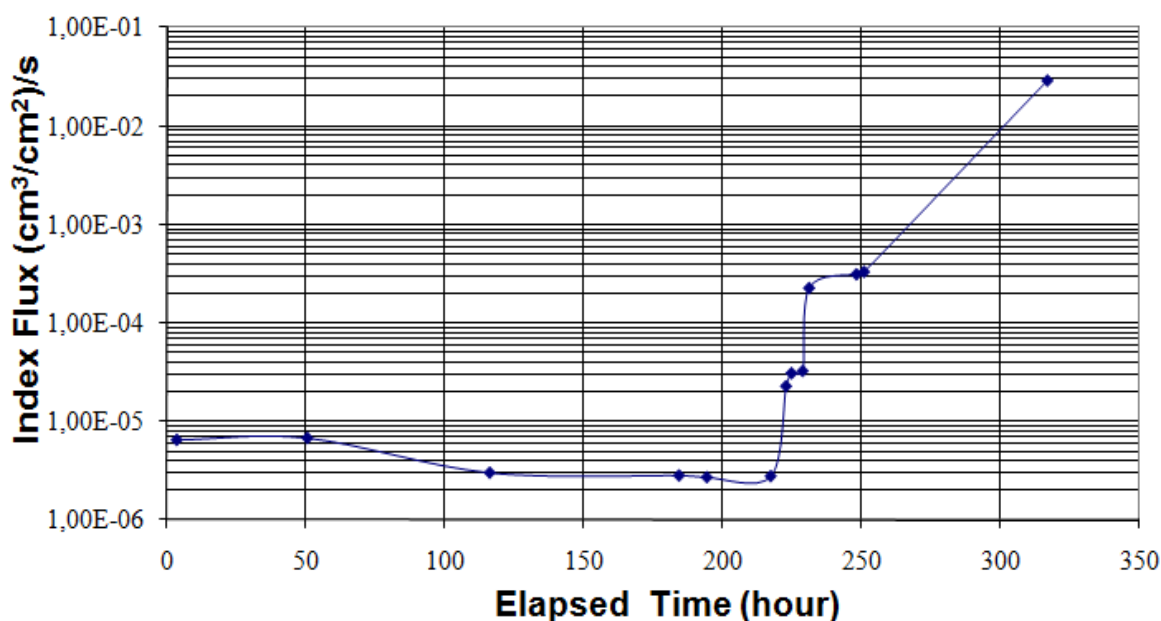


Figure 4.25. Index flux-elapsed time graph for GCL-2-NW-D2 (under 20 m of hydraulic head)

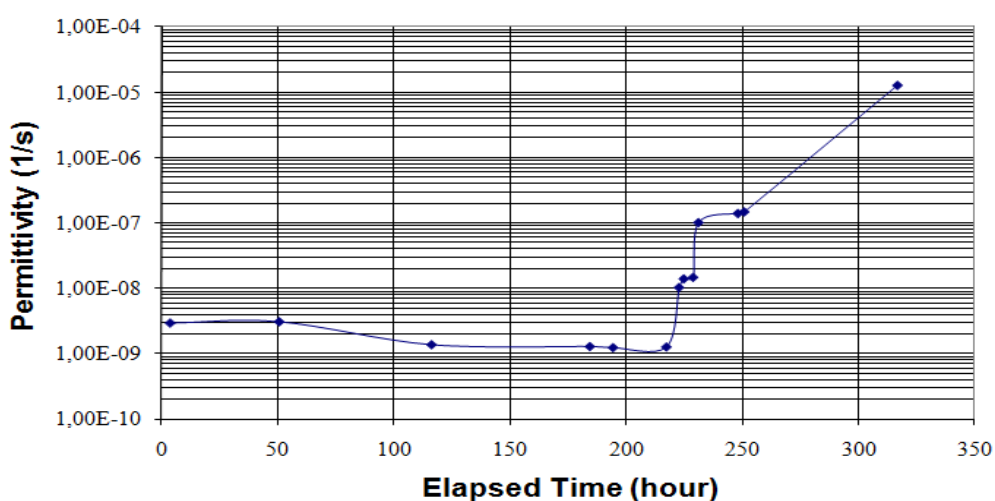


Figure 4.26. Permittivity-elapsed time graph for GCL-2-NW-D2 (under 20 m of hydraulic head)

From the start to the 208 hour-elapsed time, almost four orders of magnitude of increase was measured for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $2,8 \times 10^{-9}$ cm/s to $3,5 \times 10^{-5}$ cm/s, permittivity (Ψ) increased from $3,5 \times 10^{-9}$ 1/s to $4,3 \times 10^{-5}$ 1/s and index flux (q_i) increased from $3,7 \times 10^{-6}$ cm³/cm²/s to $4,6 \times 10^{-2}$ cm³/cm²/s.

High amount of vertical bentonite extrusion occurred from the large openings of the crest zones as shown in figure 4.29. These large openings were due to the damaged slit film tapes of the woven geotextile.

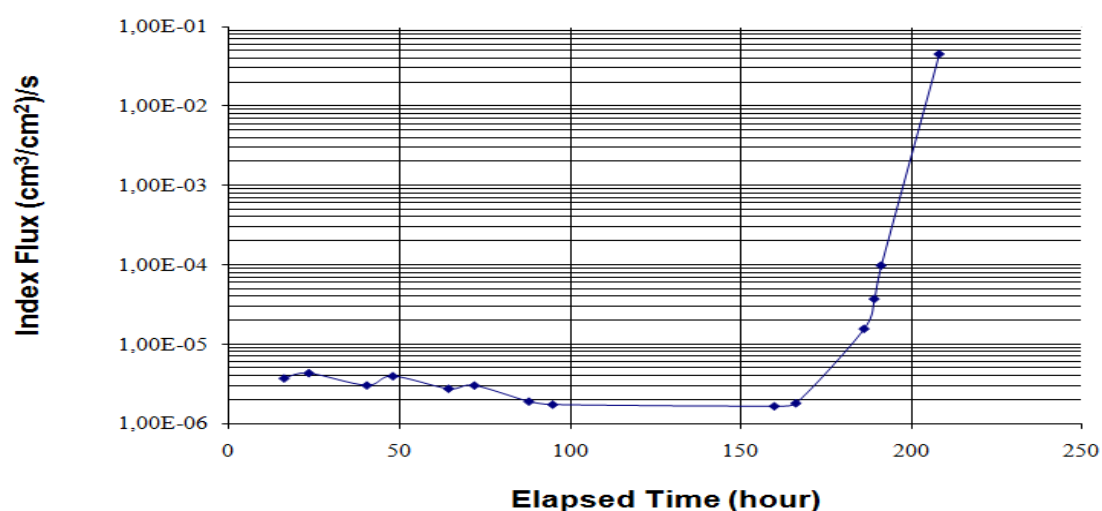


Figure 4.27. Index flux-elapsed time graph for GCL-2-W-D2 (under 10 m of hydraulic head)

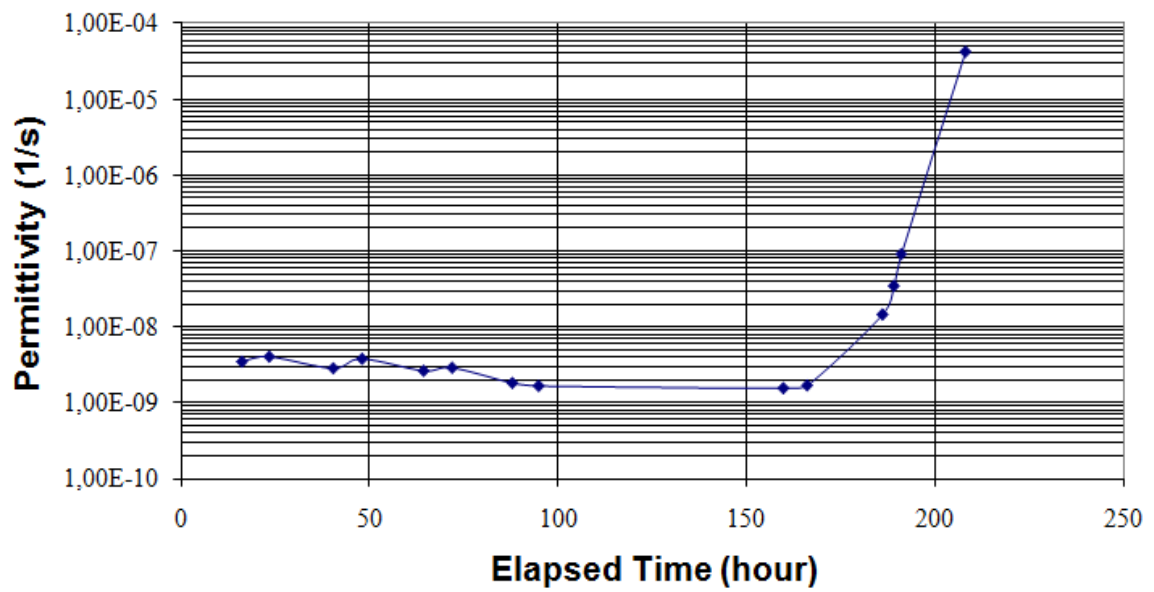


Figure 4.28. Permittivity-elapsed time graph for GCL-2-W-D2 (under 10 m of hydraulic head)

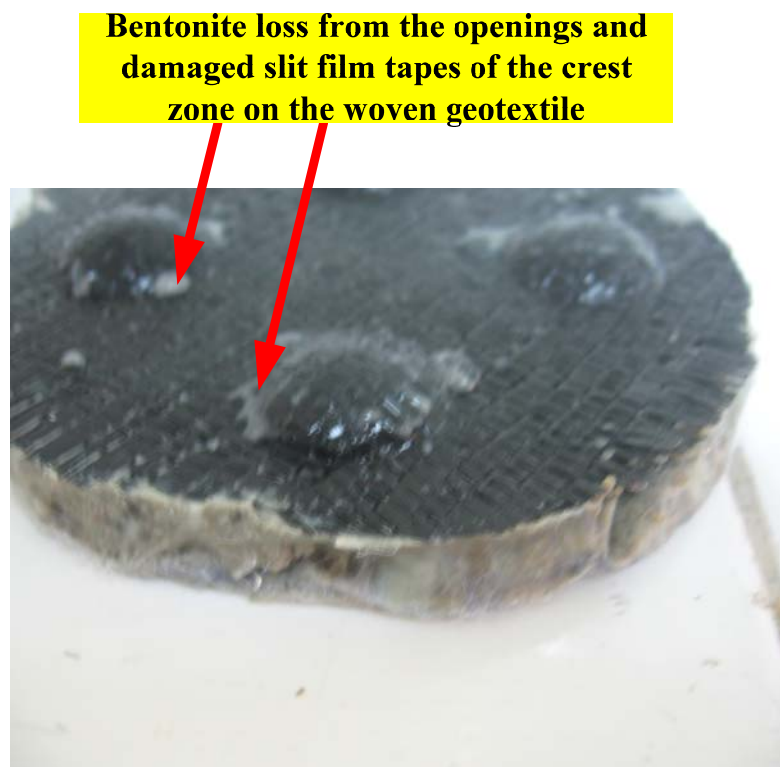


Figure. 4.29. GCL-2-W-D2 sample after the termination of the flexible wall triaxial permeability test

GCL-2-NW-D1.5: According to the test results as shown in figures 4.30 and 4.31, hydraulic conductivity parameters began to increase after about 200-205 hours from the start of the test under 35 m hydraulic head. This increase continued to 250-253 hours elapsed time. Then, a sudden increase in hydraulic conductivity was measured at 253 hours elapsed time.

From the start to the 253 hour-elapsed time, almost four orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $9,2 \times 10^{-10}$ cm/s to $9,3 \times 10^{-6}$ cm/s, permittivity (Ψ) increased from $1,4 \times 10^{-9}$ 1/s to $1,4 \times 10^{-5}$ 1/s and index flux (q_i) increased from $4,6 \times 10^{-6}$ cm³/cm²/s to $4,9 \times 10^{-2}$ cm³/cm²/s.

High increase in hydraulic conductivity was due to the high amount of bentonite migration from the crest zones of the nonwoven geotextile as shown in figure 4.32.

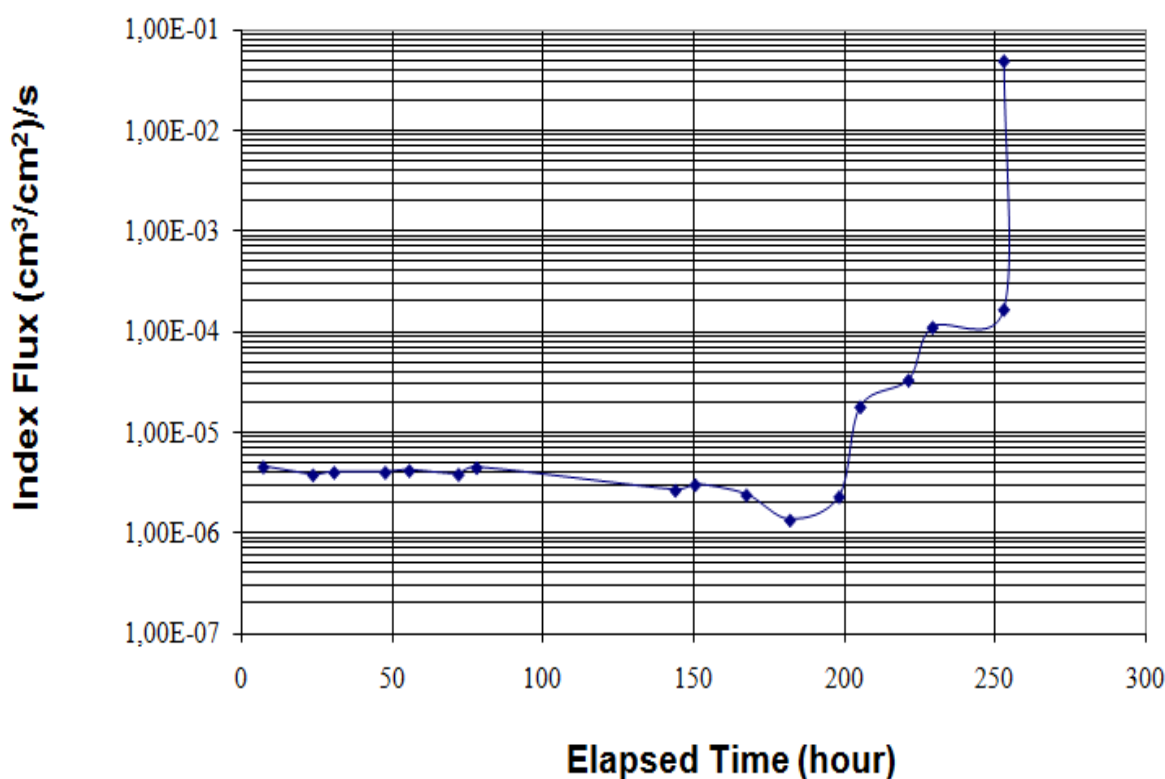


Figure 4.30. Index flux-elapsed time graph for GCL-2-NW-D1.5 (under 35 m of hydraulic head)

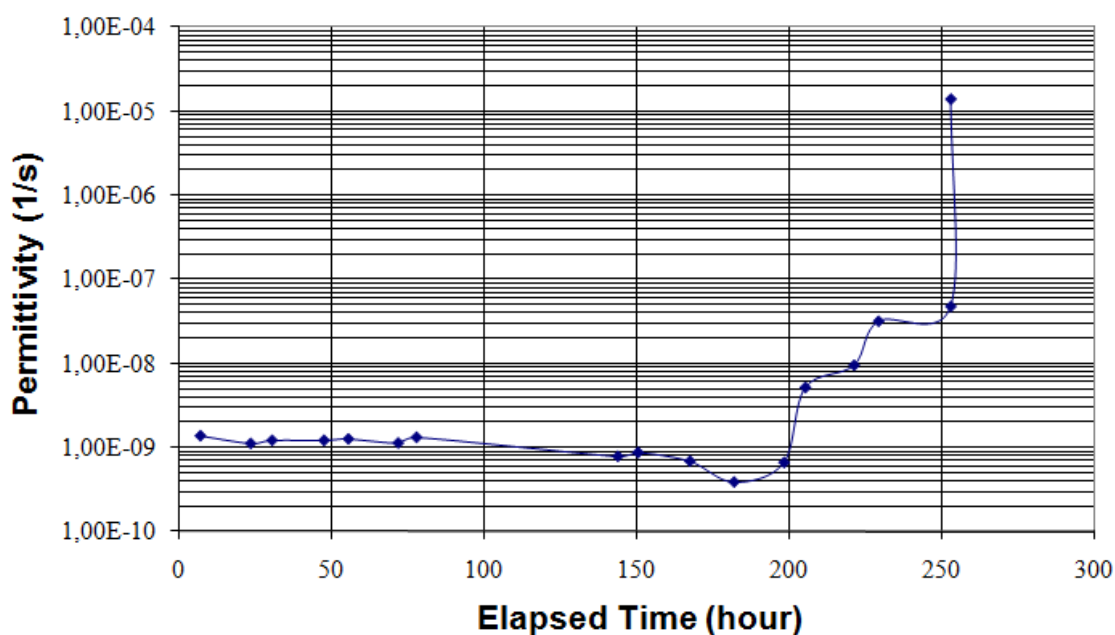


Figure 4.31. Permittivity-elapsed time graph for GCL-2-NW-D1.5 (under 35 m of hydraulic head)



Figure 4.32. GCL-2-NW-D1.5 sample after the termination of the flexible wall triaxial permeability test

GCL-2-W-D1.5: According to the test results as shown in figures 4.34 and 4.35, hydraulic conductivity parameters began to increase after about 130-135 hours from the start of the test under 15 m hydraulic head. This increase continued to 169 hours elapsed

time. Then, a sudden increase in hydraulic conductivity was measured up to 177 hours elapsed time.

From the start to the 177 hour-elapsed time, more than three orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $5,4 \times 10^{-9}$ cm/s to $9,4 \times 10^{-6}$ cm/s, permittivity (Ψ) increased from $7,3 \times 10^{-9}$ 1/s to $1,3 \times 10^{-5}$ 1/s and index flux (q_i) increased from $1,3 \times 10^{-5}$ cm³/cm²/s to $2,2 \times 10^{-2}$ cm³/cm²/s.

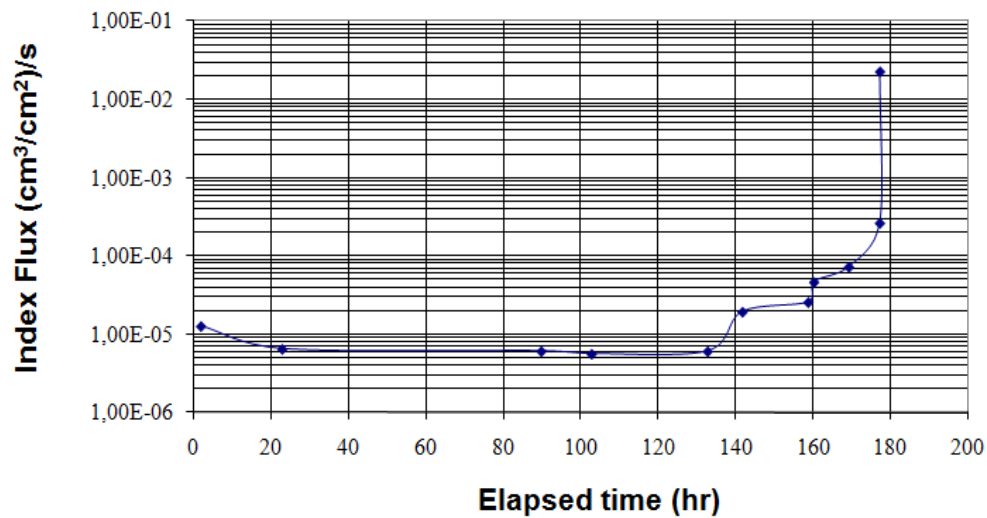


Figure 4.34. Index flux-elapsed time graph for GCL-2-W-D1.5 (under 15 m of hydraulic head)

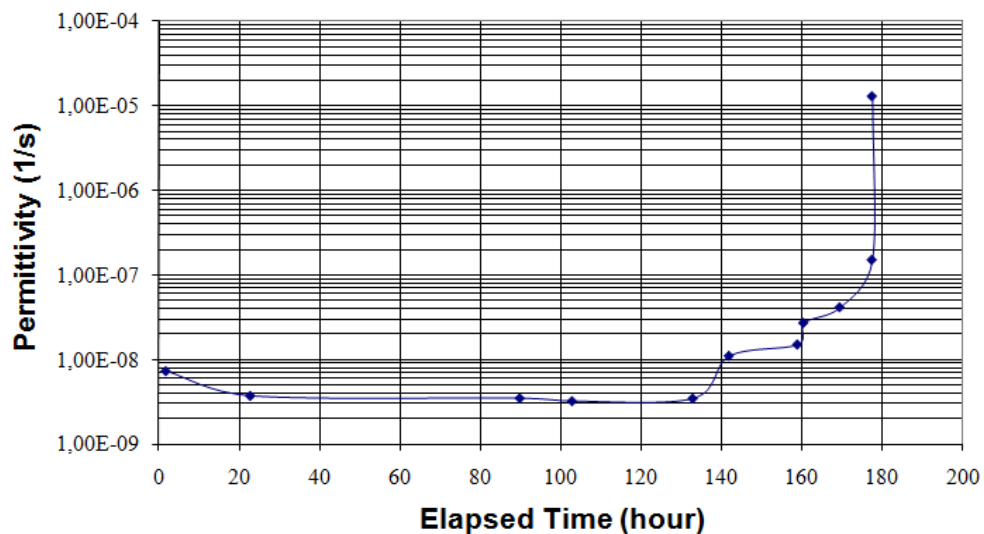


Figure 4.35. Permittivity-elapsed time graph for GCL-2-W-D1.5 (under 15 m of hydraulic head)

GCL-2-NW-D1: According to the test results as shown in figures 4.36 and 4.37, hydraulic conductivity parameters began to increase after about 95-100 hours from the start of the test under 50 m hydraulic head. This increase continued to almost 265 hours elapsed time. Then, a sudden, higher increase in hydraulic conductivity parameters took place between 265-280 hours.

From the start to the 280 hour-elapsed time, more than four and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $3,4 \times 10^{-10}$ cm/s to 1×10^{-5} cm/s, permittivity (Ψ) increased from $4,9 \times 10^{-10}$ 1/s to $1,4 \times 10^{-5}$ 1/s and index flux (q_i) increased from $2,4 \times 10^{-6}$ cm³/cm²/s to $7,2 \times 10^{-2}$ cm³/cm²/s.

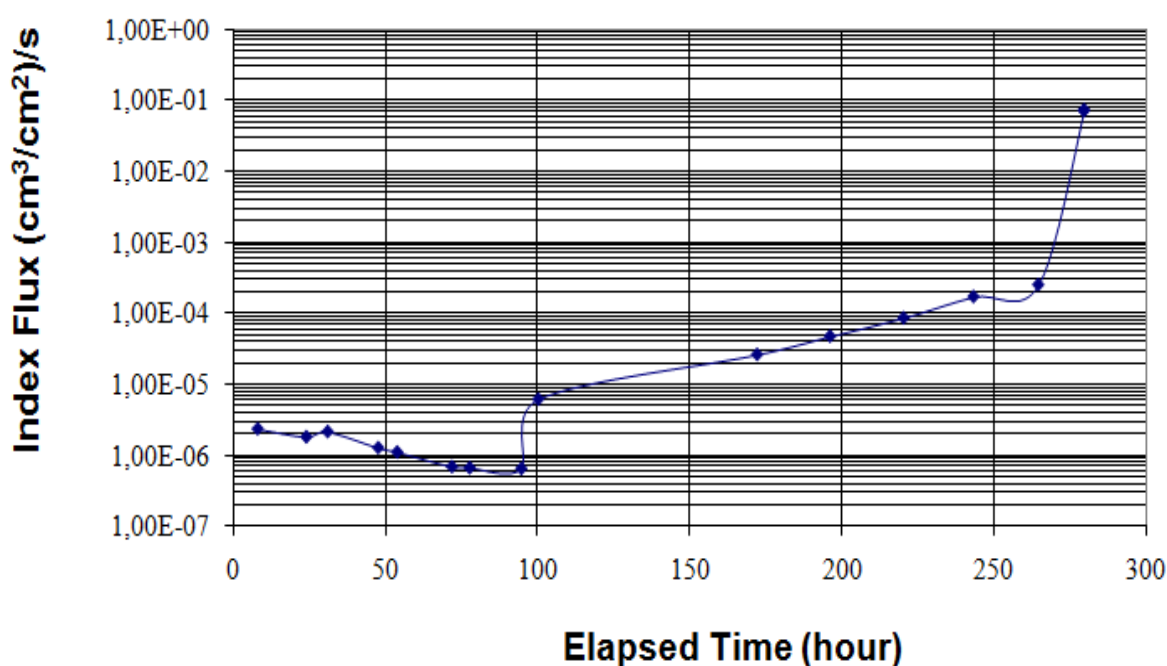


Figure 4.36. Index flux-elapsed time graph for GCL-2-NW-D1 (under 50 m of hydraulic head)

GCL-2-W-D1: According to the test results as shown in figures 4.38 and 4.39, hydraulic conductivity parameters began to increase after about 180-185 hours from the start of the test under 30 m hydraulic head. This increase continued to 226 hours elapsed time.

From the start to the 226 hour-elapsed time, almost four and a half orders of magnitude of increase was measured for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $5,5 \times 10^{-10}$ cm/s to $1,9 \times 10^{-5}$ cm/s, permittivity (Ψ) increased from $7,8 \times 10^{-10}$ 1/s to $2,7 \times 10^{-5}$ 1/s and index flux (q_i) increased from $2,3 \times 10^{-6}$ cm³/cm²/s to 8×10^{-2} cm³/cm²/s.

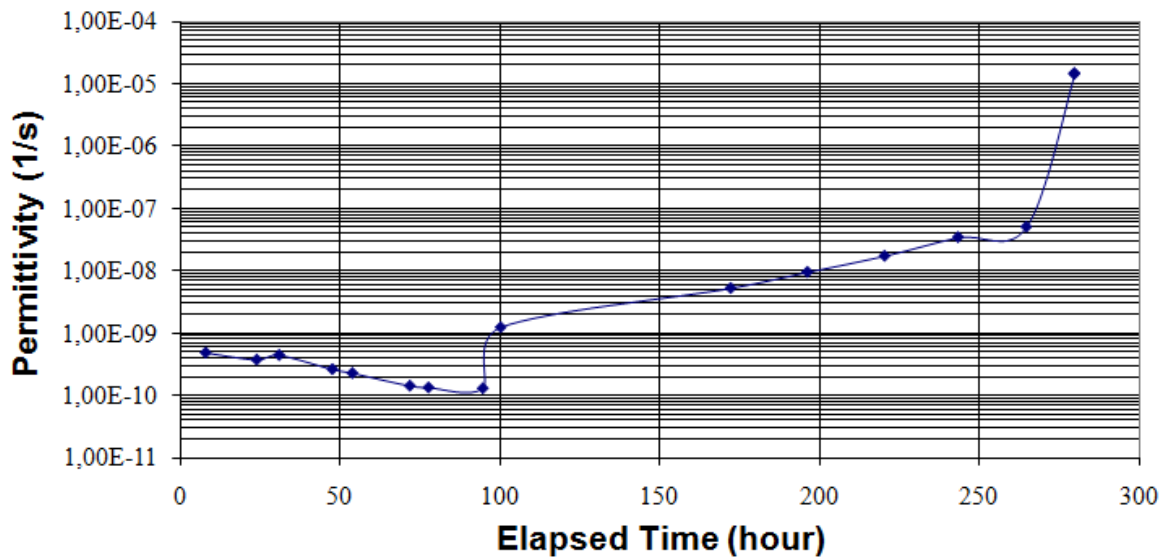


Figure 4.37. Permittivity-elapsed time graph for GCL-2-NW-D1 (under 50 m of hydraulic head)

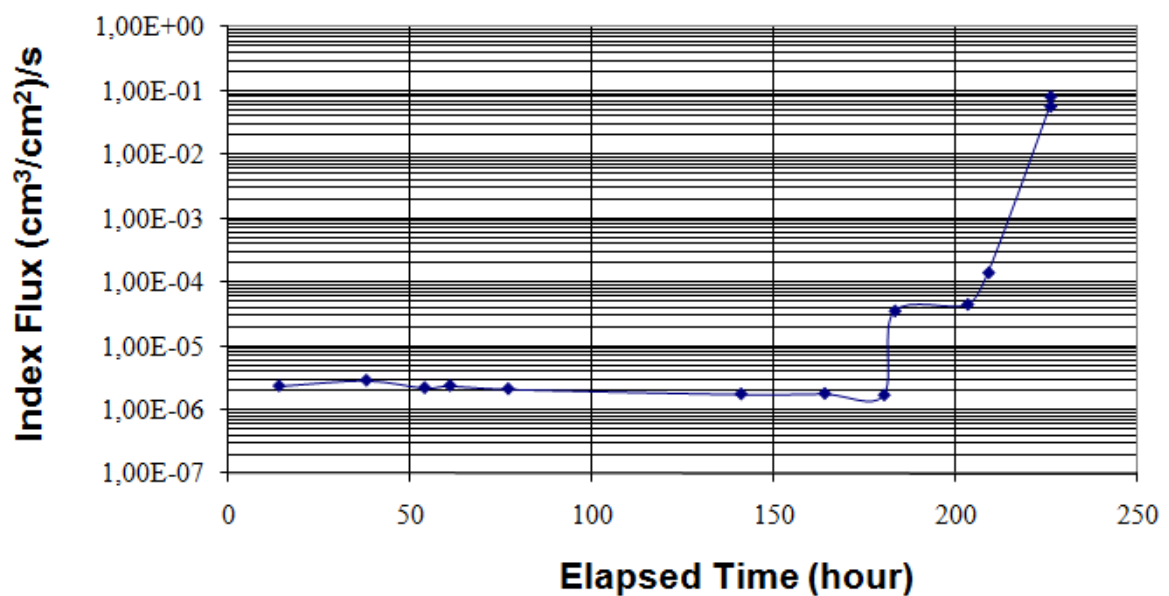


Figure 4.38. Index flux-elapsed time graph for GCL-2-W-D1 (under 30 m of hydraulic head)

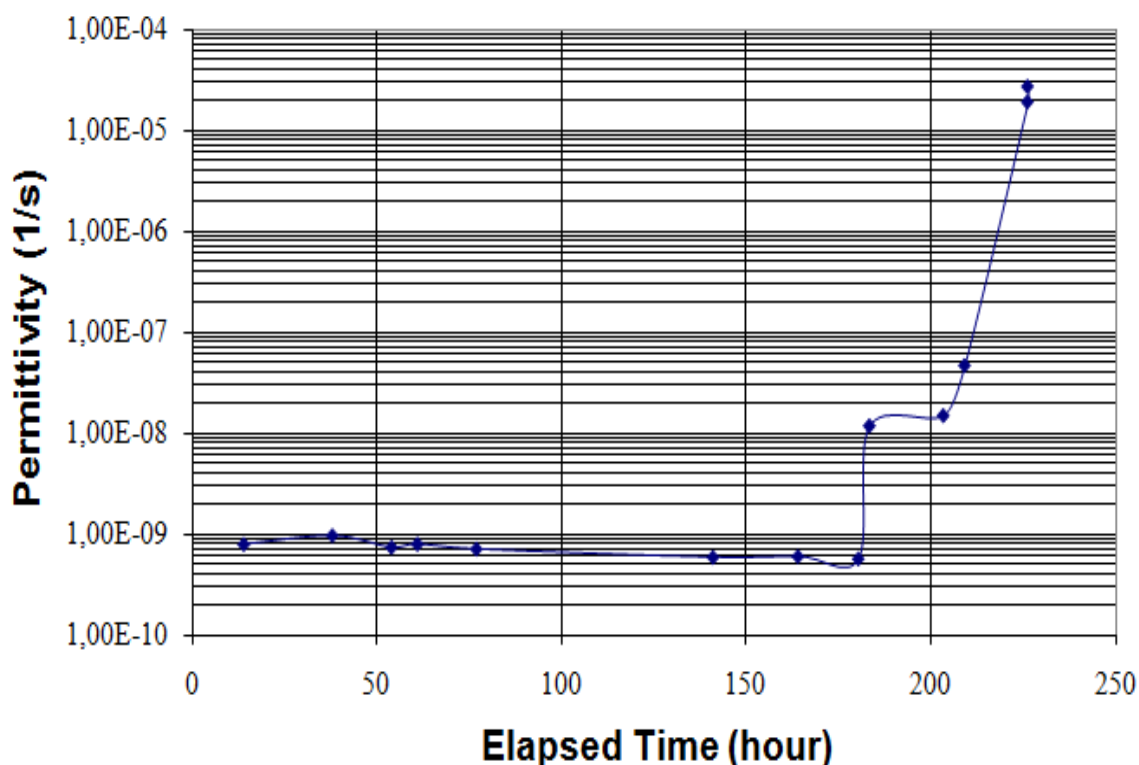


Figure 4.39. Permittivity-elapsed time graph for GCL-2-W-D1 (under 30 m of hydraulic head)

GCL-2-NW-D0.5: According to the test results as shown in figures 4.40 and 4.41, low hydraulic conductivity parameters were obtained at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 316 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were $2,6 \times 10^{-11}$ cm/s, 4×10^{-11} 1/s and 2×10^{-7} cm³/cm²/s, respectively at the end of 316 hour-elapsed time.

These results show that neither any high amount of bentonite migration from the GCL-2-NW-D0.5 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 316 hours.

Not any considerable amount of bentonite loss was observed from the GCL-2-NW-D0.5 sample as shown in figure 4.42. Low hydraulic conductivity values obtained at the end of the permeability test also support this observation.

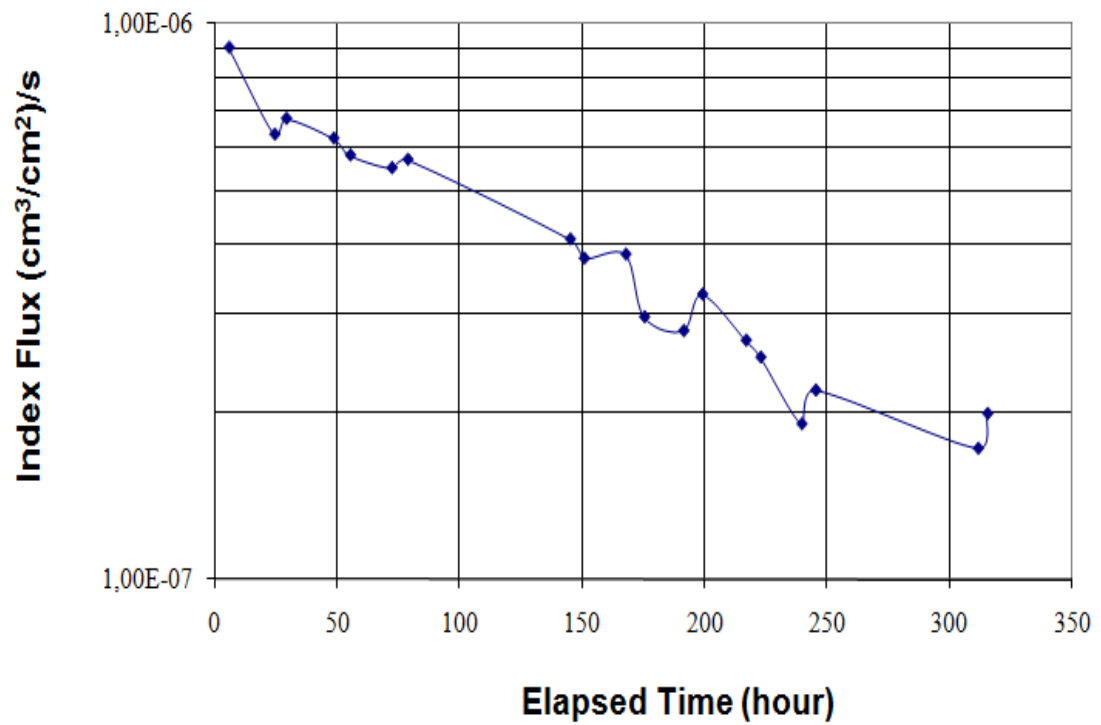


Figure 4.40. Index flux-elapsed time graph for GCL-2-NW-D0.5 (under 50 m of hydraulic head)

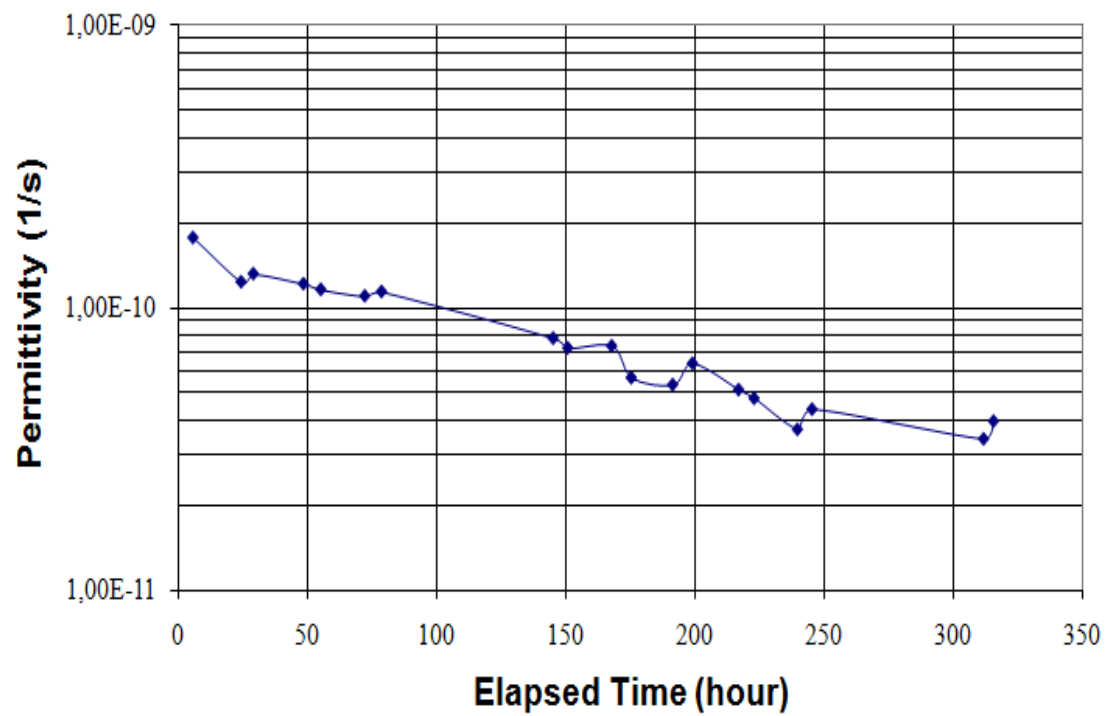


Figure 4.41. Permittivity-elapsed time graph for GCL-2-NW-D0.5 (under 50 m of hydraulic head)



Figure 4.42. GCL-2-NW-D0.5 sample after the termination of the flexible wall triaxial permeability test

GCL-2-W-D0.5: According to the test results as shown in figures 4.43 and 4.44, low hydraulic conductivity parameters were obtained at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 297 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were 7×10^{-11} cm/s, 1×10^{-10} 1/s and $5,4 \times 10^{-7}$ cm³/cm²/s, respectively at the end of 297 hour-elapsed time.

These results show that neither any high amount of bentonite migration from the GCL-2-W-D0.5 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 297 hours.

Not any considerable amount of bentonite loss was observed from the GCL-2-W-D0.5 sample as shown in figure 4.45. Low hydraulic conductivity values obtained at the end of the permeability test also support this observation.

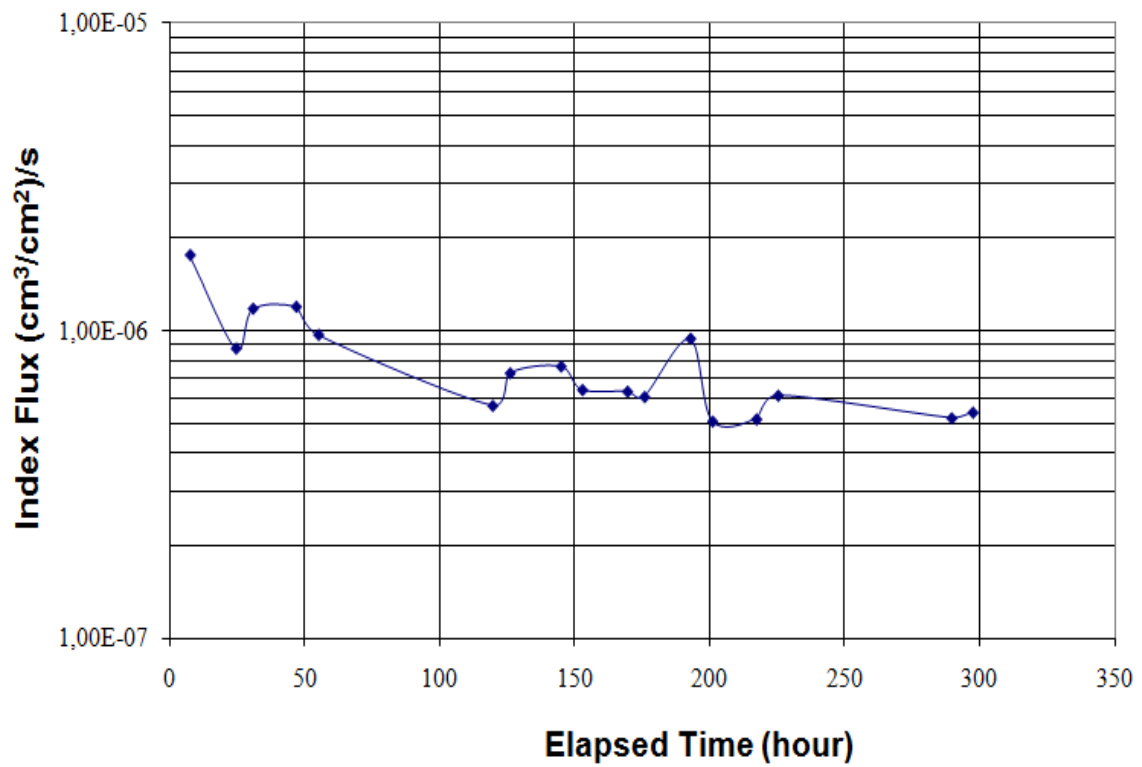


Figure 4.43. Index flux-elapsed time graph for GCL-2-W-D0.5 (under 50 m of hydraulic head)

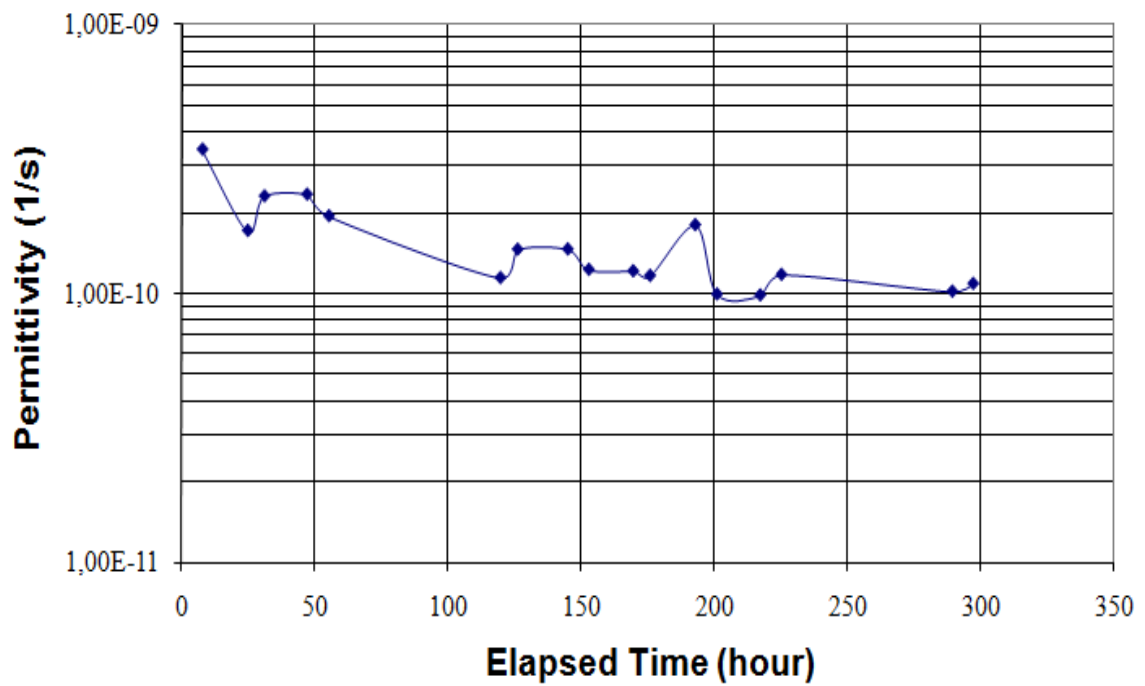


Figure 4.44. Permittivity-elapsed time graph for GCL-2-W-D0.5 (under 50 m of hydraulic head)

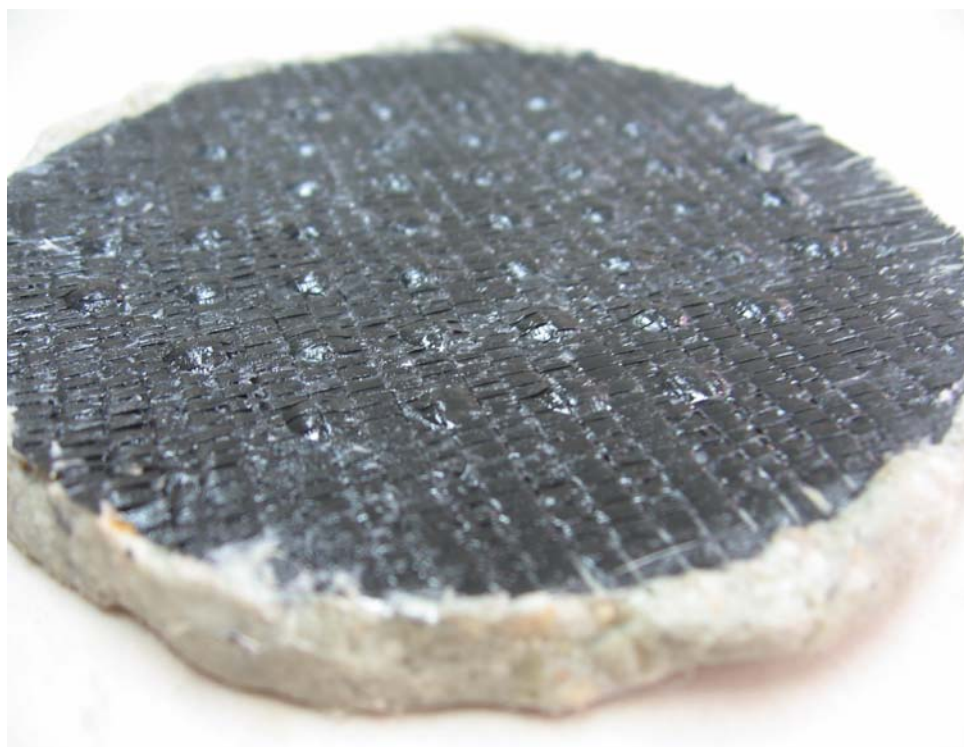


Figure 4.45. GCL-2-W-D0.5 sample after the termination of the flexible wall triaxial permeability test

4.1.3. GCL-3 Test Results

GCL-3 NW: According to the test results as shown in figures 4.46 and 4.47, low hydraulic conductivity parameters were obtained at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 295 hours. Coefficient of permeability (k) decreased from $3,2 \times 10^{-9}$ cm/s to $8,9 \times 10^{-10}$ cm/s during 295 hour-elapsed time. Permittivity (Ψ) and index flux (q_i) values also decreased as shown in figures 4.46 and 4.47, while 50 m of hydraulic water head was being applied to GCL-3 sample for 295 hours.

When the coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values obtained from GCL-2 W and GCL-2 NW are compared with those obtained from GCL-3 W and GCL-3 NW, the parameters for GCL-3 samples are almost an order of magnitude higher than those for GCL-2 samples. This result is because of the higher hydraulic conductivity of calcium bentonite (CB) than that of sodium bentonite (SB).

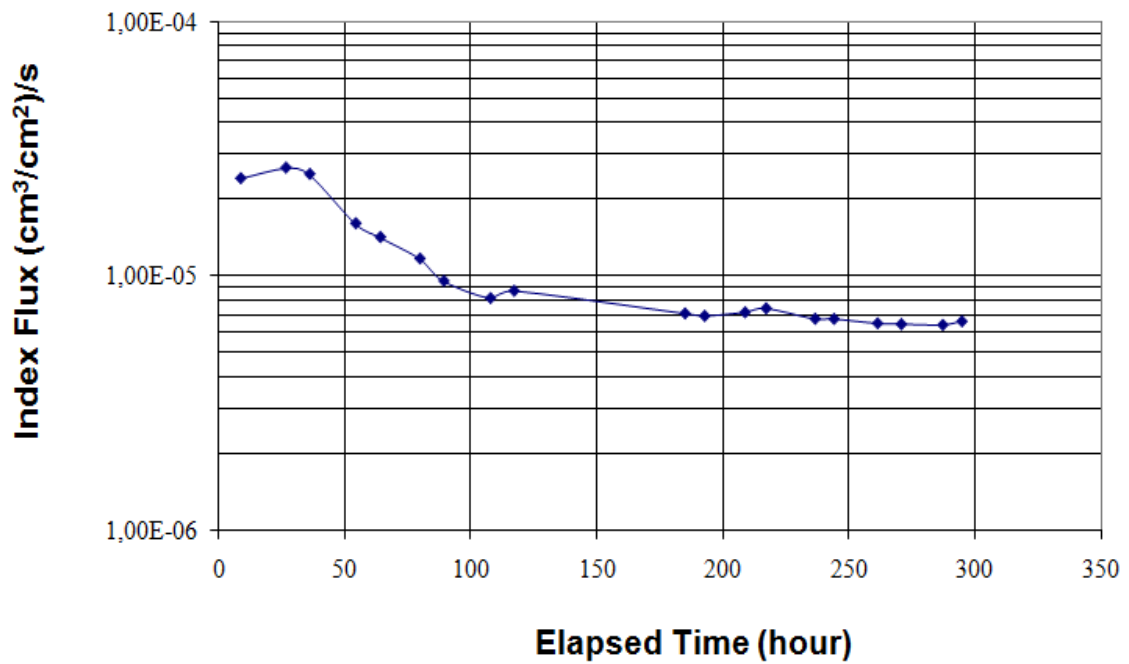


Figure 4.46. Index flux-elapsed time graph for GCL-3 NW (under 50 m of hydraulic head)

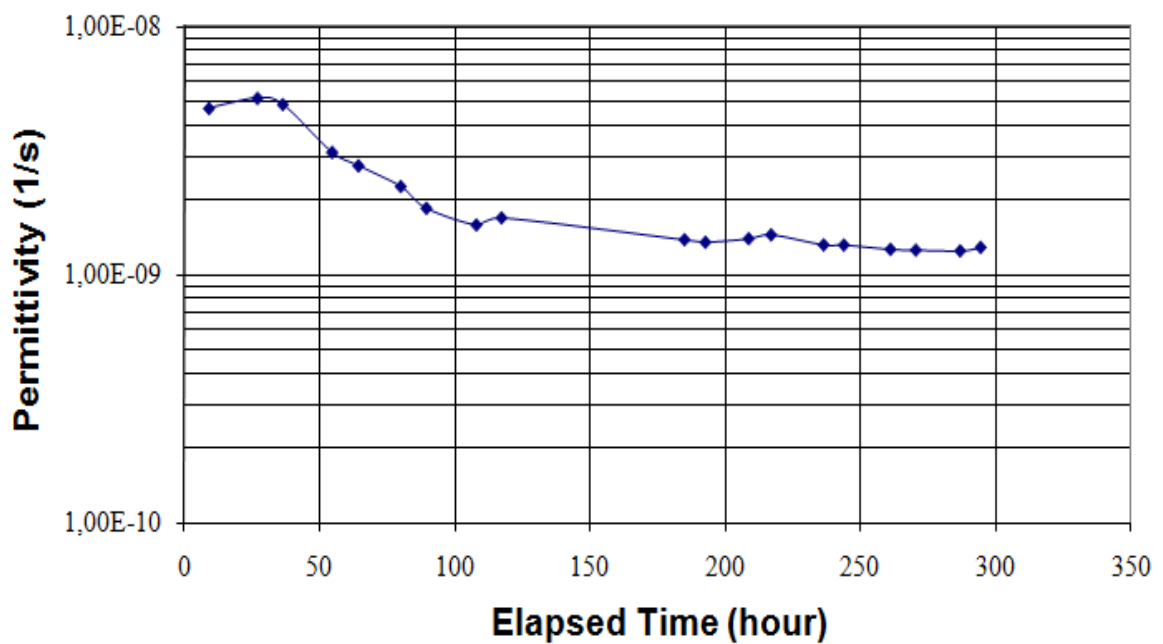


Figure 4.47. Permittivity-elapsed time graph for GCL-3 NW (under 50 m of hydraulic head)

GCL-3 W: According to the test results as shown in figures 4.48 and 4.49, low hydraulic conductivity parameters were obtained at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 292 hours. Coefficient

of permeability (k) decreased from $3,4 \times 10^{-9}$ cm/s to $9,7 \times 10^{-10}$ cm/s during 292 hour-elapsed time. Permittivity (Ψ) and index flux (q_i) values also decreased as shown in figures 4.48 and 4.49, while 50 m of hydraulic water head was being applied to GCL-3 sample for 292 hours.

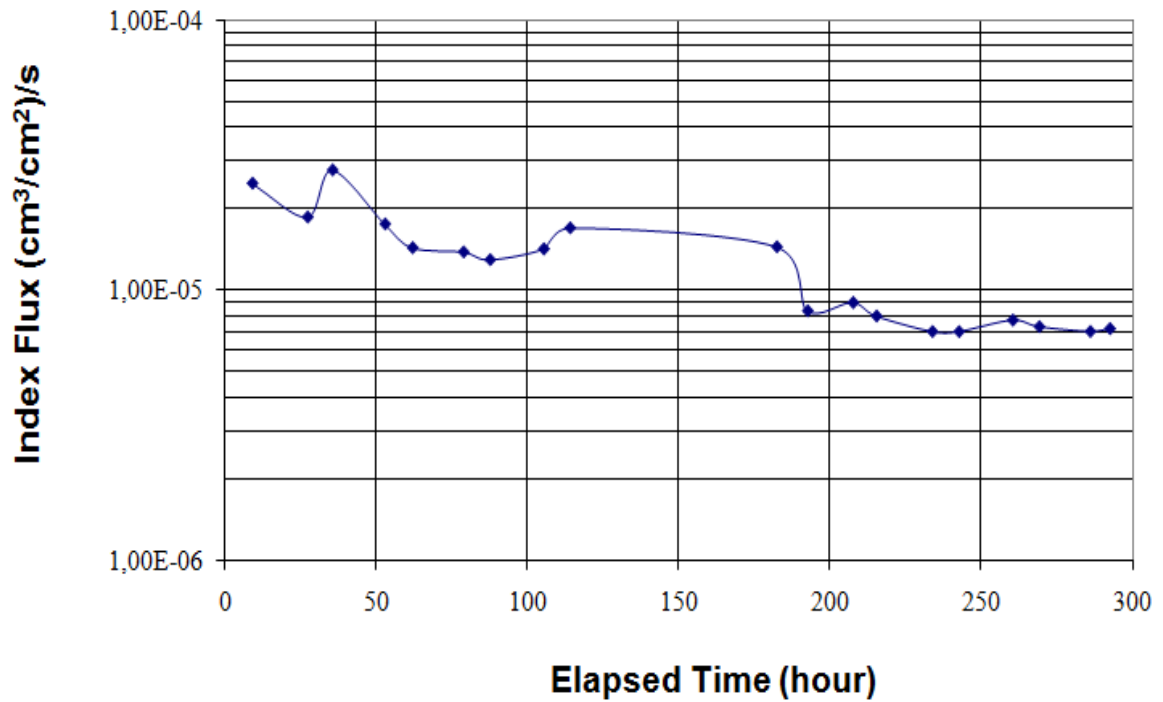


Figure 4.48. Index flux-elapsed time graph for GCL-3 W (under 50 m of hydraulic head)

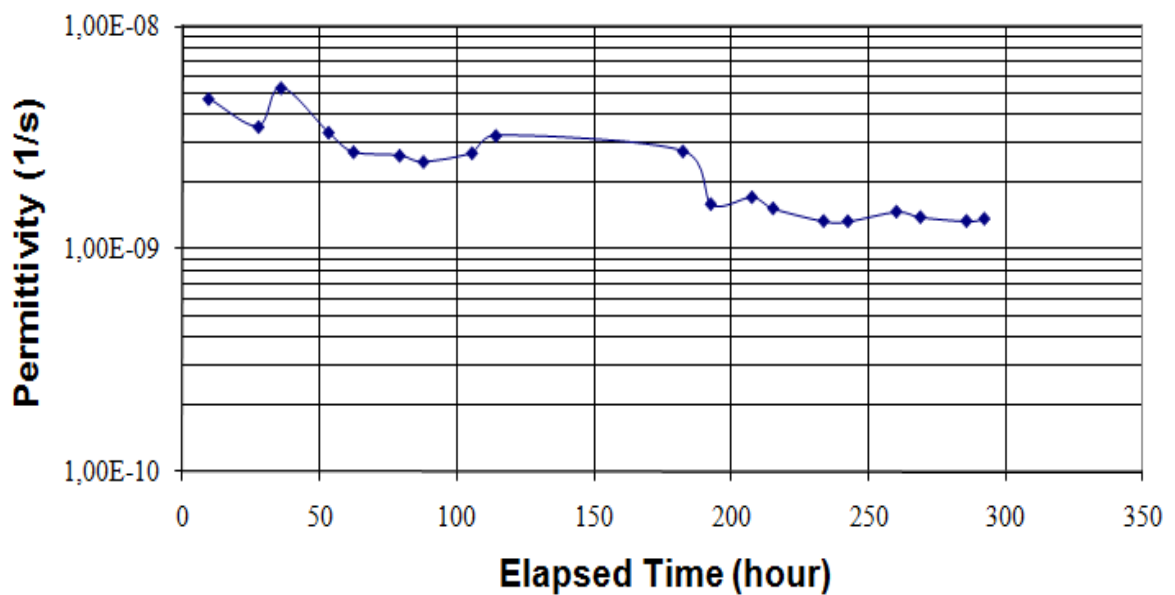


Figure 4.49. Permittivity-elapsed time graph for GCL-3 W (under 50 m of hydraulic head)

GCL-3-NW-D2: According to the test results as shown in figures 4.50 and 4.51, hydraulic conductivity parameters began to increase after about 142-147 hours from the start of the test under 20 m hydraulic head. This increase continued to almost 187 hours elapsed time. This was the peak point as seen in figures 4.50 and 4.51 and the hydraulic conductivity parameters increased to their maximum just before the clogging of the voids of the base pedestal.

From the start to the 187 hour-elapsed time, more than two and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from 2×10^{-8} cm/s to 8×10^{-6} cm/s, permittivity (Ψ) increased from $2,8 \times 10^{-8}$ 1/s to $1,1 \times 10^{-5}$ 1/s and index flux (q_i) increased from $5,9 \times 10^{-5}$ cm³/cm²/s to $2,2 \times 10^{-2}$ cm³/cm²/s.

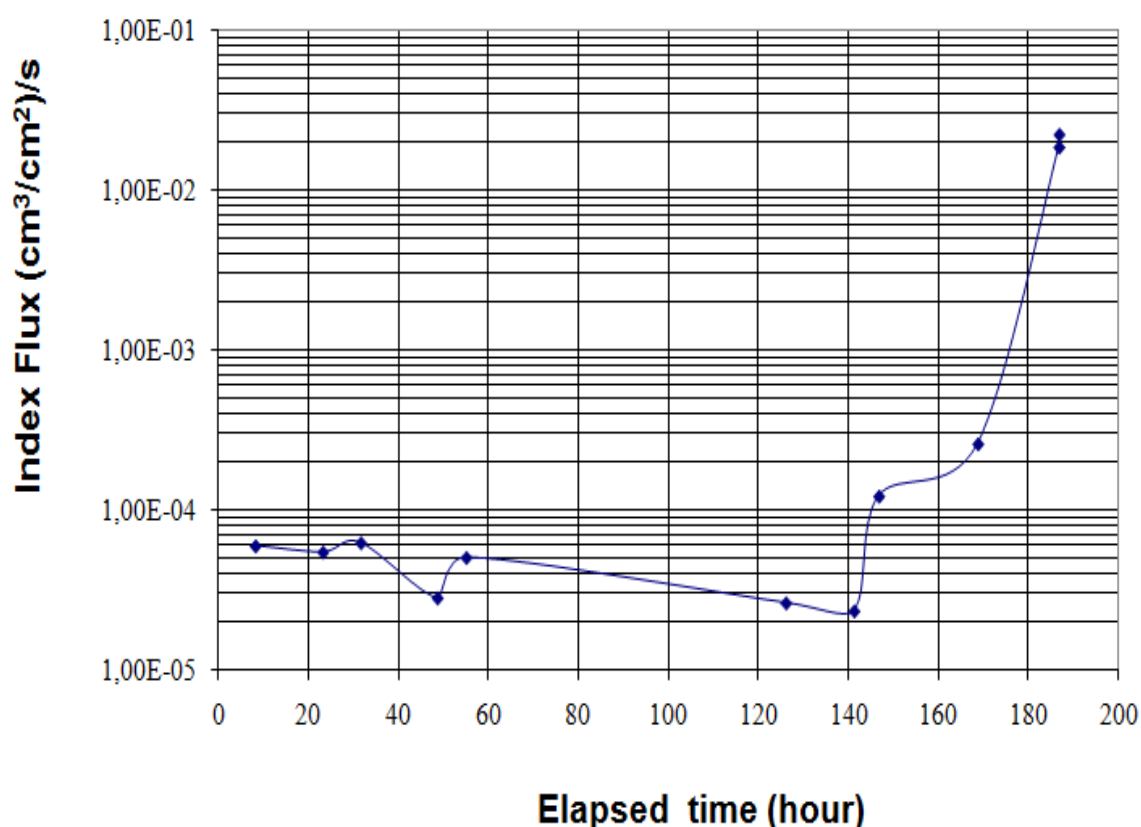


Figure 4.50. Index flux-elapsed time graph for GCL-3-NW-D2 (under 20 m of hydraulic head)

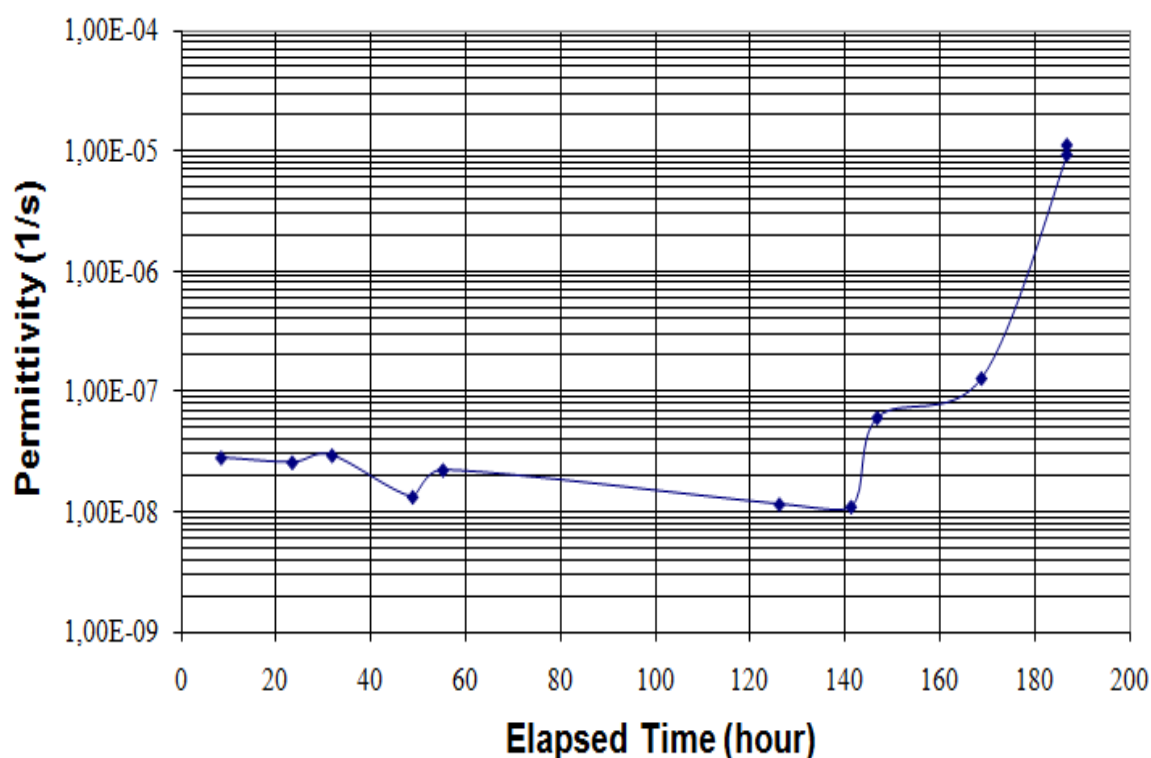


Figure 4.51. Permittivity-elapsed time graph for GCL-3-NW-D2 (under 20 m of hydraulic head)

GCL-3-W-D2: According to the test results as shown in figures 4.52 and 4.53, hydraulic conductivity parameters began to increase after about 220-225 hours from the start of the test under 5 m hydraulic head. This increase continued to almost 287 hours elapsed time.

From the start to the 287 hour-elapsed time, almost three orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $2,1 \times 10^{-8}$ cm/s to $1,4 \times 10^{-5}$ cm/s, permittivity (Ψ) increased from $2,6 \times 10^{-8}$ 1/s to $1,6 \times 10^{-5}$ 1/s and index flux (q_i) increased from $1,4 \times 10^{-5}$ cm³/cm²/s to $8,3 \times 10^{-3}$ cm³/cm²/s.

As shown in figure 4.54, high amount of bentonite migration occurred from the openings and damaged regions of the crest zones of GCL-3-W-D2 sample. High increase in hydraulic conductivity was due to this bentonite loss under 5 m of hydraulic head.

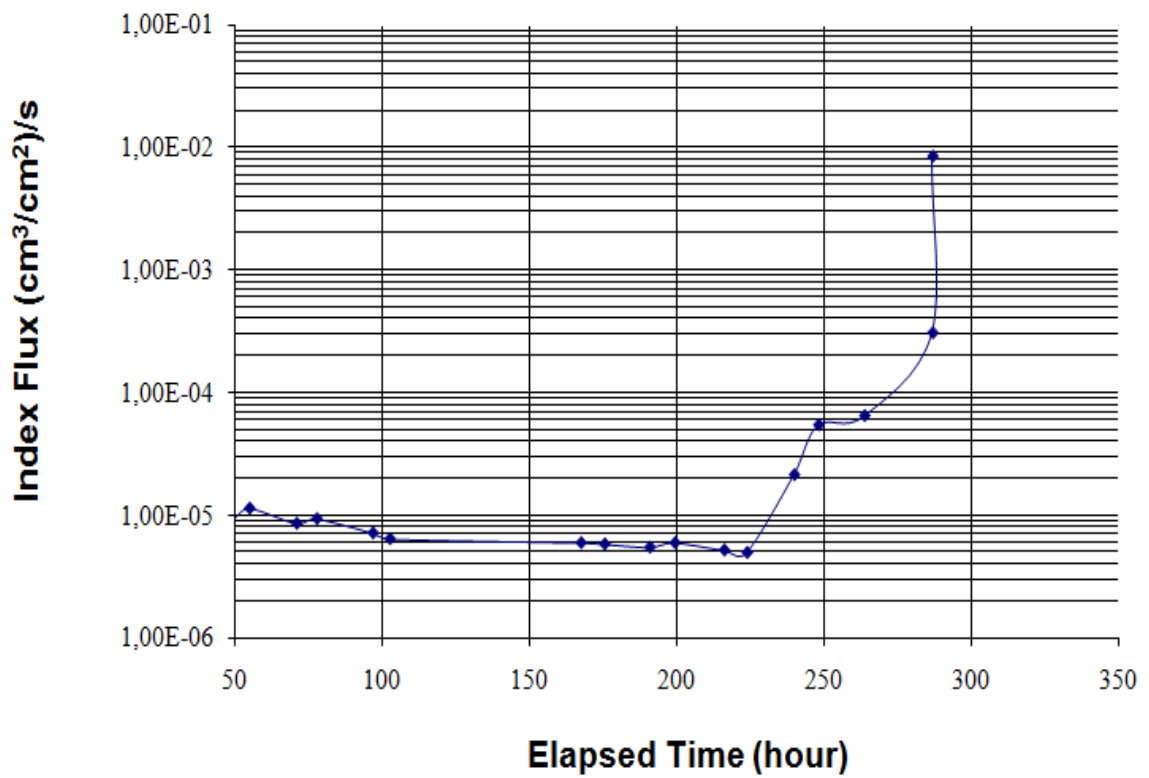


Figure 4.52. Index flux-elapsed time graph for GCL-3-W-D2 (under 5 m of hydraulic head)

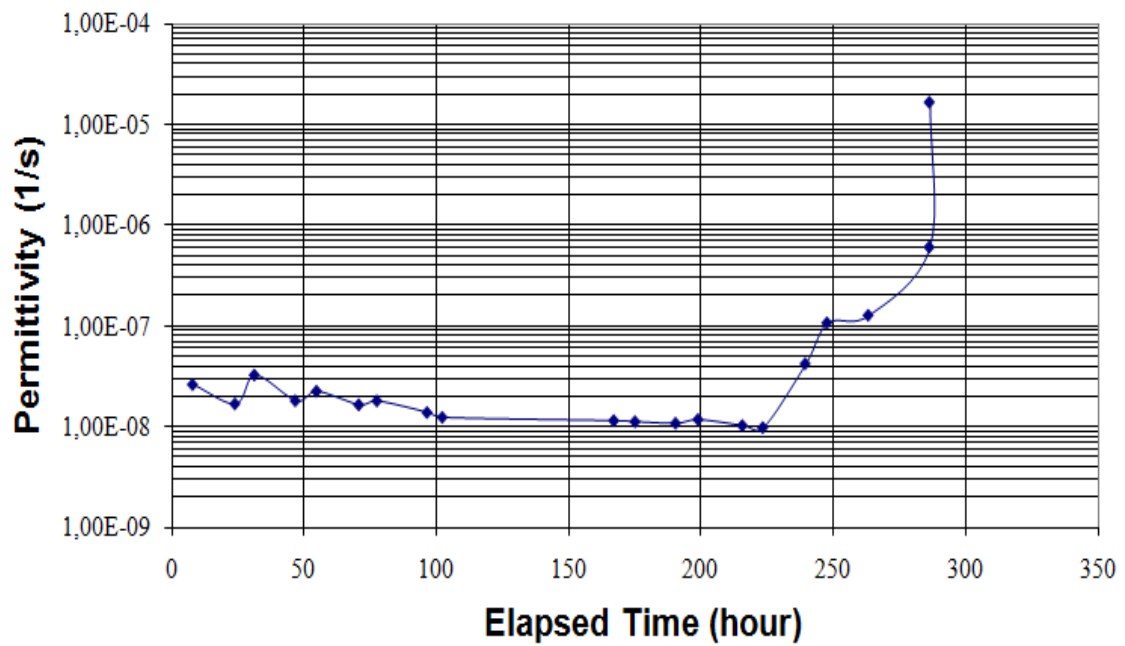


Figure 4.53. Permittivity-elapsed time graph for GCL-3-W-D2 (under 5 m of hydraulic head)



Figure 4.54. GCL-3-W-D2 sample after the termination of the flexible wall triaxial permeability test

GCL-3-NW-D1.5: According to the test results as shown in figures 4.55 and 4.56, hydraulic conductivity parameters began to increase after about 100-105 hours from the start of the test under 35 m hydraulic head. This increase continued to almost 193 hours elapsed time.

From the start to the 193 hour-elapsed time, more than three and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $7,2 \times 10^{-9}$ cm/s to $4,2 \times 10^{-5}$ cm/s, permittivity (Ψ) increased from $1,1 \times 10^{-8}$ 1/s to $6,4 \times 10^{-5}$ 1/s and index flux (q_i) increased from $4,3 \times 10^{-5}$ cm³/cm²/s to $2,5 \times 10^{-1}$ cm³/cm²/s.

GCL-3-W-D1.5: According to the test results as shown in figures 4.57 and 4.58, hydraulic conductivity parameters began to increase after about 185-190 hours from the start of the test under 15 m hydraulic head. This increase continued to almost 254 hours elapsed time.

From the start to the 254 hour-elapsed time, more than two and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient

of permeability (k) increased from $1,6 \times 10^{-8}$ cm/s to $8,8 \times 10^{-6}$ cm/s, permittivity (Ψ) increased from $2,1 \times 10^{-8}$ 1/s to $1,2 \times 10^{-5}$ 1/s and index flux (q_i) increased from $3,2 \times 10^{-5}$ cm³/cm²/s to $1,8 \times 10^{-2}$ cm³/cm²/s.

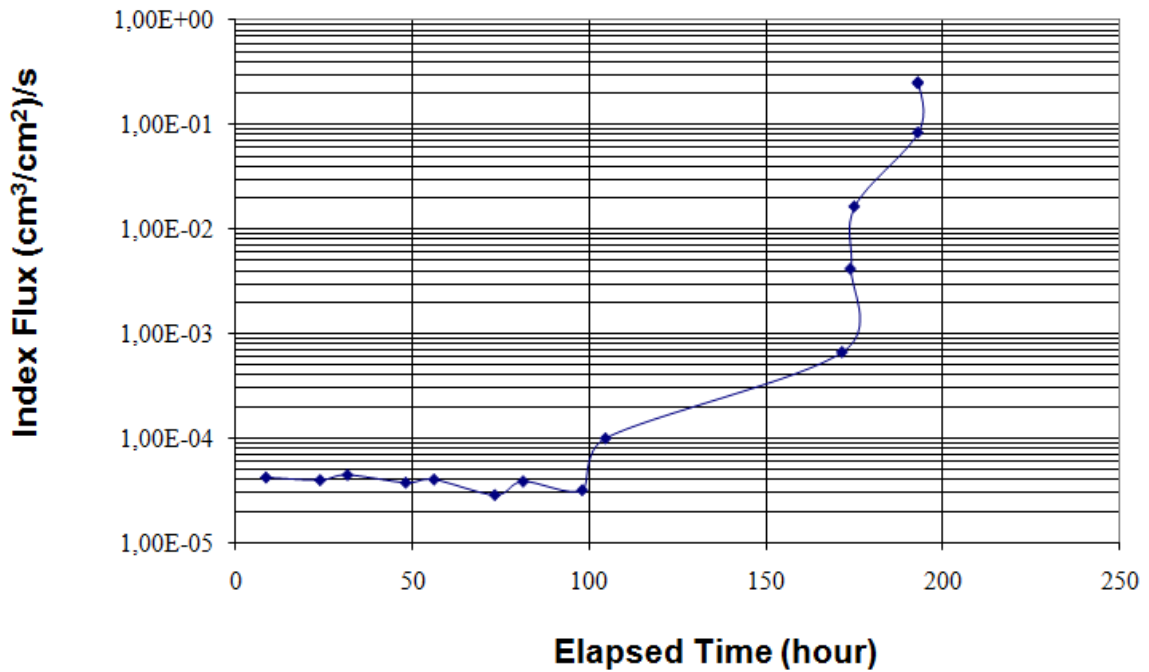


Figure 4.55. Index flux-elapsed time graph for GCL-3-NW-D1.5 (under 35 m of hydraulic head)

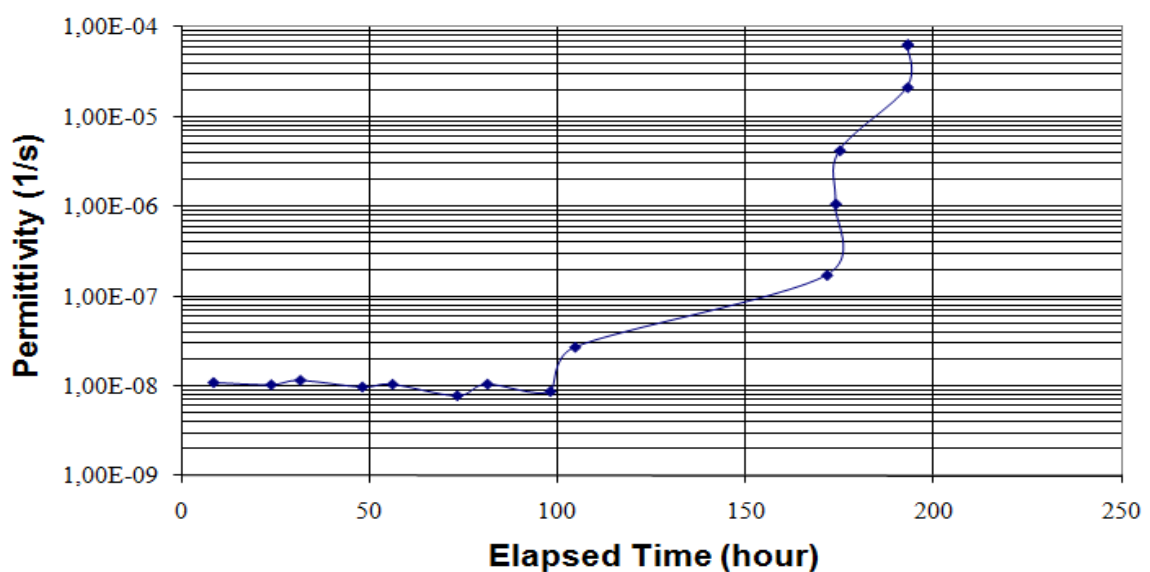


Figure 4.56. Permittivity-elapsed time graph for GCL-3-NW-D1.5 (under 35 m of hydraulic head)

As shown in figure 4.59, high amount of bentonite migration occurred from the openings of the crest zones on the woven geotextile. The damaged slit film tapes of the woven geotextile also caused higher bentonite to extrude through the woven geotextile.

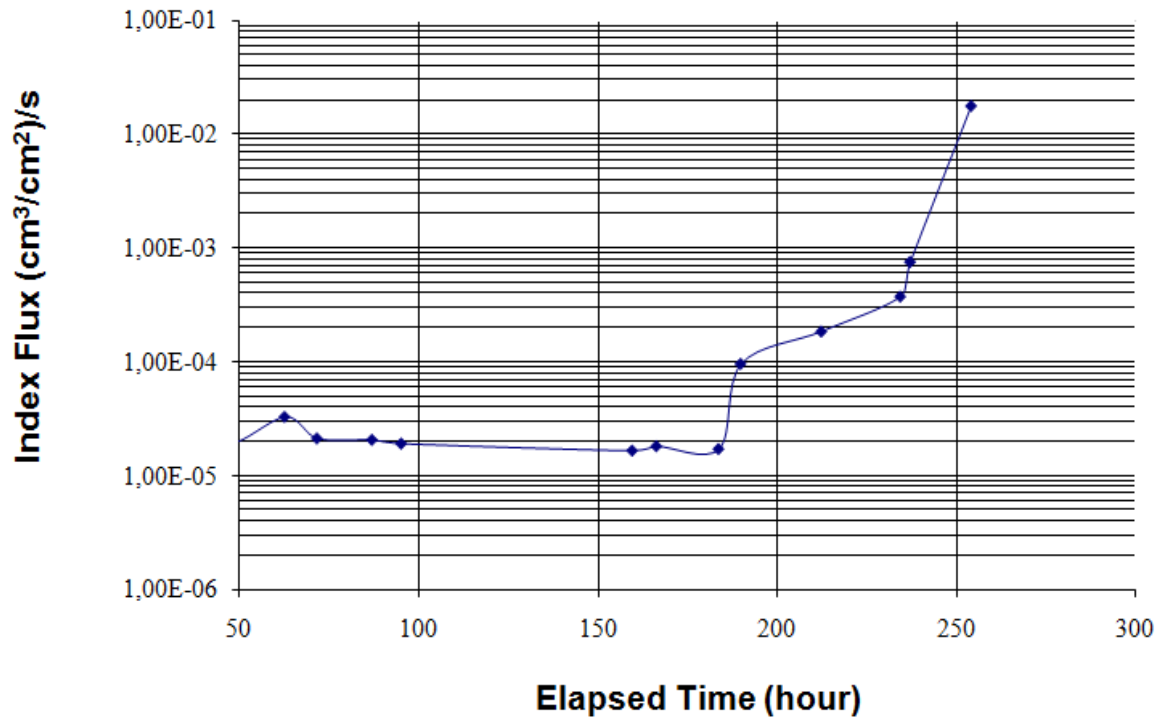


Figure 4.57. Index flux-elapsed time graph for GCL-3-W-D1.5 (under 15 m of hydraulic head)

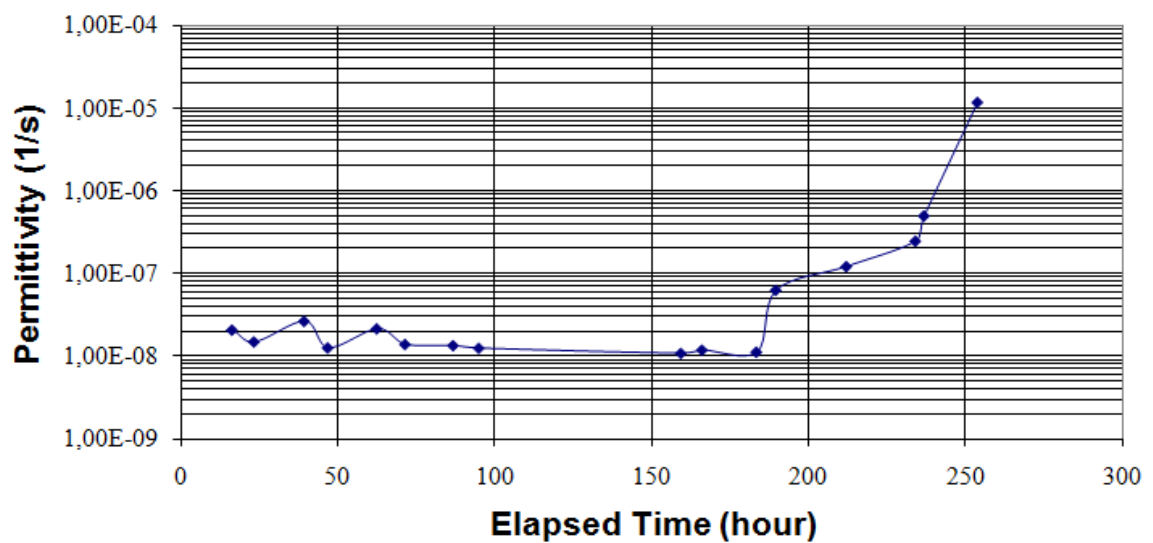


Figure 4.58. Permittivity-elapsed time graph for GCL-3-W-D1.5 (under 15 m of hydraulic head)

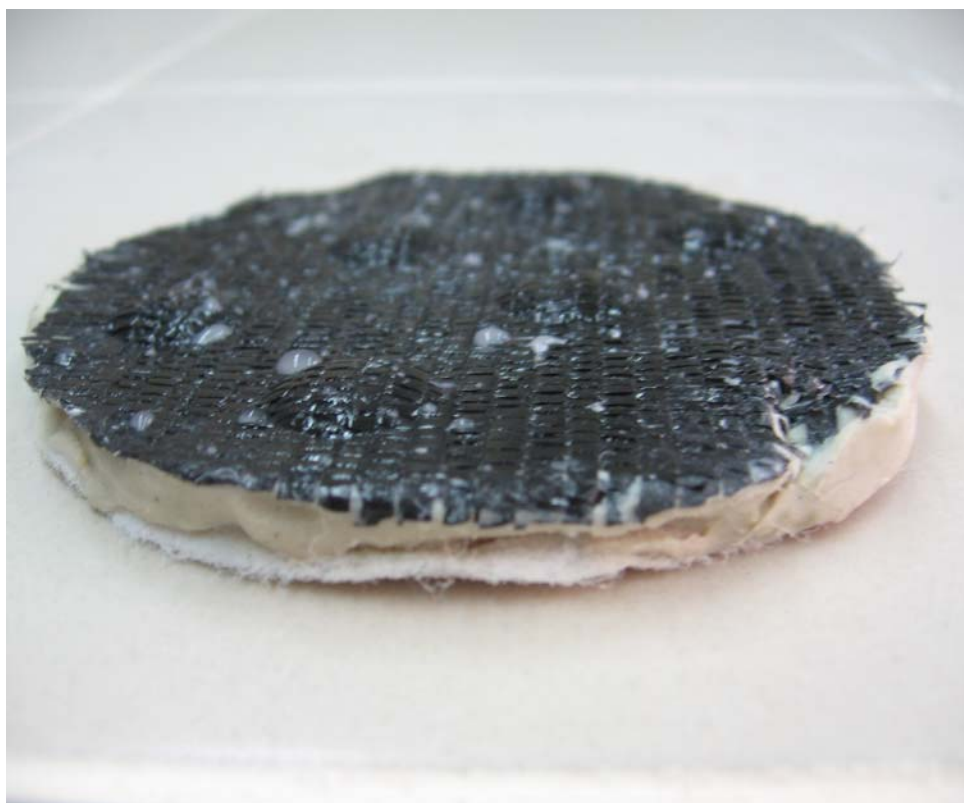


Figure 4.59. GCL-3-W-D1.5 sample after the termination of the flexible wall triaxial permeability test

GCL-3-NW-D1: According to the test results as shown in figures 4.60 and 4.61, hydraulic conductivity parameters began to increase after about 75-90 hours from the start of the test under 50 m hydraulic head. This increase continued to almost 195 hours elapsed time.

From the start to the 195 hour-elapsed time, more than three and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $9,2 \times 10^{-10}$ cm/s to 2×10^{-5} cm/s, permittivity (Ψ) increased from $1,4 \times 10^{-9}$ 1/s to $3,2 \times 10^{-5}$ 1/s and index flux (q_i) increased from $8,1 \times 10^{-6}$ cm³/cm²/s to $1,7 \times 10^{-1}$ cm³/cm²/s.

GCL-3-W-D1: According to the test results as shown in figures 4.62 and 4.63, hydraulic conductivity parameters began to increase after about 235 hours from the start of the test under 25 m hydraulic head. This increase continued to almost 255 hours elapsed time.

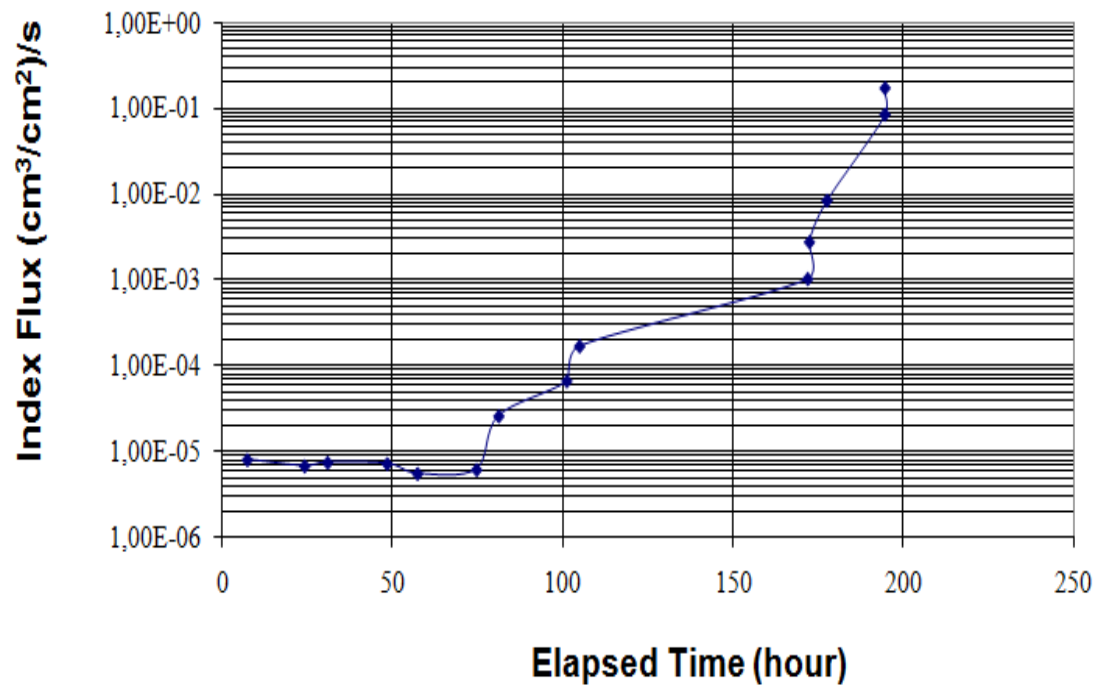


Figure 4.60. Index flux-elapsed time graph for GCL-3-NW-D1 (under 50 m of hydraulic head)

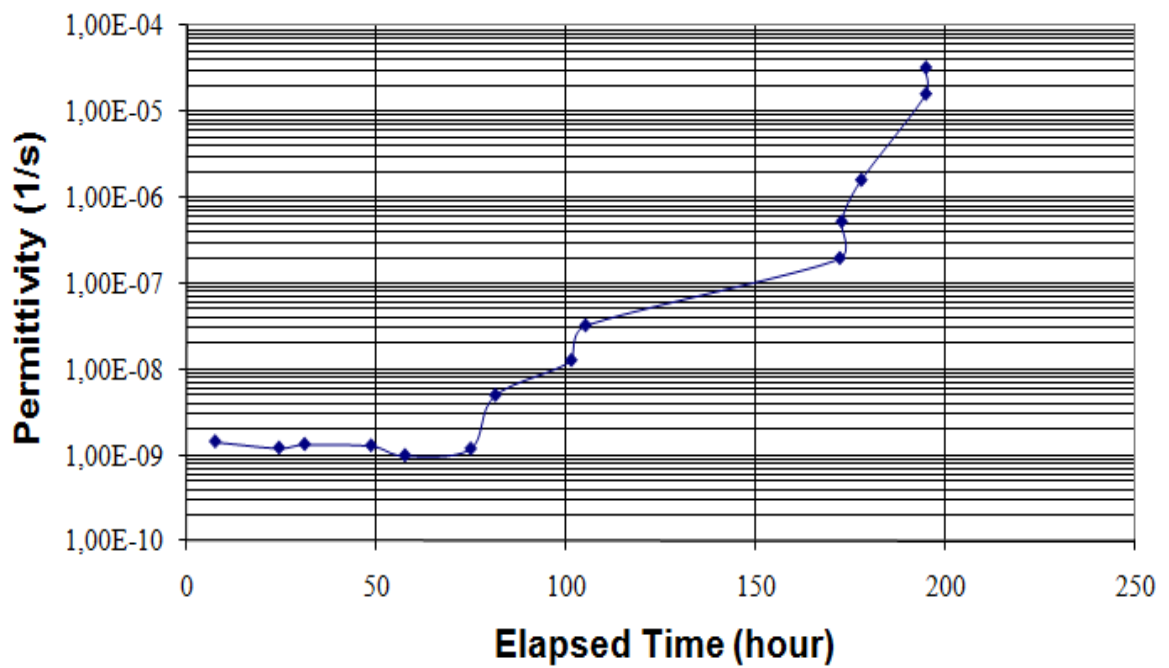


Figure 4.61. Permittivity-elapsed time graph for GCL-3-NW-D1 (under 50 m of hydraulic head)

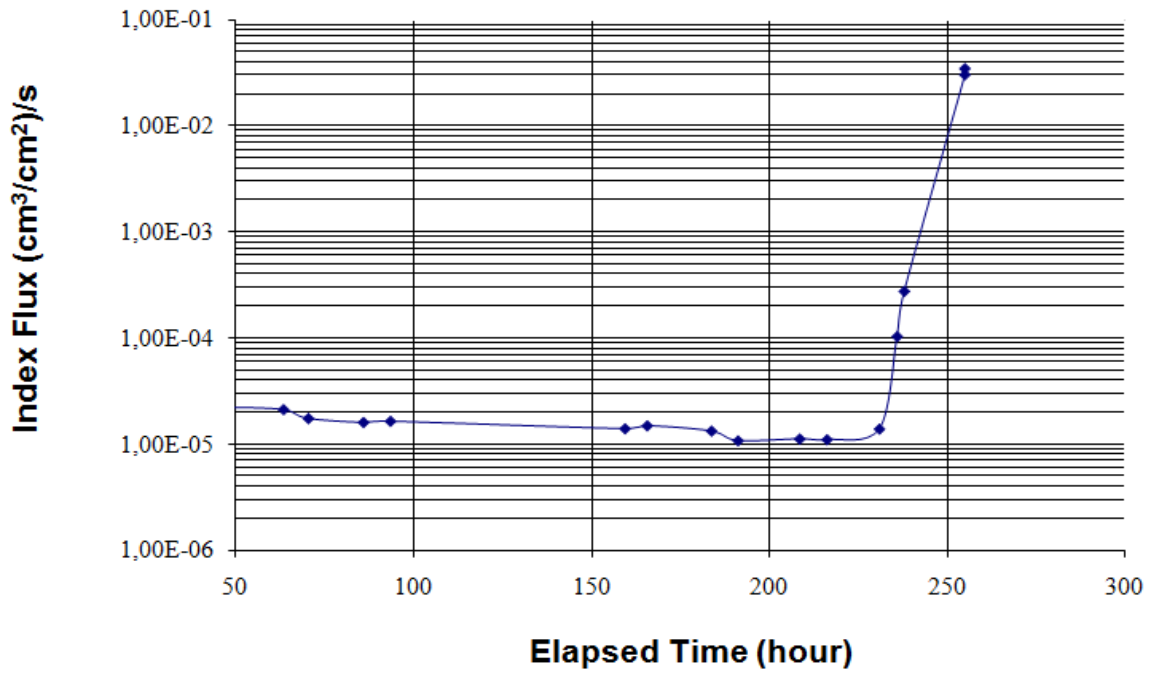


Figure 4.62. Index flux-elapsed time graph for GCL-3-W-D1 (under 25 m of hydraulic head)

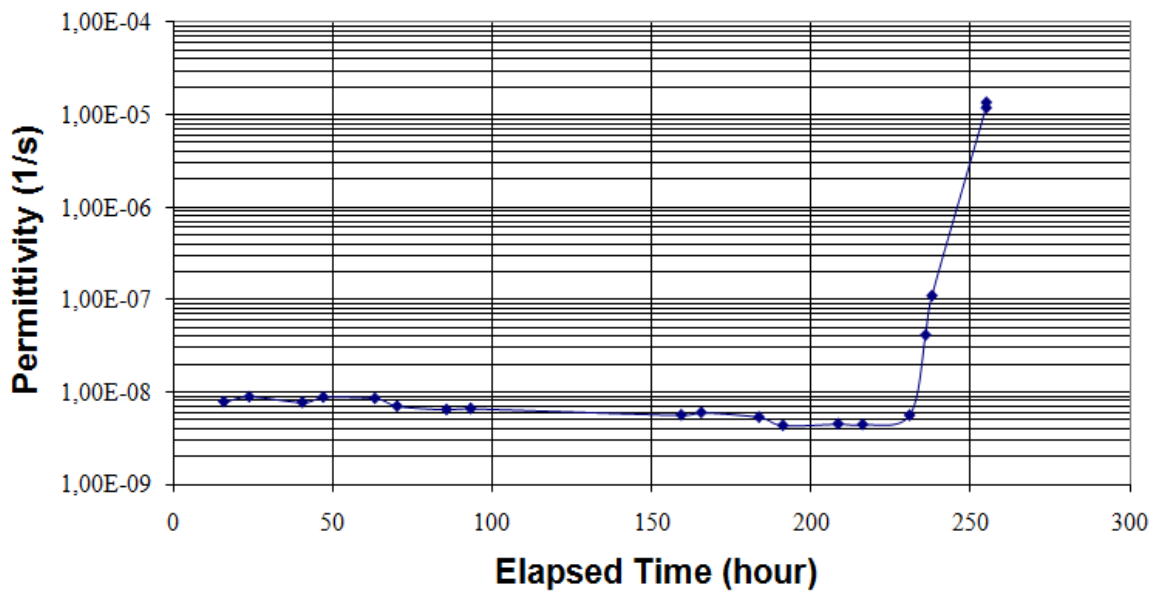


Figure 4.63. Permittivity-elapsed time graph for GCL-3-W-D1 (under 25 m of hydraulic head)

From the start to the 255 hour-elapsed time, more than three and a half orders of magnitude of increase was obtained for the hydraulic conductivity parameters. Coefficient of permeability (k) increased from $5,8 \times 10^{-9}$ cm/s to 1×10^{-5} cm/s, permittivity (Ψ)

increased from $7,8 \times 10^{-9}$ 1/s to $1,4 \times 10^{-5}$ 1/s and index flux (q_i) increased from $1,9 \times 10^{-5}$ $\text{cm}^3/\text{cm}^2/\text{s}$ to $3,4 \times 10^{-2}$ $\text{cm}^3/\text{cm}^2/\text{s}$.

The GCL sample after the termination of the test was shown in figure 4.64. The openings of the crest zones got larger under high hydraulic heads and high amount of bentonite particles escaped from these openings to the effluent burette easily.



Figure 4.64. GCL-3-W-D1 sample after the termination of the flexible wall triaxial permeability test

GCL-3-W-D0.5: According to the test results as shown in figures 4.65 and 4.66, low hydraulic conductivity parameters were obtained at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 280 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were $6,6 \times 10^{-10}$ cm/s, $8,7 \times 10^{-10}$ 1/s and $4,3 \times 10^{-6}$ $\text{cm}^3/\text{cm}^2/\text{s}$, respectively at the end of 280 hour-elapsd time.

These results show that neither any high amount of bentonite migration from the GCL-3-W-D0.5 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 280 hours.

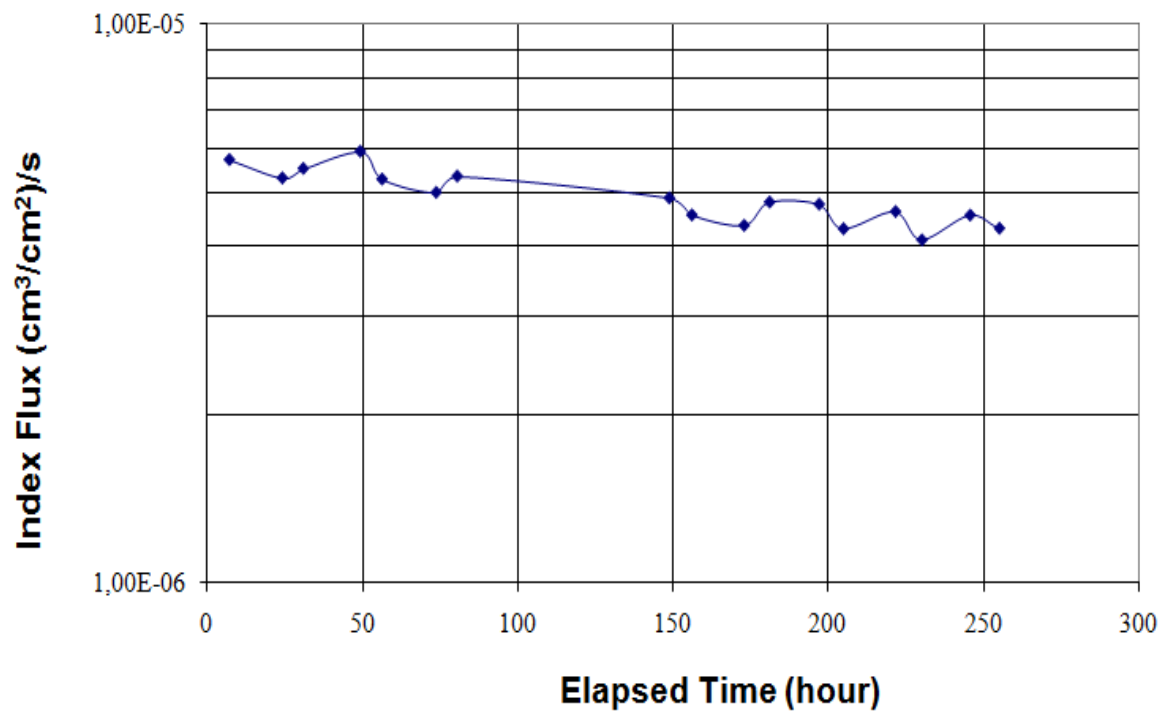


Figure 4.65. Index flux-elapsed time graph for GCL-3-W-D0.5 (under 50 m of hydraulic head)

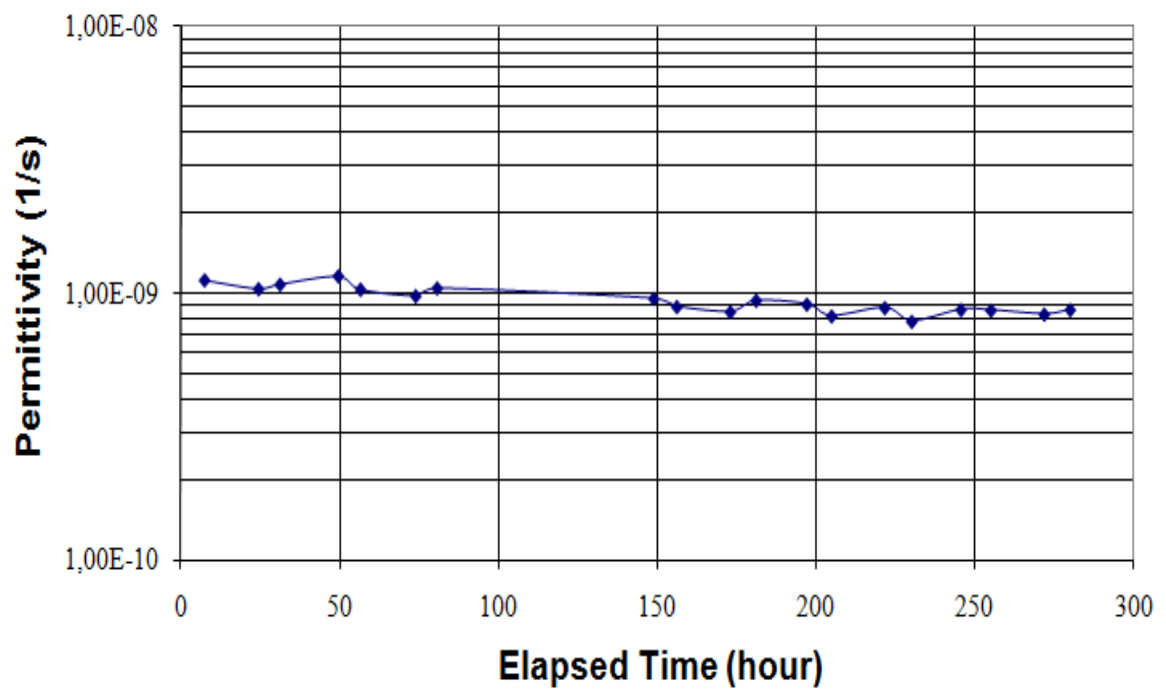


Figure 4.66. Permittivity-elapsed time graph for GCL-3-W-D0.5 (under 50 m of hydraulic head)

4.1.4. GCL-4 Test Results

GCL-4-W-D2: According to the test results as shown in figures 4.67 and 4.68, low hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 251 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were $1,6 \times 10^{-10}$ cm/s, 2×10^{-10} 1/s and $1,1 \times 10^{-6}$ cm³/cm²/s, respectively at the end of 251 hour-elapsed time.

These results show that neither any high amount of bentonite migration from the GCL-4-W-D2 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 251 hours.

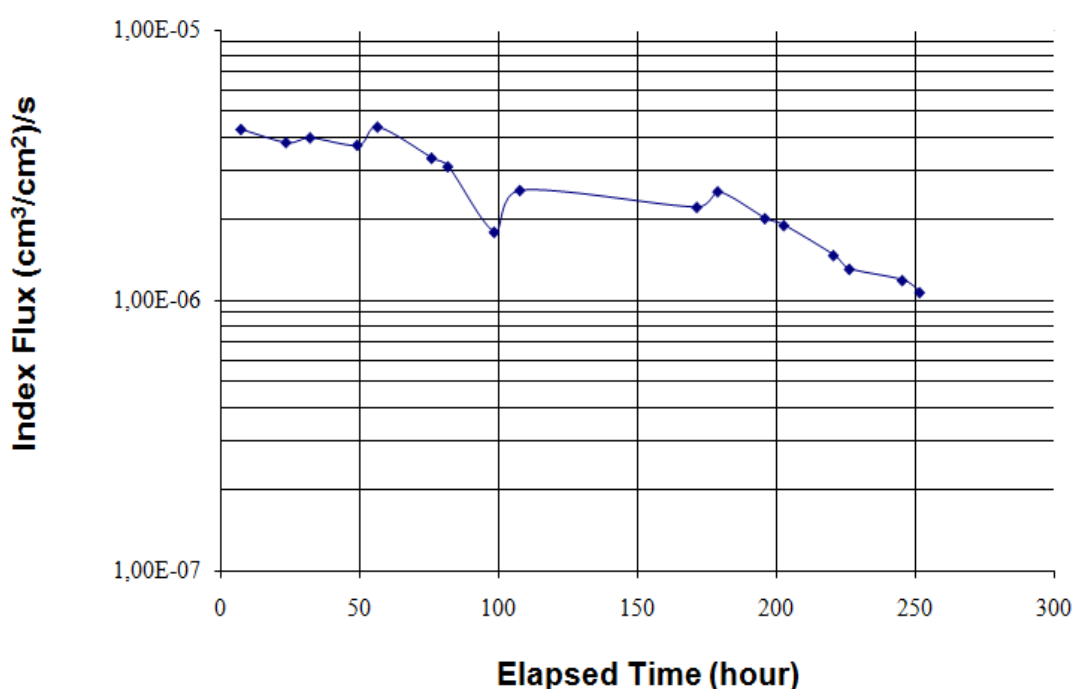


Figure 4.67. Index flux-elapsed time graph for GCL-4-W-D2 (under 50 m of hydraulic head)

As shown in figure 4.69, high amount of bentonite was not migrated from the openings of the crest zones on GCL-4-W-D2 sample under 50 m of hydraulic head. The thickness of the crests was also not as high as that of the crests of GCL-1, GCL-2 and GCL-3 samples. Lower thickness of the crests of GCL-4-W-D2 was due to higher tensile strength of W2 than that of W1.

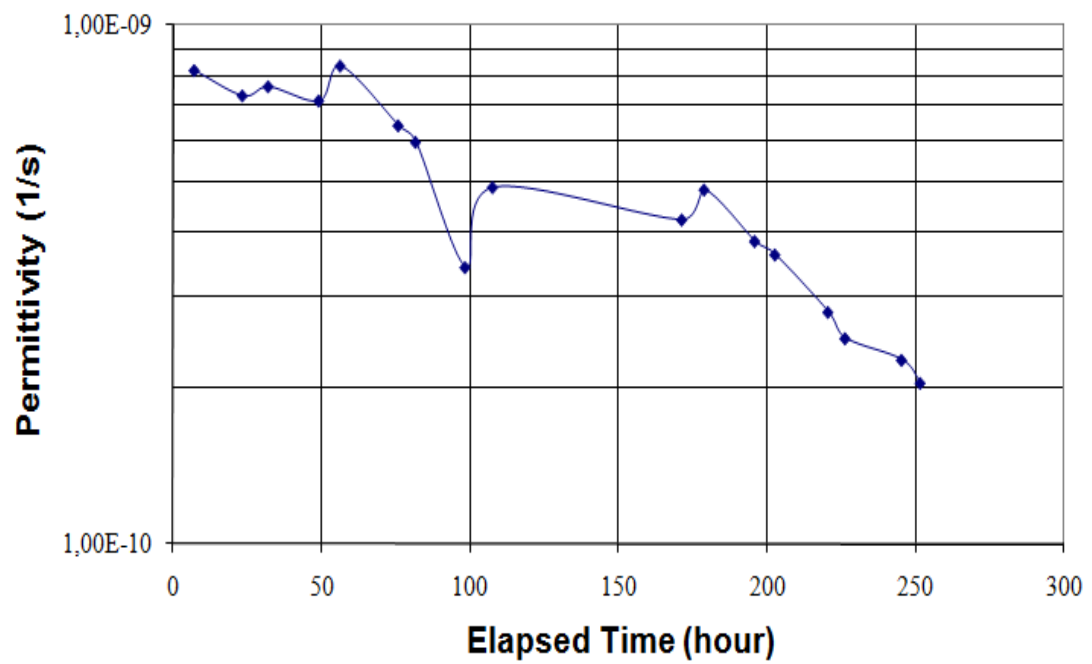


Figure 4.68. Permittivity-elapsed time graph for GCL-4-W-D2 (under 50 m of hydraulic head)



Figure 4.69. GCL-4-W-D2 sample after the termination of the flexible wall triaxial permeability test

GCL-4-W-D1.5: According to the test results as shown in figures 4.70 and 4.71, low hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 239 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were $7,3 \times 10^{-11}$ cm/s, $8,9 \times 10^{-11}$ 1/s and $4,7 \times 10^{-7}$ cm³/cm²/s, respectively at the end of 239 hour-elapsed time.

These results show that neither any high amount of bentonite migration from the GCL-4-W-D1.5 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 239 hours.

As shown in figure 4.72, the thickness of the crests of the GCL sample was not high. When even 50 m of hydraulic head was applied, the woven geotextile component (W2) of the GCL sample over the voids of the base did not deform so much. Low deformations of the crest zones were due to the high tensile strength and durability of the woven geotextile component (W2). When the deformations were low, the openings of the crest zones remained small which prevented high amount of bentonite extrusion. The slit film tapes on the woven geotextile (W2) were not damaged due to the high tensile strength of the woven geotextile (W2) which also prevented high amount of bentonite migration through the woven geotextile (W2).

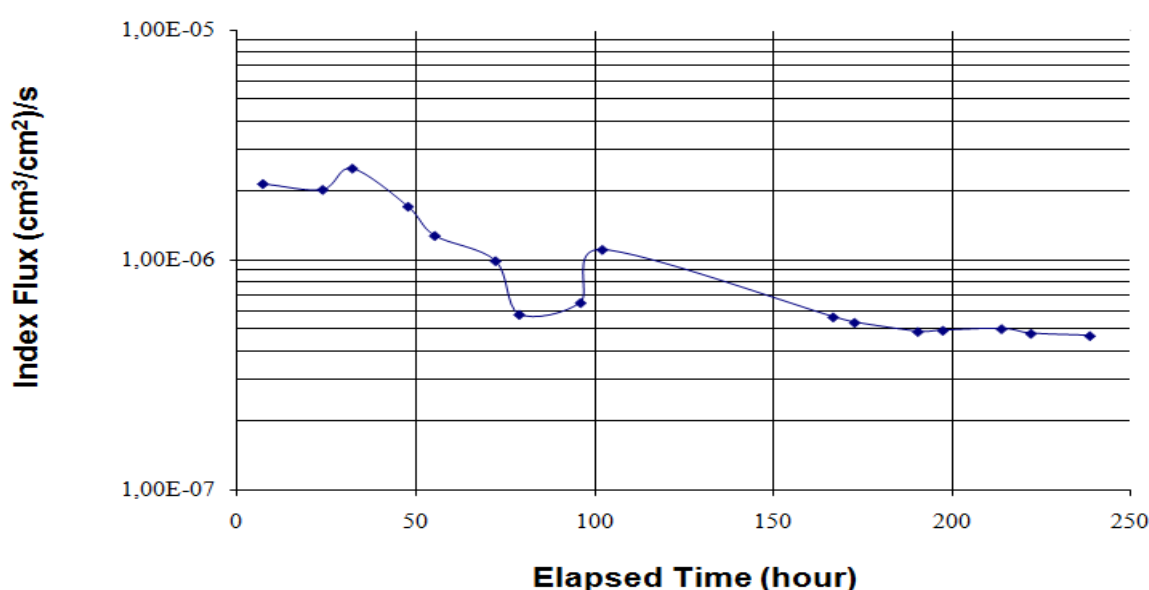


Figure 4.70. Index flux-elapsed time graph for GCL-4-W-D1.5 (under 50 m of hydraulic head)

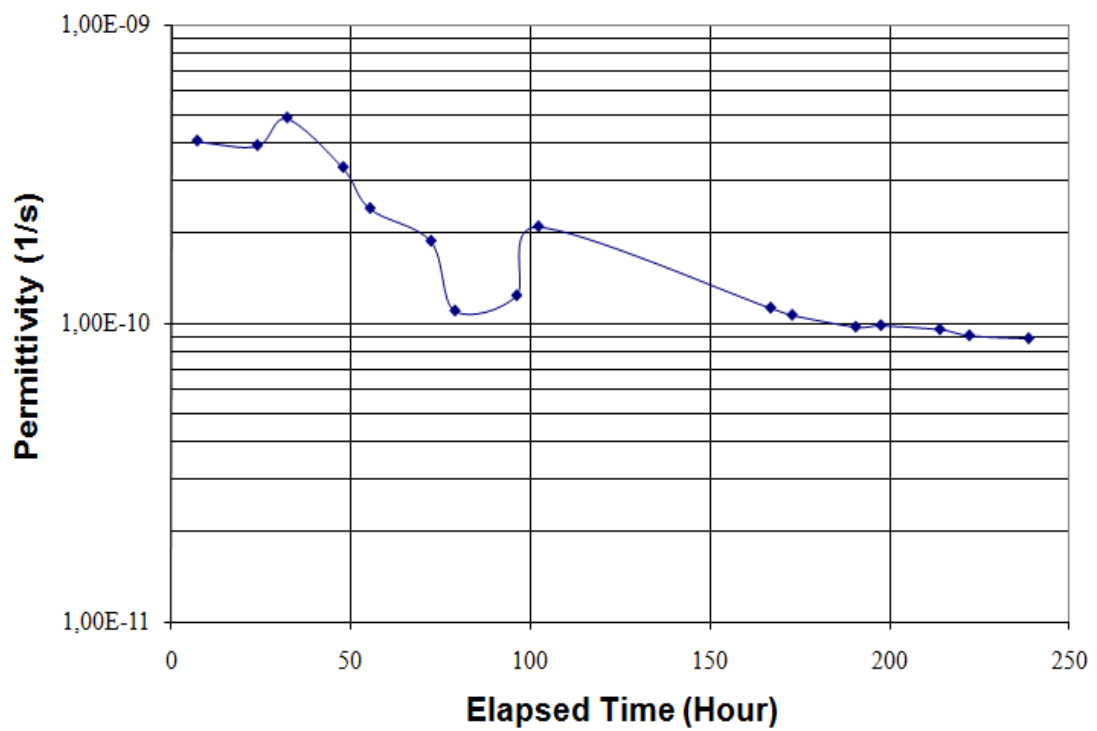


Figure 4.71. Permittivity-elapsed time graph for GCL-4-W-D1.5 (under 50 m of hydraulic head)

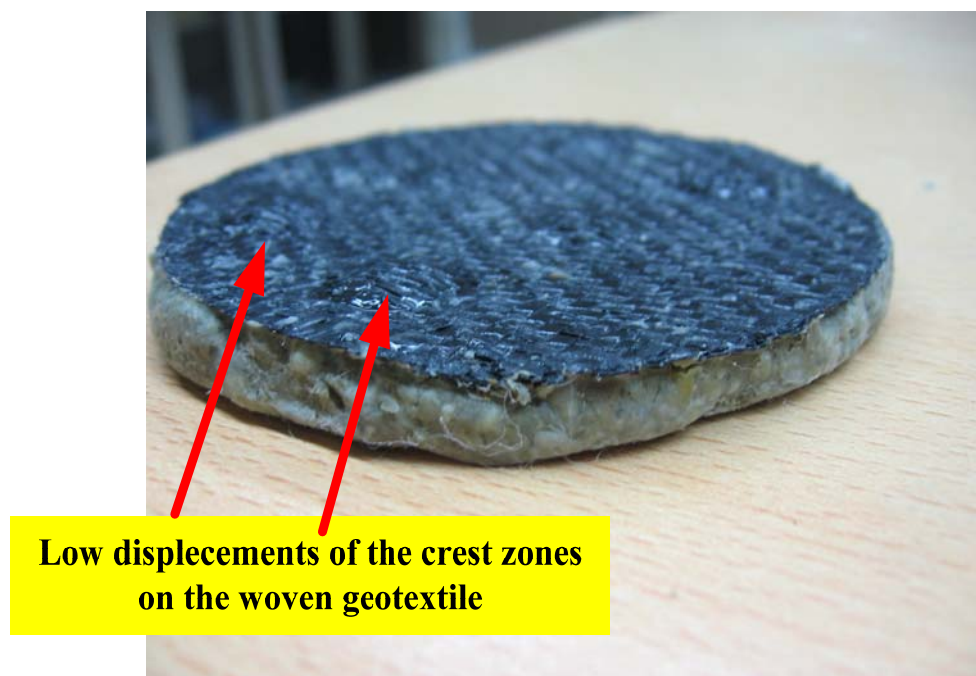


Figure 4.72. GCL-4-W-D1.5 sample after the termination of the flexible wall triaxial permeability test

GCL-4-W-D1: According to the test results as shown in figures 4.73 and 4.74, low hydraulic conductivity parameters were measured at the end of the test when the hydraulic head had been increased up to 50 m and remained like that almost 243 hours. Coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) values were $4,8 \times 10^{-11}$ cm/s, $6,5 \times 10^{-11}$ 1/s and $3,3 \times 10^{-7}$ cm³/cm²/s, respectively at the end of 243 hour-elapsed time.

These results show that neither any high amount of bentonite migration from the GCL-4-W-D1 sample nor internal erosion occurred under 50 m of hydraulic head during a time period of 243 hours. Hydraulic conductivity remained low enough at the end of the triaxial permeability test.

Maximum thickness values were very low for the GCL-4-W-D1 sample. Due to the reasons explained for GCL-4-W-D2 and GCL-4-W-D1.5, the deformations of the crest zones remained low which prevented high amount of bentonite extrusion from the openings of the woven geotextile as shown in figure 4.75.

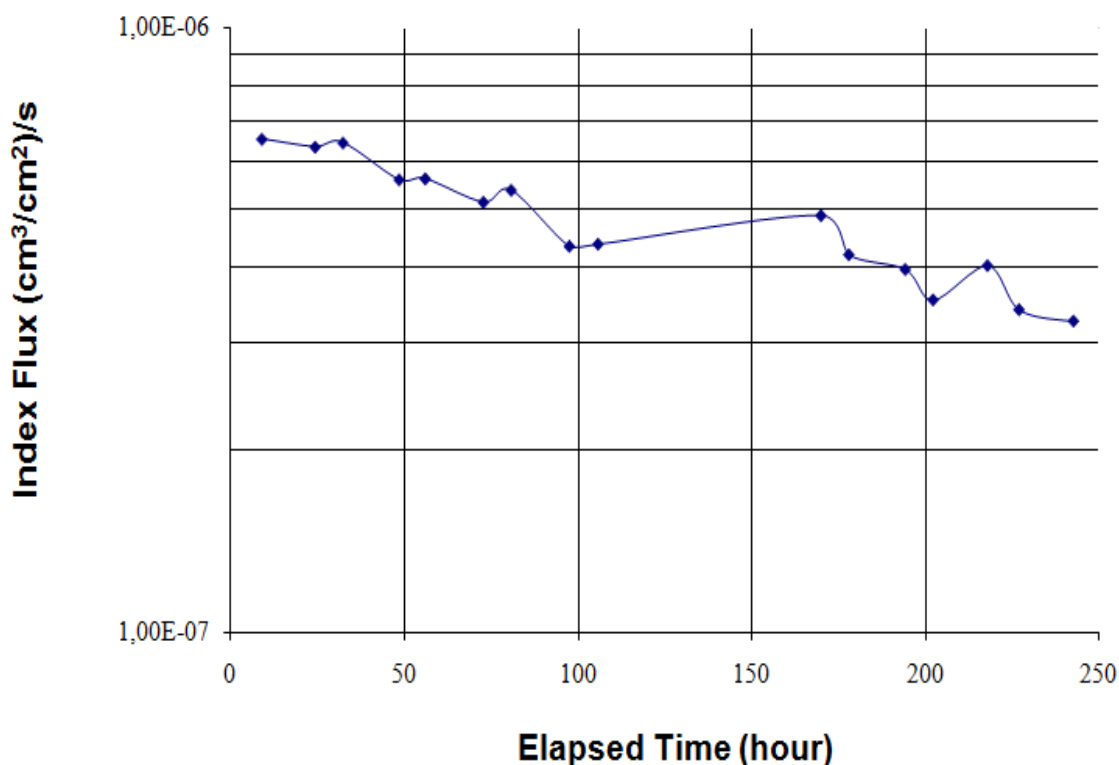


Figure 4.73. Index flux-elapsed time graph for GCL-4-W-D1 (under 50 m of hydraulic head)

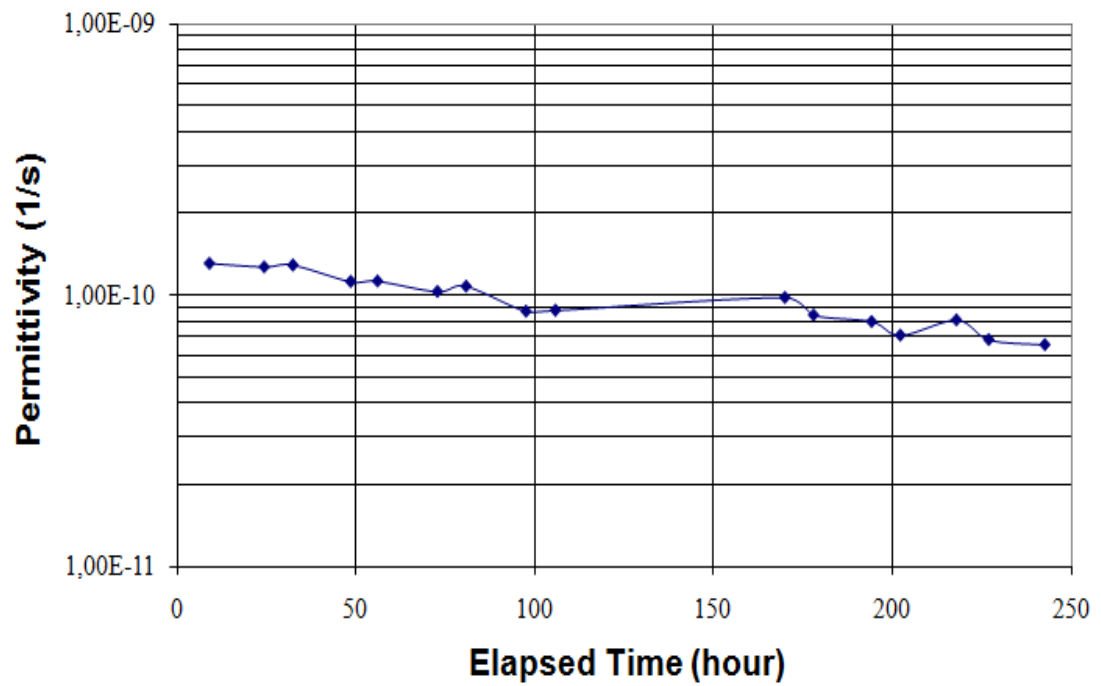


Figure 4.74. Permittivity-elapsed time graph for GCL-4-W-D1 (under 50 m of hydraulic head)



Figure 4.75. GCL-4-W-D1 sample after the termination of the flexible wall triaxial permeability test

4.2. Observed Deformations

As explained in “Test Results” section, the GCL samples were deformed at locations where the GCL samples were in contact with the voids of the base. In this section, the geometry of these deformations will be tried to be quantified. In the below tables, the average thickness refers to the thickness of the GCL sample measured after the permeability test and maximum thickness refers to the distance between the base of the average GCL sample to the peak of the deformed GCL sample. Δt is the difference between the maximum and the average GCL thickness.

Table 4.1. GCL-1-W-D2 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
12,5	8,3	4,2

Table .4.2. GCL-1-NW-D2 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
13,7	8,7	5,0

Table 4.3. GCL-1-W-D1.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
11,1	7,5	3,6

According to the results shown in tables 4.1, 4.2, 4.3, 4.4, 4.5, 4.6 and figure 4.76, GCL-1 samples had highest maximum thickness and Δt values when the diameter of the

voids of the base was greatest. When the diameter of the voids of the base was 2 cm, Δt was 5,0 mm and 4,2 mm for GCL-1-NW-D2 and GCL-1-W-D2, respectively. However, Δt decreased to 3,3 mm and 2,7 mm for GCL-1-NW-D1 and GCL-1-W-D1 when the diameter of the voids of the base was 1 cm where internal erosion did not occur.

Table 4.4. GCL-1-NW-D1.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
11,8	7,7	4,1

Table 4.5. GCL-1-W-D1 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
9,5	6,8	2,7

Table 4.6. GCL-1-NW-D1 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
9,8	6,5	3,3

Table 4.7. GCL-2-W-D2 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
13	8,1	4,9

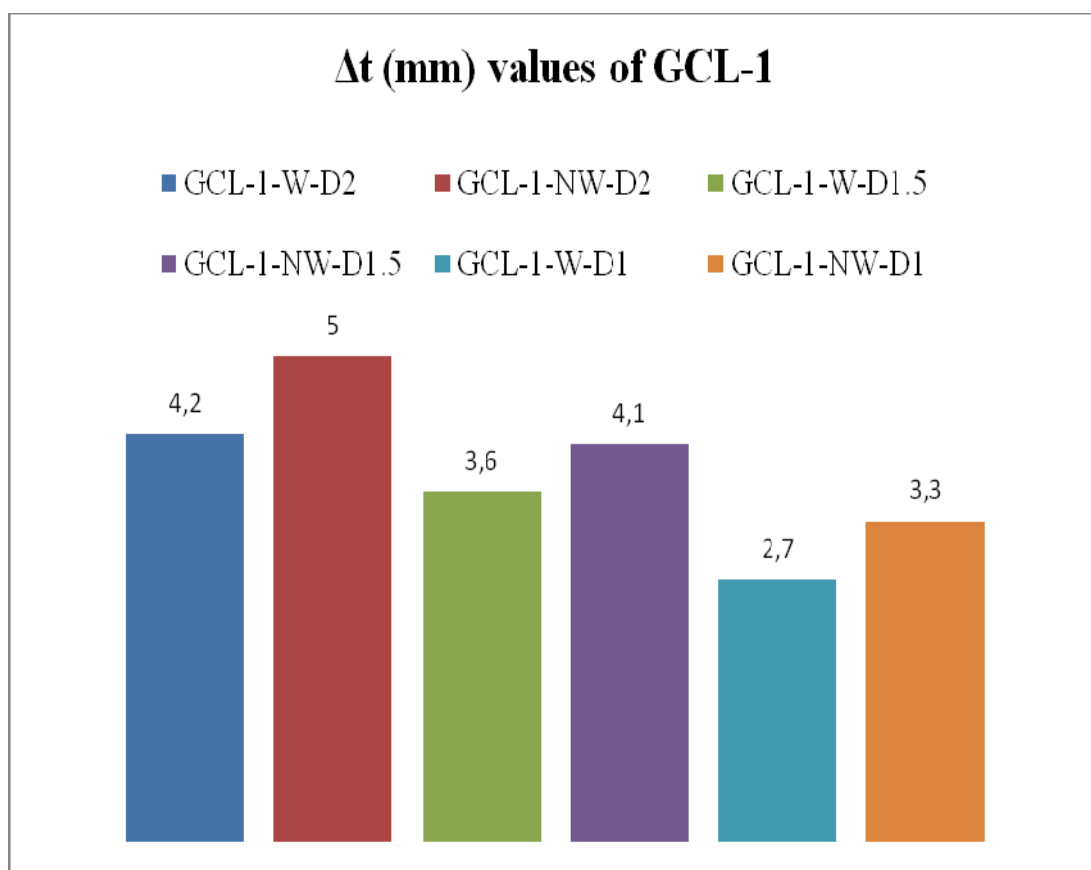


Figure 4.76. Observed deformations (Δt) on GCL-1 samples

Table 4.8. GCL-2-NW-D2 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
12,5	6,7	5,8

Table 4.9. GCL-2-W-D1.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
11,4	7,3	4,1

Table 4.10. GCL-2-NW-D1.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
11,9	6,7	5,2

Table 4.11. GCL-2-W-D1 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
10,4	7	3,4

Table 4.12. GCL-2-NW-D1 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
11	6,9	4,1

Table 4.13. GCL-2-W-D0.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
8,4	6,5	1,9

According to the results shown in tables 4.7, 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, 4.14 and figure 4.77, GCL-2 samples had also highest maximum thickness and Δt values when the diameter of the voids of the base was greatest. When the diameter of the voids of the base was 2 cm, Δt was 5,8 mm and 4,9 mm for GCL-2-NW-D2 and GCL-2-W-D2, respectively.

However, Δt decreased to 2,2 mm and 1,9 mm for GCL-2-NW-D0.5 and GCL-2-W-D0.5 when the diameter of the voids of the base was 0.5 cm where internal erosion did not occur. These values are even lower than those obtained for GCL-1-NW-D1 and GCL-1-W-D1 where internal erosion did also not occur. When the void diameter of the base became 0.5 cm, the maximum thickness of the GCL sample also decreased. Slightly lower Δt values for GCL-1 than those for GCL-2 is due to the manufacturing type of GCL-1 by needlepunching. The needlepunched fibres prevented the GCL-1 samples to deform vertically too much. Even if Δt for GCL-1-NW-D1.5 was 4.1 mm under 50 m of hydraulic head, internal erosion did not occur due to the effect of the fibres.

Table 4.14. GCL-2-NW-D0.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
8,7	6,5	2,2

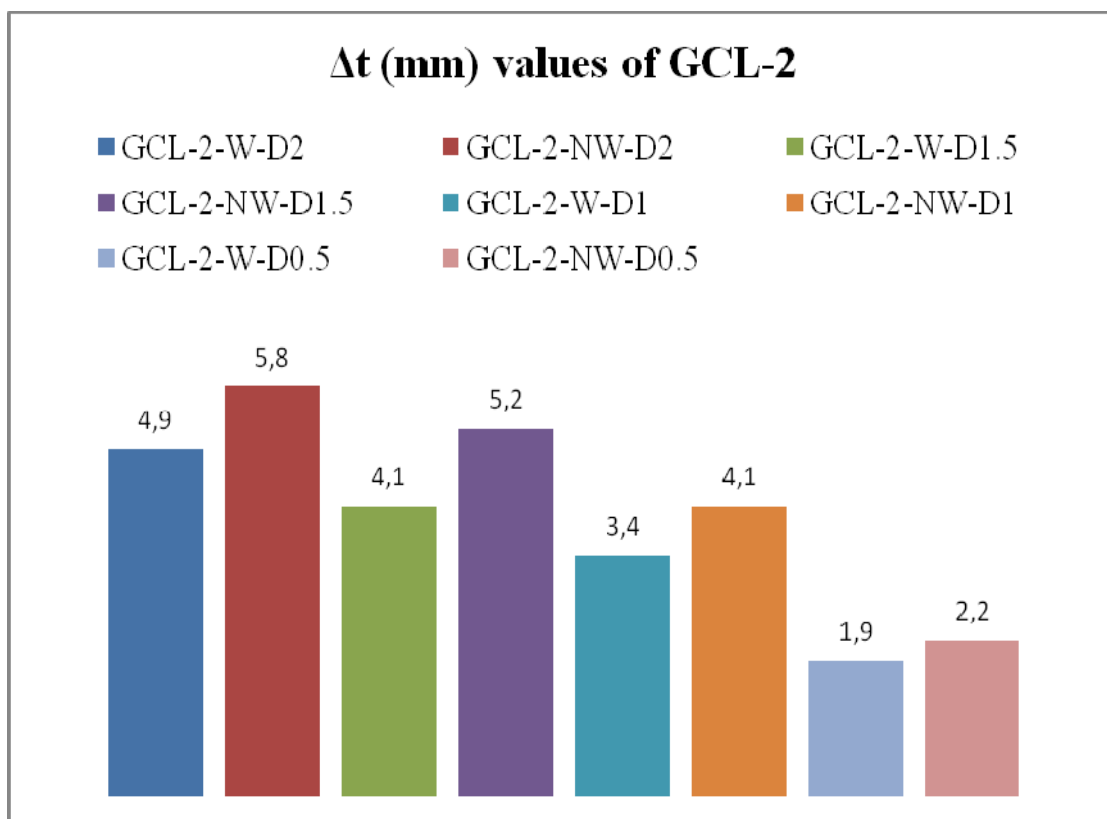


Figure 4.77. Observed deformations (Δt) on GCL-2 samples

Table 4.15. GCL-3-W-D2 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
12,3	8,3	4

Table 4.16. GCL-3-NW-D2 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
12,7	7,2	5,5

Table 4.17. GCL-3-W-D1.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
10,9	7,6	3,3

Table 4.18. GCL-3-NW-D1.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
11,4	6,6	4,8

According to the results shown in tables 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21 and figure 4.78, GCL-3 samples had also highest maximum thickness and Δt values when the diameter of the voids of the base was greatest. When the diameter of the voids of the base was 2 cm, Δt was 5,5 mm and 4,0 mm for GCL-3-NW-D2 and GCL-3-W-D2, respectively.

However, Δt decreased to 1,7 mm for GCL-3-W-D0.5 when the diameter of the voids of the base was 0.5 cm where internal erosion did not occur. All of GCL-1, GCL-2 and GCL-3 samples where the nonwoven geotextile component was in contact with the voids, had higher Δt values than GCL-1, GCL-2 and GCL-3 samples where the woven geotextile component was in contact with the voids when the GCL samples were tested over the same bases as shown in figures 4.75, 4.76 and 4.77. This observation is due to the rigidity of the woven geotextile (W1). Because of higher rigidity, lower deformations were measured on woven geotextiles (W1) than those were measured on nonwoven geotextiles (N1) when they were damaged and caused high amount of bentonite extrusion.

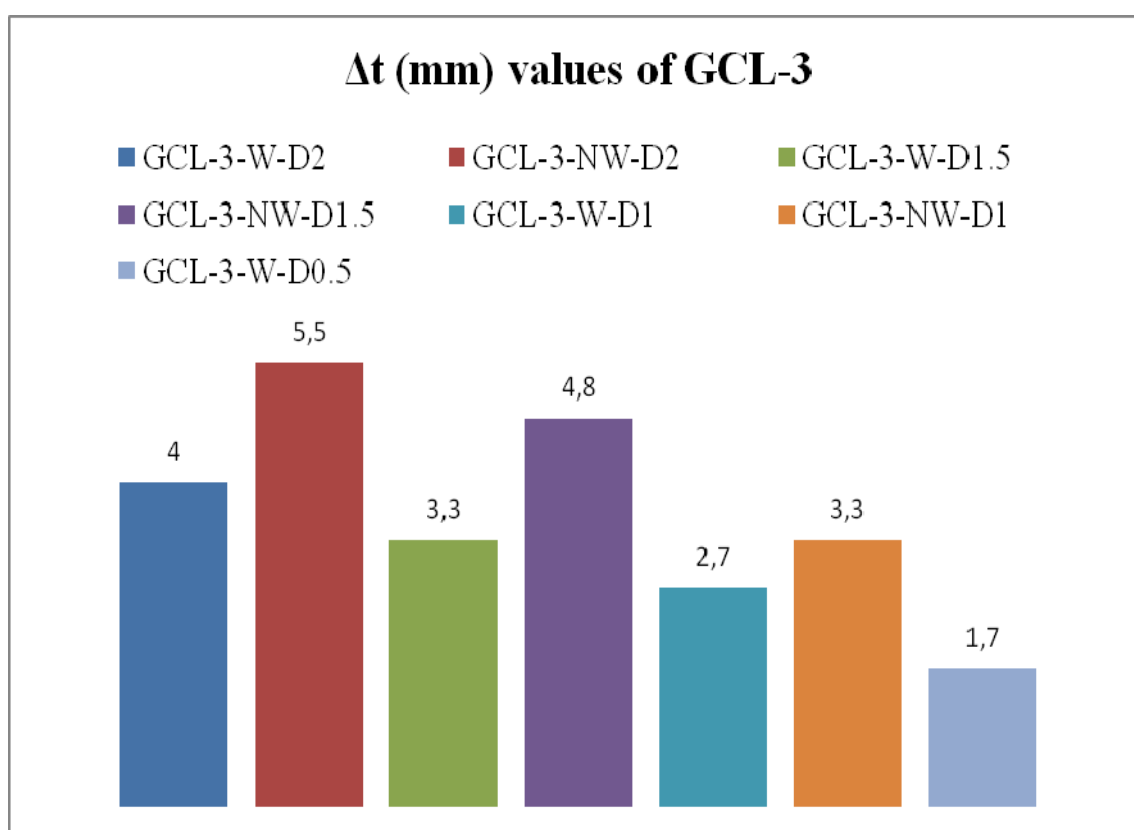


Figure 4.78. Observed deformations (Δt) on GCL-3 samples

Table 4.19. GCL-3-W-D1 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
10,2	7,5	2,7

Table 4.20. GCL-3-NW-D1 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
9,7	6,4	3,3

Table 4.21. GCL-3-W-D0.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
9,3	7,6	1,7

Table 4.22. GCL-4-W-D2 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
10,3	7,8	2,5

Table 4.23. GCL-4-W-D1.5 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
9,9	8,2	1,7

According to the results shown in tables 4.22, 4.23, 4.24 and figure 4.79, GCL-4 samples had very low maximum thickness and Δt values, which were attributed to the very low amount of bentonite migration from GCL-4 samples when they were tested over the bases with voids having diameters of 2 cm, 1.5 cm and 1 cm, respectively. When the diameter of the voids was 2 cm, Δt was 2,5 cm for GCL-4-W-D2 and when the diameter of

the voids was 1 cm, Δt became 0,7 cm for GCL-4-W-D1. Very low maximum thickness and Δt values obtained from GCL-4 samples are due to the engineering properties of the woven geotextile component (W2) of GCL-4. W2 has higher tensile strength than W1.

Table 4.24. GCL-4-W-D1 thickness results

Max. GCL Thickness (mm)	Average GCL Thickness (mm)	Δt (mm)
8	7,3	0,7

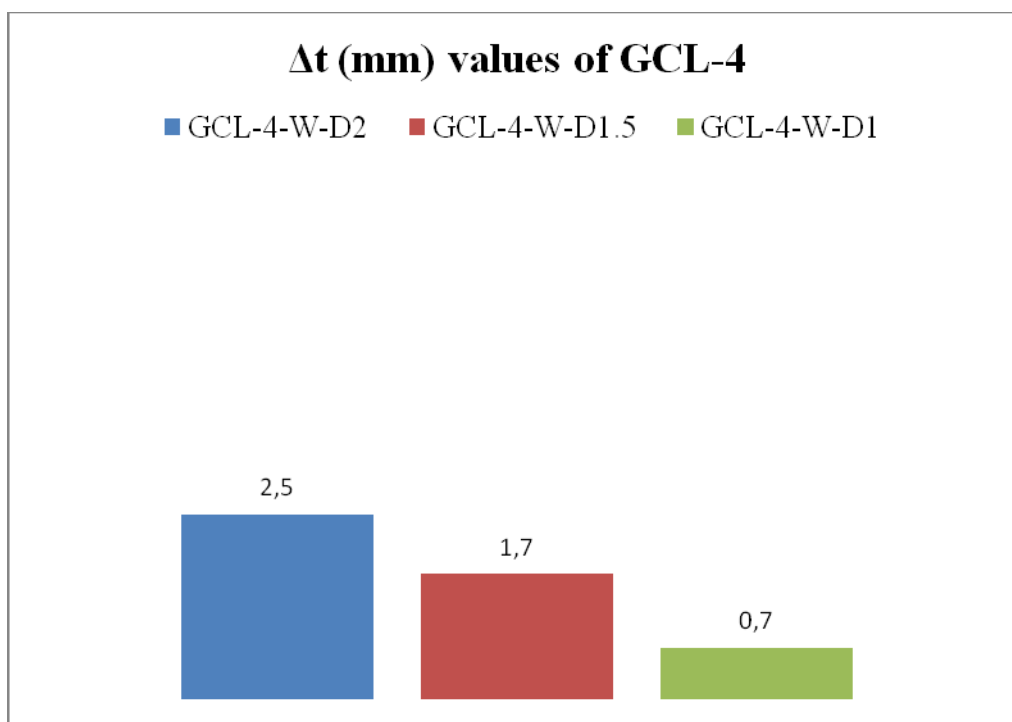


Figure 4.79. Observed deformations (Δt) on GCL-4 samples

4.3. Mass per Unit Area Results

As described in “Testing Methods” section, mass per unit area of the bentonite component of GCL-2, GCL-3 and GCL-4 was measured by taking four samples from the zones where a GCL sample faced the voids of the base (crest zones) and four samples from the zones where a GCL sample faced the solid base (flat zones) randomly.

The figures below for GCL-2, GCL-3 and GCL-4 show the average of the four measurements of mass per unit area values from both crests and flats. Mass per unit area values were higher for flat zones than those for crest zones. 0,61-0,66 g/cm² of mass per unit area was obtained when GCL-2 samples were tested over a porous stone instead of a base with voids. But low mass per unit area values such as 0,20-0,25 g/cm² were obtained from crests especially when the diameter of the voids of the base was higher and high mass per unit area values such as 0,55-0,63 g/cm² were obtained from flats when there was a base beneath a GCL-2 sample. However, the average difference of mass per unit area values between the crests and the flats was as low as 0,02 g/cm² as seen in figure 4.80 and 4.81 for GCL-2-W-D0.5 and GCL-2-NW-D0.5 samples because not any considerable amount of bentonite migration or internal erosion was detected for these GCL-2 samples.

As shown in figure 4.81, average mass per unit area values were obtained from the crest zones of GCL-2-NW-D2 with an average of 0,29 g/cm². Slightly higher mass per unit area values were obtained from the crests on the nonwoven geotextile components of the GCL-2 samples than the crests on the woven geotextile components of the GCL-2 samples when the GCL-2 samples were tested over the base that had the same void diameter. Average mass per unit area values were 0,25-0,40 g/cm² from the crests of the GCL samples that experienced internal erosion. However, average mass per unit area values were 0,61 g/cm² from the crests of the GCL samples that did not experience internal erosion. Lowest mass per unit area values were measured from the flat zones of GCL-2-W-D2 with an average of 0,54 g/cm².

0,64-0,66 g/cm² of mass per unit area was obtained when GCL-3 samples were tested over a porous stone instead of a base with voids. Low mass per unit area values with an average of 0,30-0,35 g/cm² were obtained from crests as seen in figure 4.83 and high mass per unit area values with an average of 0,54-0,58 g/cm² were obtained from flats as seen in figure 4.82 when there was a base beneath a GCL-3 sample. However, difference of mass per unit area values between the crests and the flats was as low as 0,03 g/cm² for GCL-3-W-D0.5 because not any considerable amount of bentonite migration or internal erosion occurred on GCL-3-W-D0.5 sample.

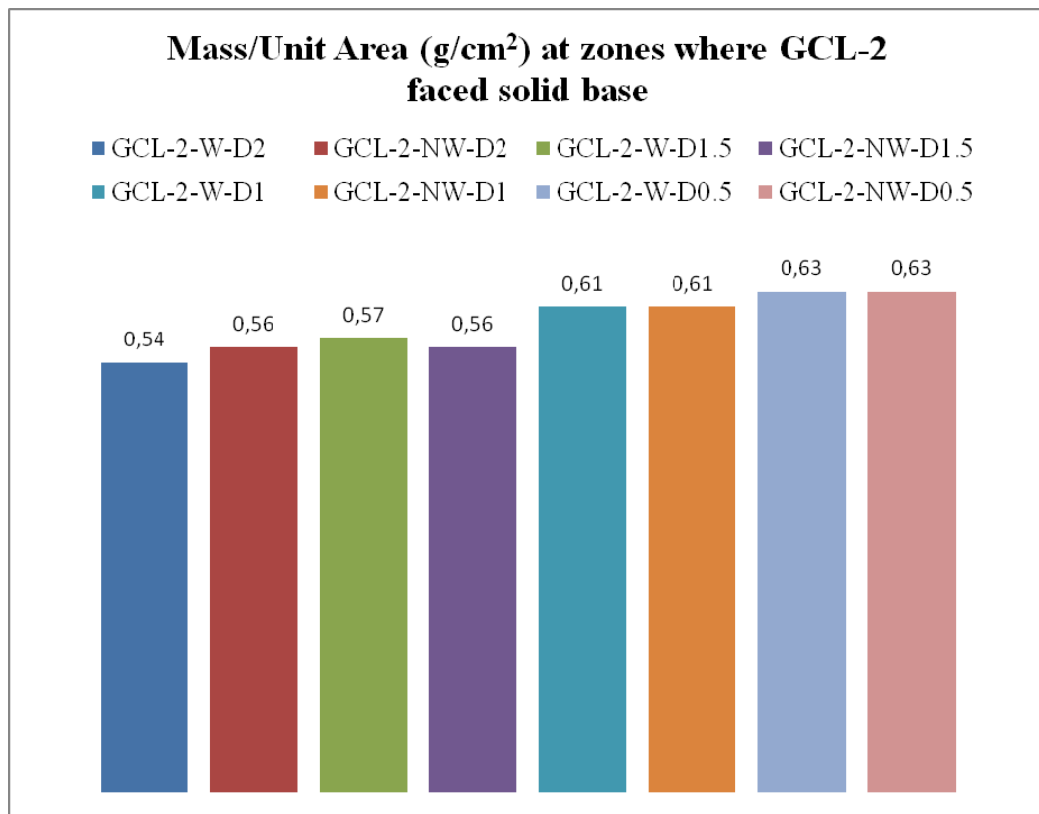


Figure 4.80. Mass per unit area measurements at zones where GCL-2 samples faced the solid base

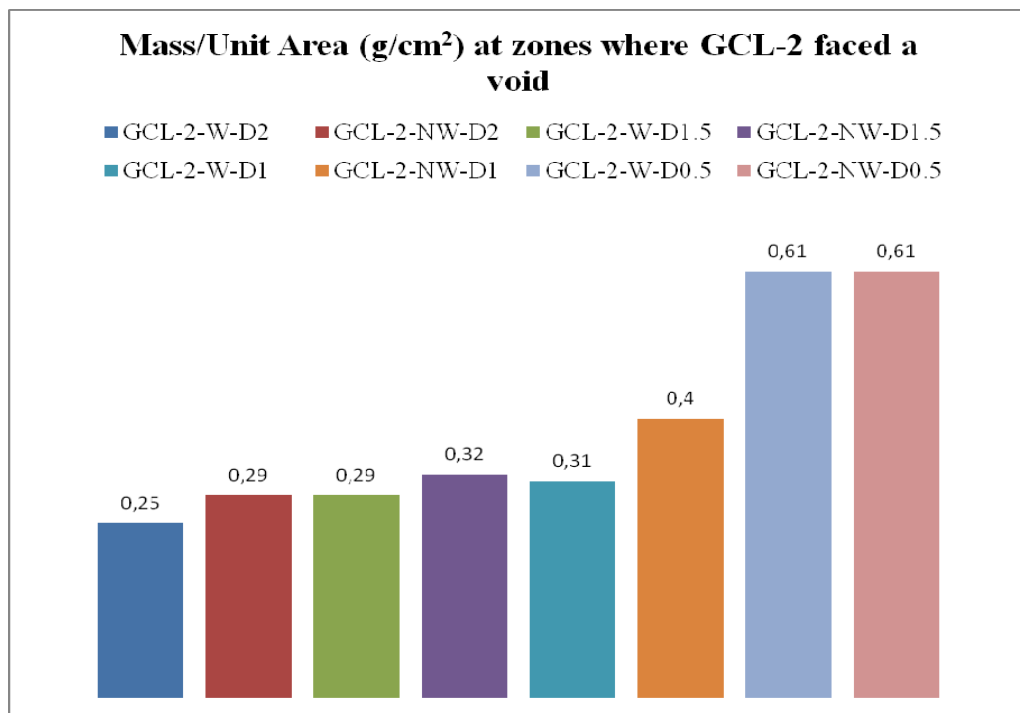


Figure 4.81. Mass per unit area measurements at zones where GCL-2 samples faced the voids

Mass per unit area values were 0,18-0,47 g/cm² from the crests of the GCL samples that experienced internal erosion. However, mass per unit area values were 0,58-0,62 g/cm² from the crests of the GCL sample that did not experience internal erosion. Lowest mass per unit area values were measured from the flat zones of GCL-3-W-D2 with an average of 0,54 g/cm².

0,66-0,68 g/cm² of mass per unit area was obtained when GCL-4 samples were tested over a porous stone instead of a base with voids. Differences between the mass per unit area values obtained from the crest and flat zones were very low as seen in figure 4.84 and 4.85 (with an average of 0,05 g/cm² for GCL-4-W-D2, 0,03 g/cm² for GCL-4-W-D1.5 and 0 for GCL-4-W-D1) for GCL-4 samples because bentonite migration or internal erosion did not occur when GCL-4 samples were tested over the bases under 50 m of hydraulic heads.

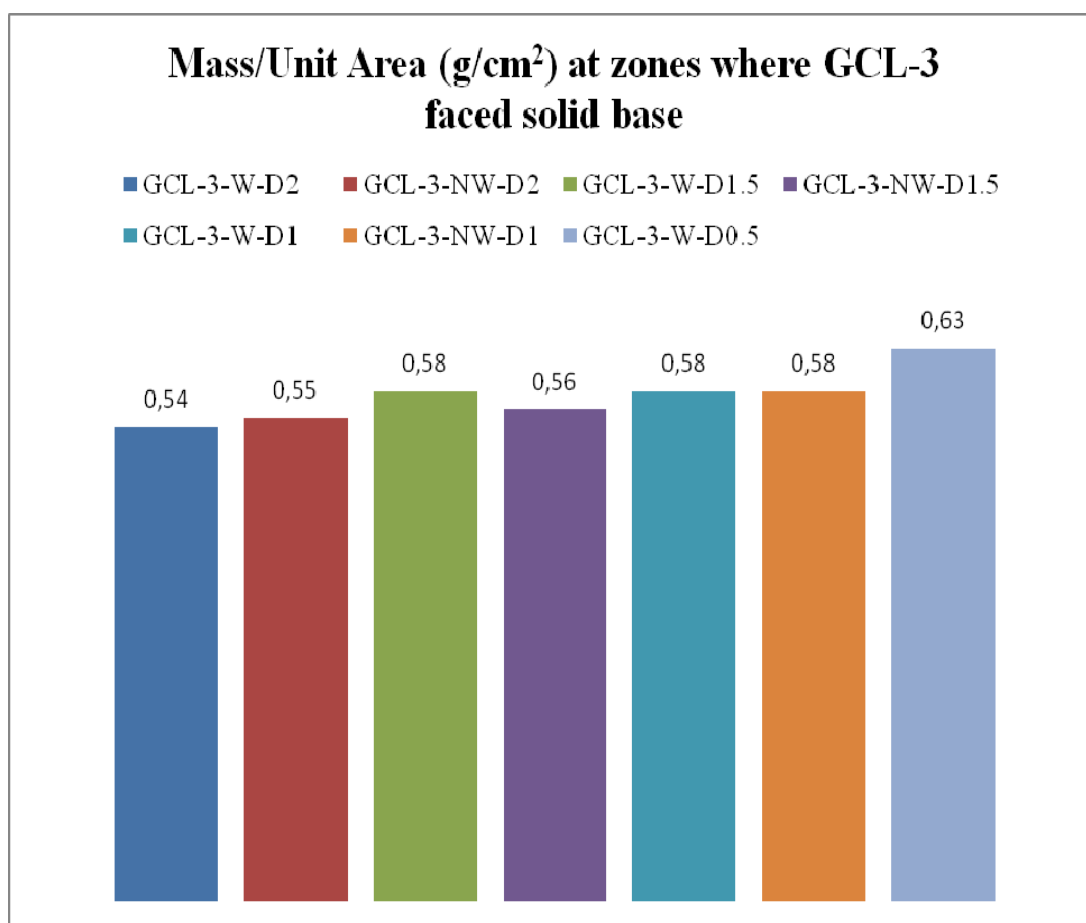


Figure 4.82. Mass per unit area measurements at zones where GCL-3 samples faced the solid base

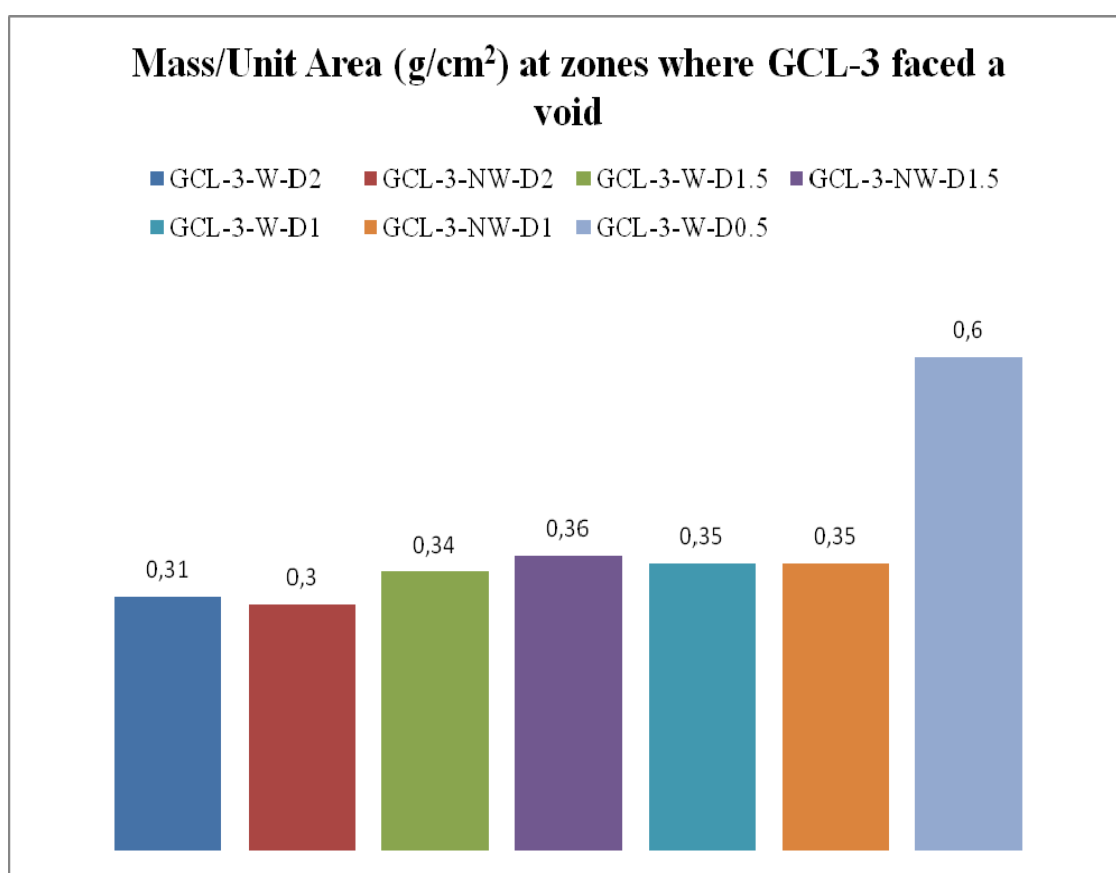


Figure. 4.83. Mass per unit area measurements at zones where GCL-3 samples faced the voids

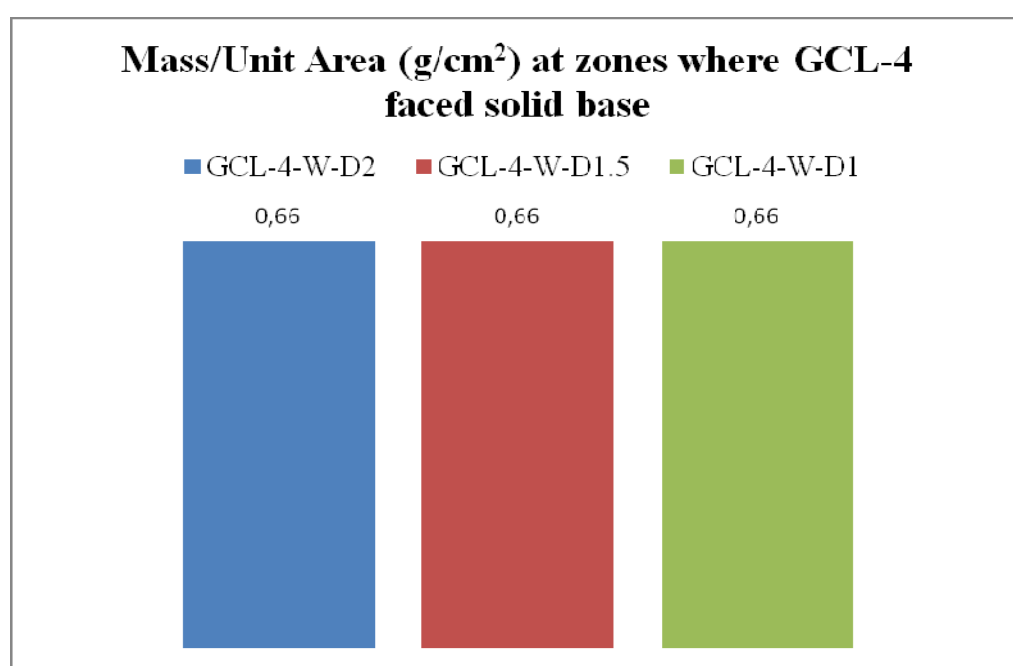


Figure 4.84. Mass per unit area measurements at zones where GCL-4 samples faced the solid base

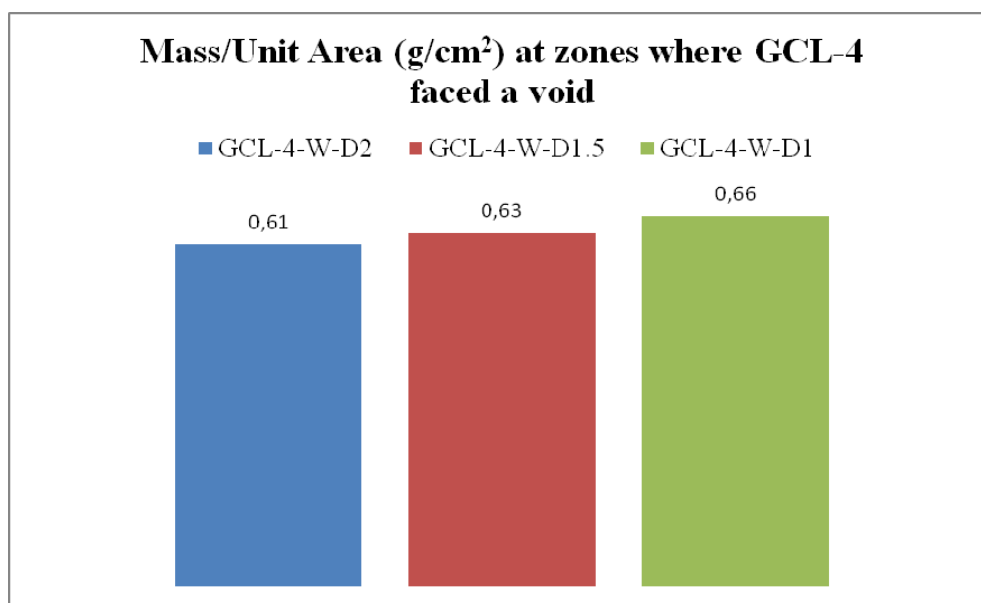


Figure 4.85. Mass per unit area measurements at zones where GCL-4 samples faced the voids

As shown in figure 4.85, lowest mass per unit area values were obtained from the crest zones of GCL-4-W-D2 with an average of $0,61 \text{ g/cm}^2$. Highest mass per area values among the crest zones were obtained from the crests of GCL-4-W-D1 with an average of $0,63 \text{ g/cm}^2$. For flat zones, average mass per unit area values of the GCL-4 samples were $0,66 \text{ g/cm}^2$ as seen in figure 4.84.

As a result, GCL-2, GCL-3 and GCL-4 samples behaved almost the same in terms of mass per unit area when they were tested over the bases with uniform voids under high hydraulic heads. Low mass per unit area values were obtained from the zones where a GCL sample faced the voids (crest zones). The samples which did not experience internal erosion or high amount of bentonite migration had also low mass per unit area differences between their crests and flats.

4.4. Moisture Content Results

As shown in figures 4.86 and 4.87, higher moisture contents were measured at the zones on the bentonite where a GCL sample faced a void (crest zone) than where a GCL sample faced the solid base (flat zone). Crests of GCL-1 samples tested over the bases with higher void diameters had higher water contents.

GCL-1-W-D2 crest samples had the highest water content with an average of 156 per cent among the samples taken from the crests. Crests of GCL-1-W-D1 and GCL-1-NW-D1 samples had the lowest water content values among the crest zones of GCL-1 samples. These samples were tested over the base which had the smallest void diameters as 1 cm. GCL-1-W-D1 and GCL-1-NW-D1 crest samples had water contents with averages of 91 per cent and 90 per cent, respectively. GCL-1 flat samples had average water contents not drastically different from each other ranging from 84 per cent to 97 per cent.

The difference between the average water contents measured at crest and flat zones was higher for the GCL-1 samples tested over the base with the higher void diameter. This difference was approximately 60 per cent for GCL-1-W-D2 sample while 6 per cent for GCL-1-W-D1 and GCL-1-NW-D1 samples. It is also observed from figures 4.86 and 4.87 that the difference of water content between the crests and the flats of the GCL-1 samples was lowest for the GCL samples which did not experience internal erosion. The crest zones of the GCL-1 samples that experienced internal erosion had high average water contents ranging from 147 per cent to 156 per cent.

As shown in figures 4.88 and 4.89, higher moisture contents were measured at the zones on the bentonite where a GCL sample faced a void (crest zone) than where a GCL sample faced the solid base (flat zone). Crests of GCL-2 samples tested over the bases with higher void diameters had higher water contents. The bentonite in contact with the woven geotextile component of the GCL-2 crest samples had also higher water contents than the bentonite in contact with the nonwoven geotextile component as seen in figures 4.88 and 4.89 when the GCL samples were tested over the same base.

GCL-2-W-D2 crest samples had the highest water content with an average of 191 per cent. GCL-2-W-D0.5 and GCL-2-NW-D0.5 samples had the lowest water content values among the crests. These samples were tested over the base that had the smallest void diameters as 0.5 cm. GCL-2-W-D0.5 and GCL-2-NW-D0.5 crest samples had average water contents of 89 per cent and 88 per cent. GCL-2 flat samples had water content values ranging from 65 per cent to 100 per cent.

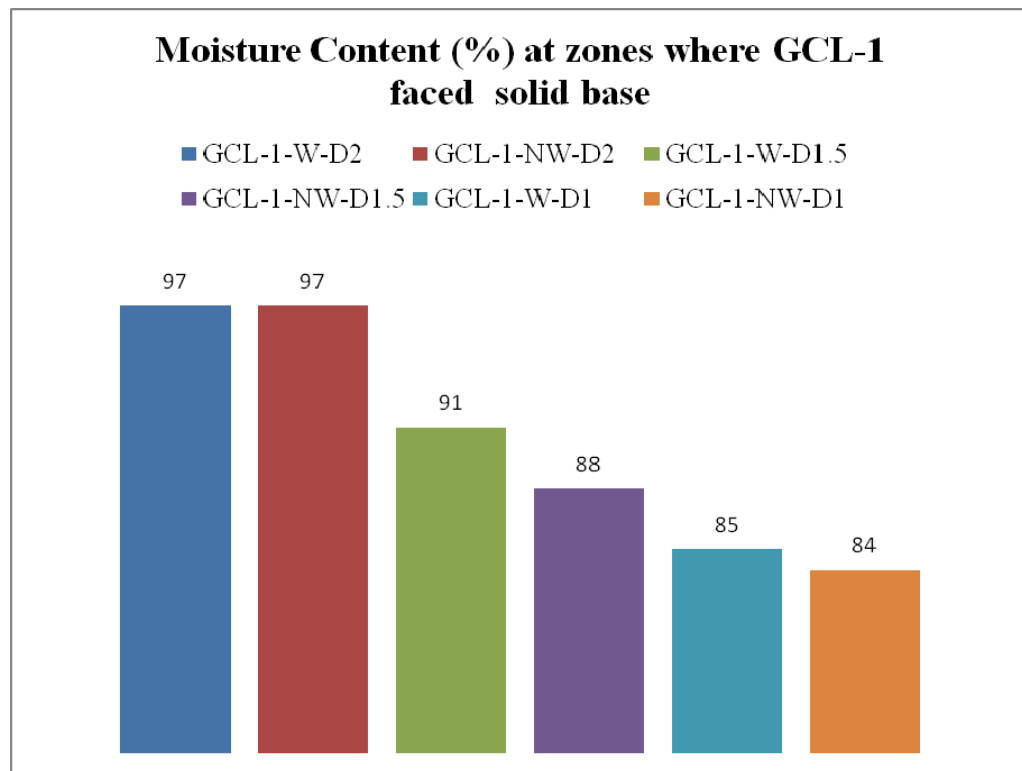


Figure 4.86. Moisture content measurements at zones where GCL-1 samples faced the solid base

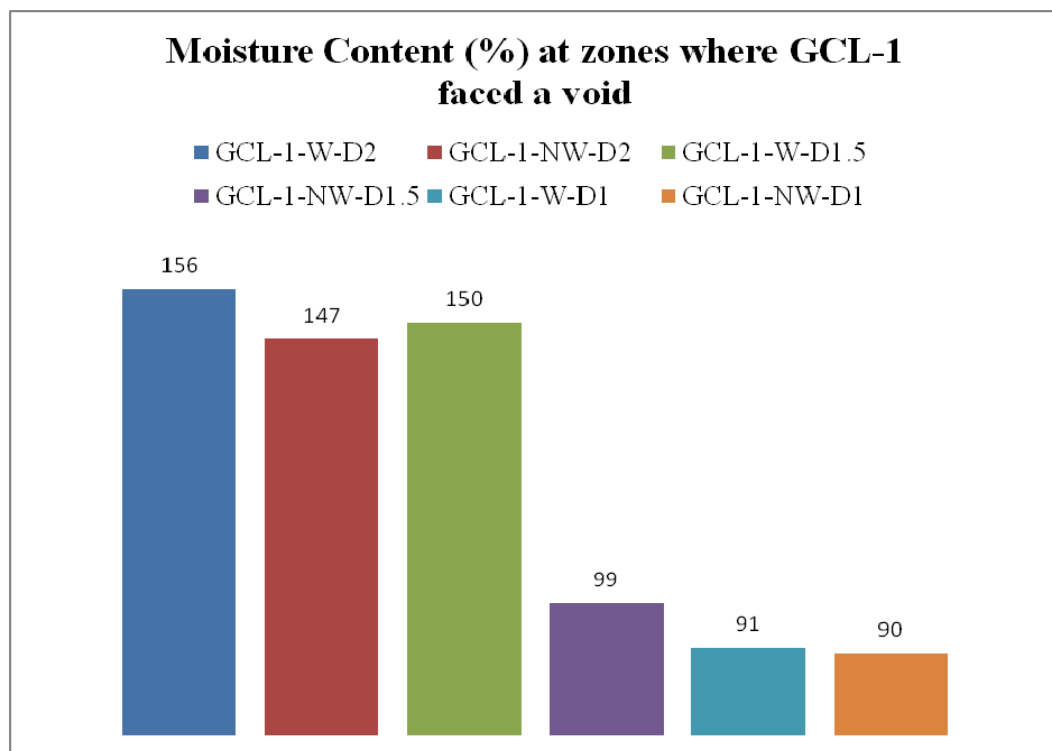


Figure 4.87. Moisture content measurements at zones where GCL-1 samples faced the voids

The difference between the average water contents measured at crest and flat zones was higher for the GCL-2 samples tested over the base with the higher void diameter. This difference was approximately 90 per cent for GCL-2-W-D2 sample while 6-7 per cent for GCL-2-W-D0.5 and GCL-1-NW-D1 samples. These differences were similar with those obtained from GCL-1 samples. It is also observed from figures 4.88 and 4.89 that the difference of water contents between the crests and the flats of the GCL-2 samples was lowest for the GCL samples which did not experience internal erosion or high amount of bentonite migration. The crest zones of the GCL-1 samples that experienced internal erosion had average water contents ranging from 132 per cent to 191 per cent.

As shown in figures 4.90 and 4.91, higher moisture contents were measured at the zones on the bentonite where a GCL sample faced a void (crest zone) than where a GCL sample faced the solid base (flat zone). Crests of GCL-3 samples tested over the bases with higher void diameters had higher water contents. The bentonite in contact with the woven geotextile component of the GCL-3 crest samples had also higher water contents than the bentonite in contact with the nonwoven geotextile component as seen in figures 4.90 and 4.91 when the GCL samples were tested over the same base.

GCL-3-W-D2 crest samples had the highest water content with an average of 196 per cent. Crests of GCL-3-W-D0.5 sample had the lowest water content values among the crests. This sample was tested over the base which had the smallest void diameters as 0.5 cm. GCL-3-W-D0.5 crest samples had water contents with an average of 86 per cent. GCL-3 flat samples had average water content values ranging from 82 per cent to 102 per cent.

The difference of water contents between the crests and flats was higher for the GCL-3 samples tested over the base with the higher void diameter. This difference was approximately 95 per cent for GCL-3-W-D2 sample while 4 per cent for GCL-3-W-D0.5 sample. These differences were similar with those obtained from GCL-1 and GCL-2 samples. The crest zones of the GCL-1 samples that experienced internal erosion had high average water contents ranging from 141 per cent to 196 per cent.

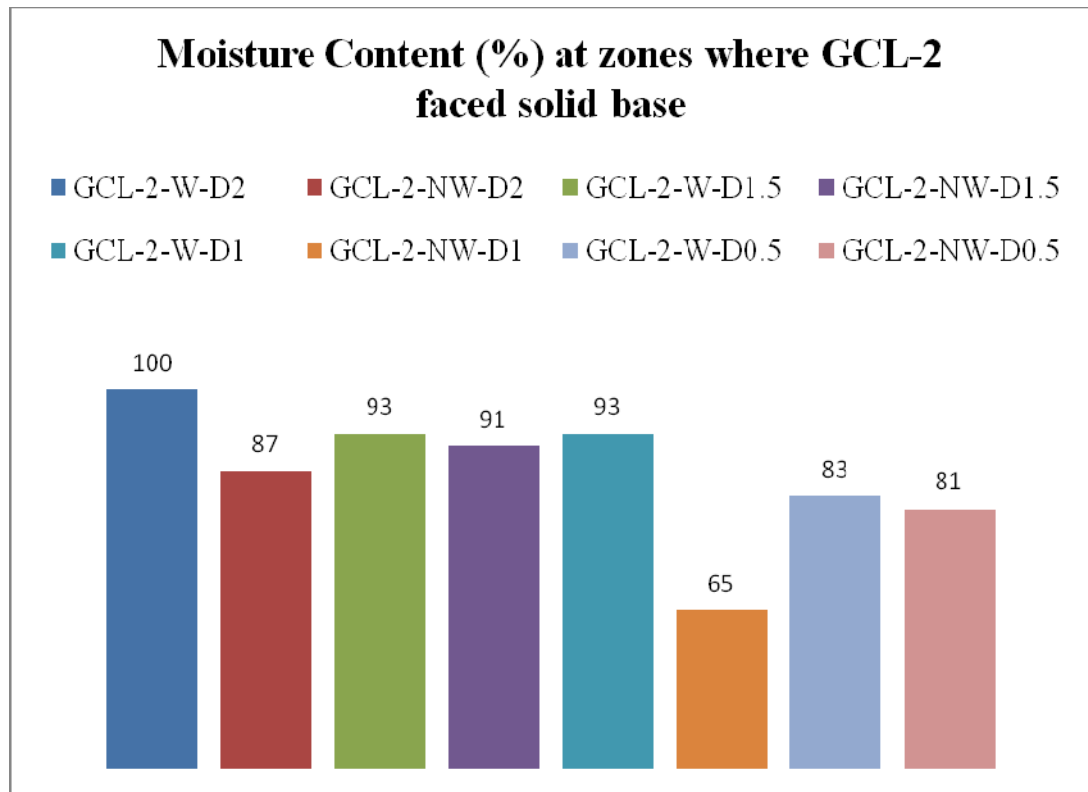


Figure 4.88. Moisture content measurements at zones where GCL-2 samples faced the solid base

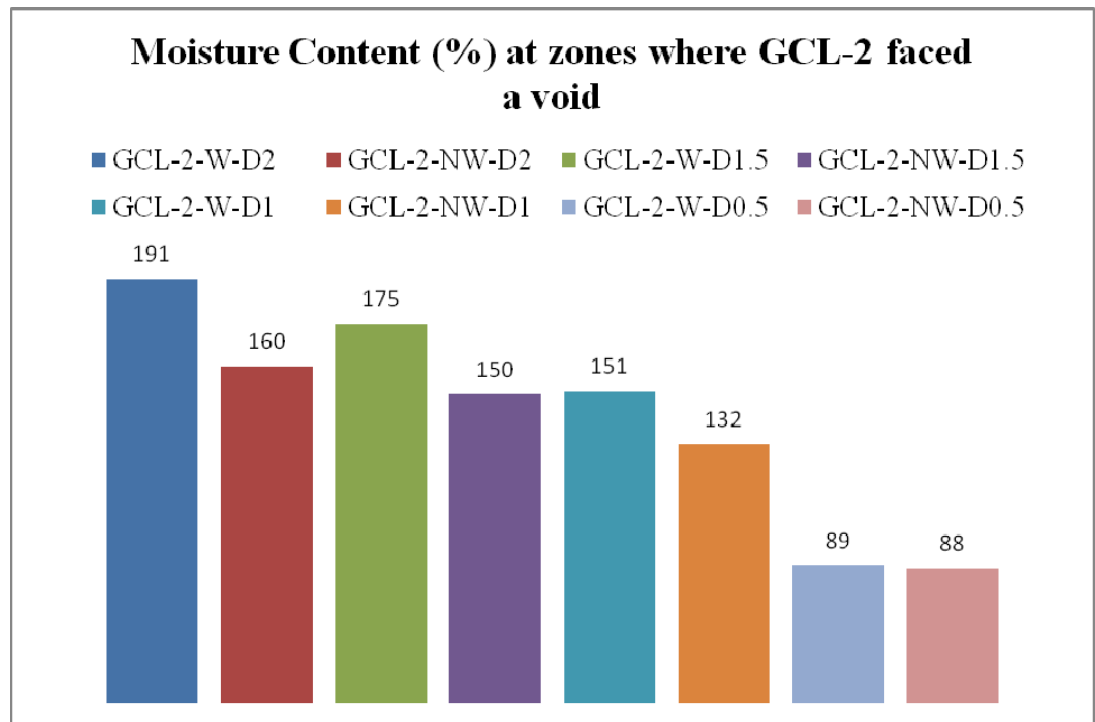


Figure 4.89. Moisture content measurements at zones where GCL-2 samples faced the voids

As shown in figures 4.92 and 4.93, crest zones of GCL-4 samples had almost the same water contents as flat zones had. Only the woven geotextile components of the GCL-4 samples over the bases having uniform void diameters of 2 cm, 1.5 cm and 1 cm were tested. Internal erosion and high amount of bentonite migration were not experienced for all of the tests conducted on GCL-4 samples. Because of this reason, water contents from the crest zones were not drastically higher than those from the flat zones.

GCL-4-W-D2 crest samples had average water contents of 93 per cent while GCL-4-W-D1 crest samples had 83 per cent. The average water contents from the flat zones were between 81 per cent and 84 per cent as shown in figure 4.92.

Even if the difference of average water contents between the crests and flats for GCL-4-W-D2 was 9 per cent and this value was the highest among the GCL-4 samples, this water content difference was a very low value when compared with GCL-1, GCL-2 and GCL-3 samples. This low difference also explains that all of the GCL-4 samples did not have high hydraulic conductivities due to very low amount of bentonite loss.

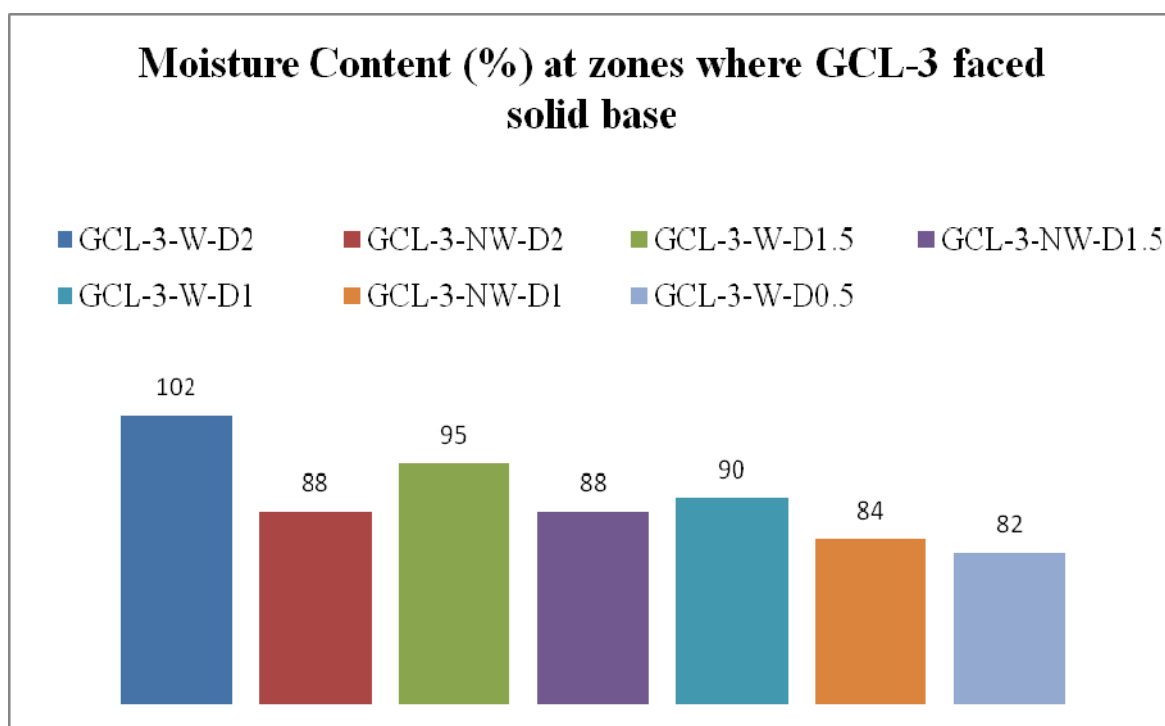


Figure 4.90. Moisture content measurements at zones where GCL-3 samples faced the solid base

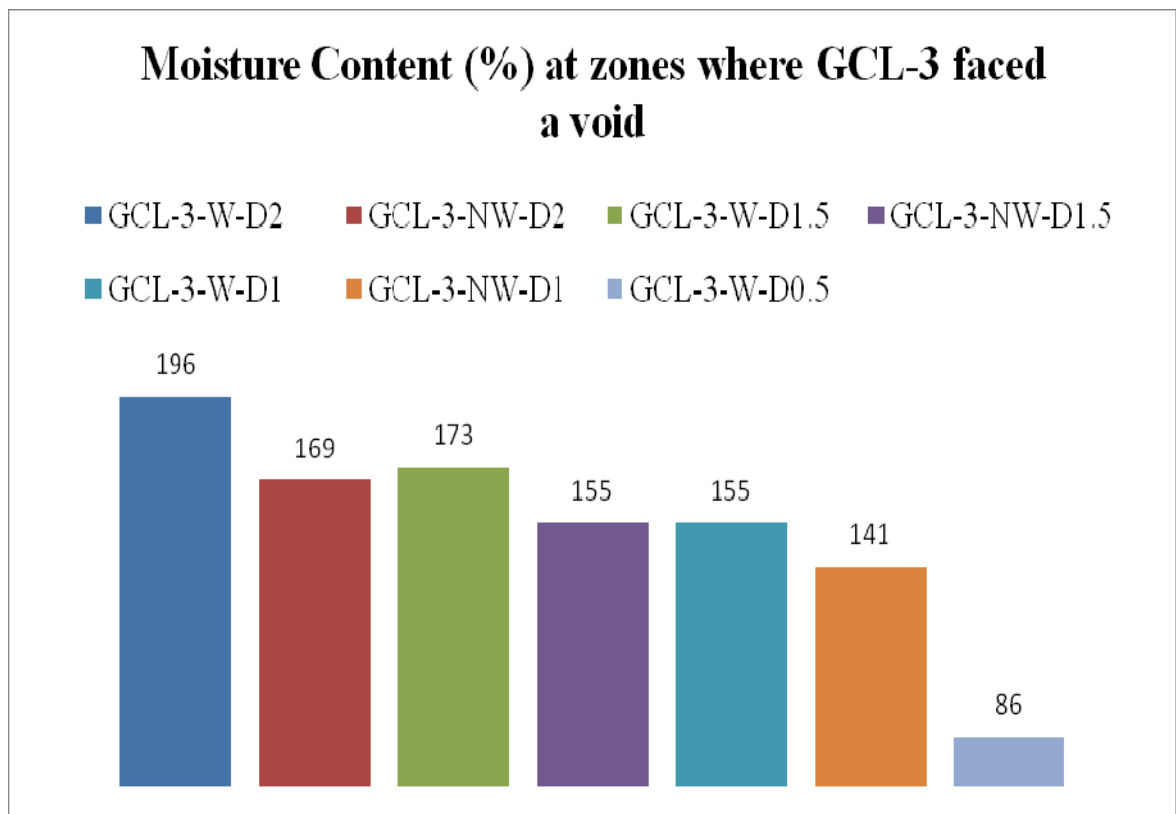


Figure 4.91. Moisture content measurements at zones where GCL-3 samples faced the voids

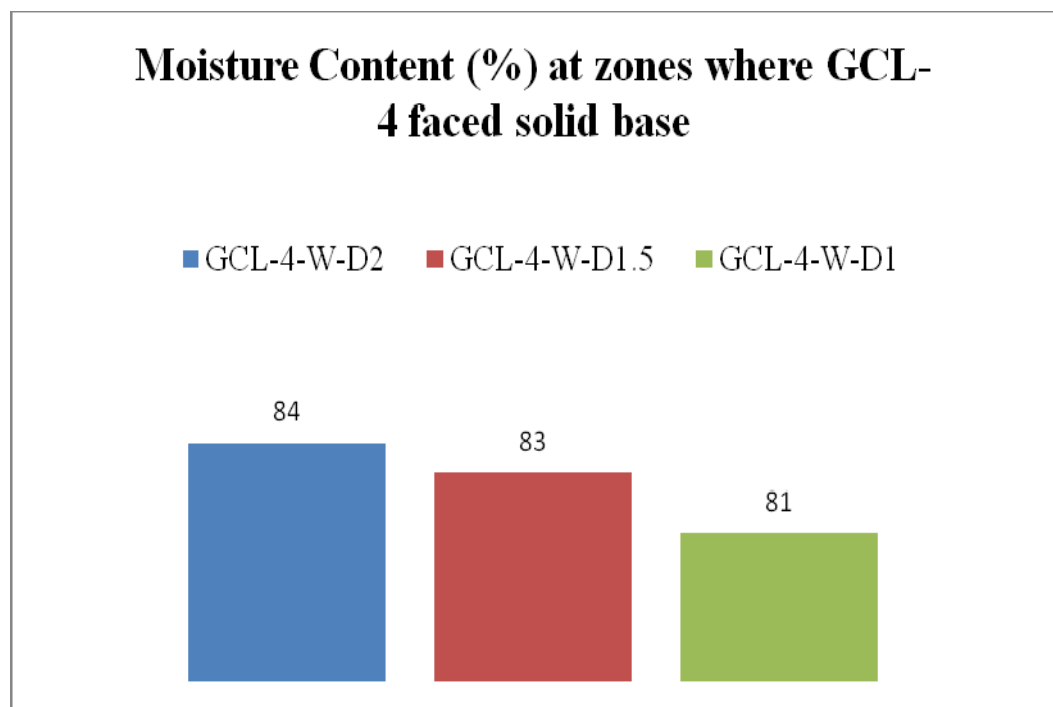


Figure 4.92. Moisture content measurements at zones where GCL-4 samples faced the solid base

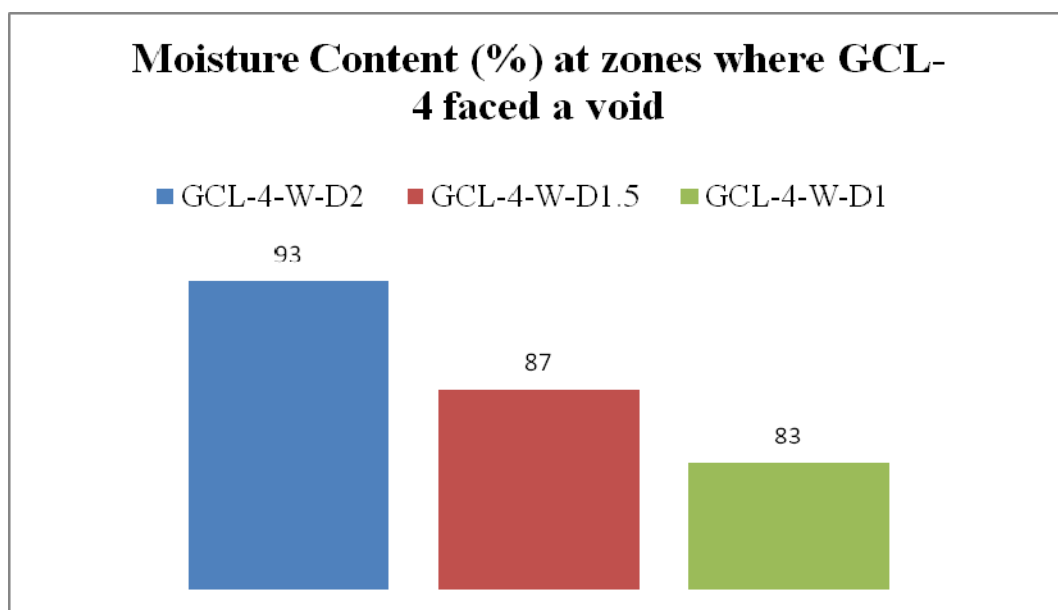


Figure 4.93. Moisture content measurements at zones where GCL-4 samples faced the voids

As a result, GCL-1, GCL-2, GCL-3 and GCL-4 samples behaved almost the same in terms of moisture content when they were tested over the bases with uniform voids under high hydraulic heads. High water contents were obtained at the zones on the bentonite where a GCL sample faced a void (crest zone), especially when the void diameter of the base was the highest. The difference of moisture content between the crest and flat zones was also higher for the samples tested over the base with the higher void diameter. The samples which did not experience internal erosion or high amount of bentonite migration had also low moisture content differences between their crests and flats.

5. EVALUATION OF TEST RESULTS

5.1. Hydraulic Conductivity and Internal Erosion

According to the flexible wall triaxial permeability test results, hydraulic conductivity parameters such as coefficient of permeability (k), permittivity (Ψ) and index flux (q_i) of the GCL samples increased approximately 3-5 orders of magnitude when a crucial amount of bentonite had migrated from the GCL samples under high hydraulic heads up to 50 m. The process where high amount of bentonite migration from a GCL sample occurred is called internal erosion. During internal erosion, hydraulic properties of the GCL sample deteriorate and the hydraulic conductivity parameters increase enormously.

High hydraulic water head was the reason to cause internal erosion for a GCL sample in this thesis. It took approximately 12 days which is equal to 288 hours to terminate a triaxial permeability test after the water head had been increased to the desired level. 12 day-elapsed time was chosen as the maximum period to decide whether internal erosion occurred or not for the GCL samples upon many trials. According to the results, internal erosion usually began during 100-200 hours after the desired hydraulic head had been maintained. Some of the GCL samples had not experienced internal erosion for 12 days even if the hydraulic head had been increased up to 50 m.

As shown in figure 5.1, only three of the eight GCL-1 samples experienced high amount of bentonite migration and internal erosion. Internal erosion occurred on GCL-1-W-D2, GCL-1-NW-D2 and GCL-1-W-D1.5 under 30 m, 35 m and 45 m hydraulic heads, respectively. Permittivities of these three samples increased more than four orders of magnitude in 100-200 elapsed time as seen in figure 5.1. However, the hydraulic conductivity parameters of the other GCL-1 samples did not increase drastically during almost 300-hour elapsed time.

As shown in figure 5.2, six of the ten GCL-2 samples experienced high amount of bentonite migration and internal erosion. Internal erosion occurred for GCL-2-W-D2, GCL-

2-NW-D2, GCL-2-W-D1.5, GCL-2-NW-D1.5, GCL-2-W-D1 and GCL-2-NW-D1 under 10 m, 20 m, 15 m, 35 m, 30 m and 50 m hydraulic heads, respectively. Permittivities of these samples increased approximately 4-5 orders of magnitude in 100-220 elapsed time as seen in figure 5.2. However, the permittivities of the other GCL-2 samples which were tested over the bases having 0.5 cm of void diameter and tested over only porous stone; not a base, did not increase during almost 300-hour elapsed time when the hydraulic head was 50 m.

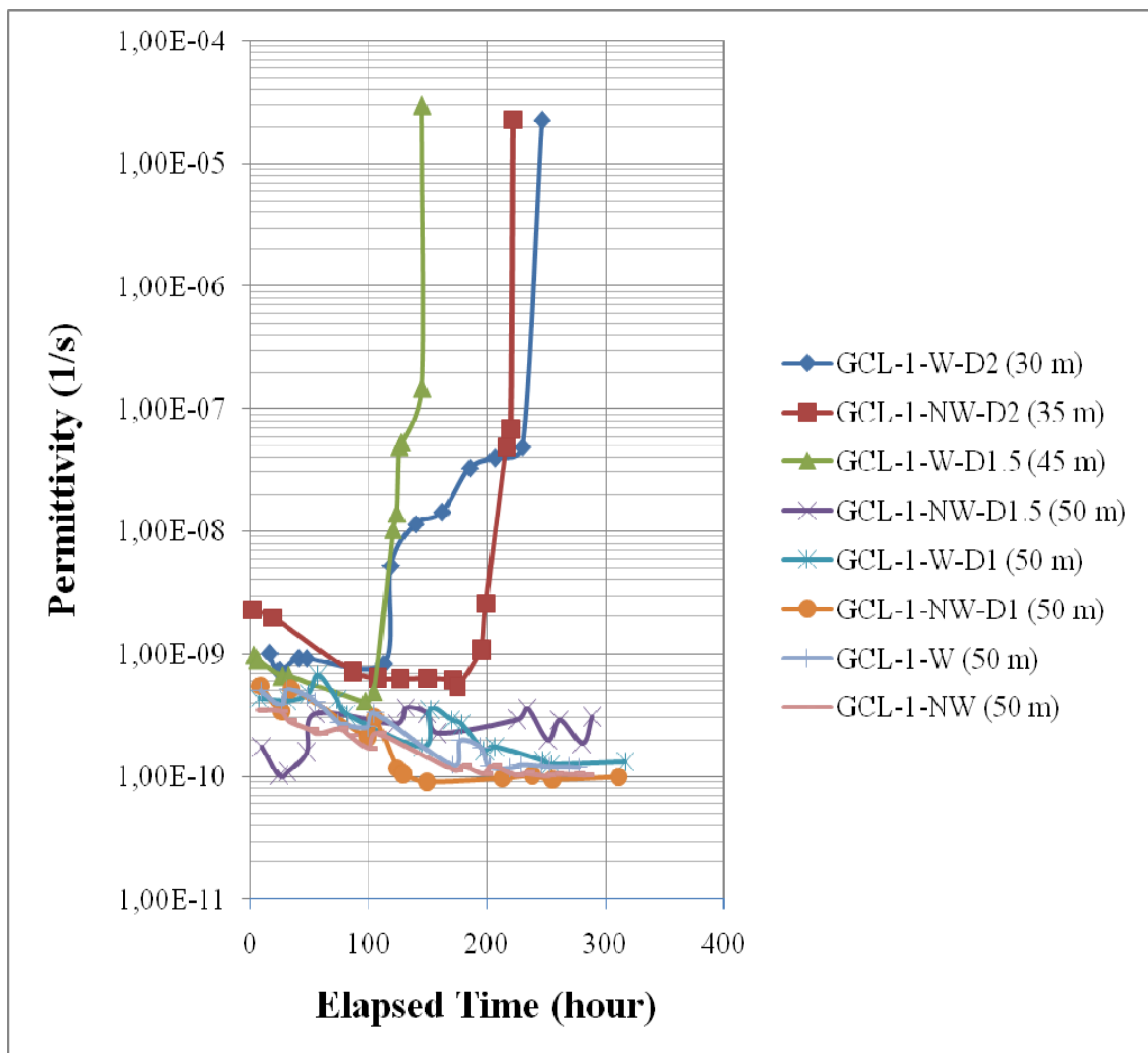


Figure 5.1. Permittivity (Ψ)-Elapsed Time (t) Graph for GCL-1 samples

As shown in figure 5.3, six of the ten GCL-3 samples also experienced high amount of bentonite migration and internal erosion. Internal erosion occurred for GCL-3-W-D2, GCL-3-NW-D2, GCL-3-W-D1.5, GCL-3-NW-D1.5, GCL-3-W-D1 and GCL-3-NW-D1 under 5

m, 20 m, 15 m, 35 m, 25 m and 50 m hydraulic heads, respectively. Permittivities of these samples increased approximately 3-5 orders of magnitude in 75-225 elapsed time as seen in figure 5.3. However, the permittivities of the other GCL-3 samples which were tested over the bases having 0.5 cm of void diameter and tested over only porous stone; not a base, did not increase during almost 300-hour elapsed time when the hydraulic head was 50 m.

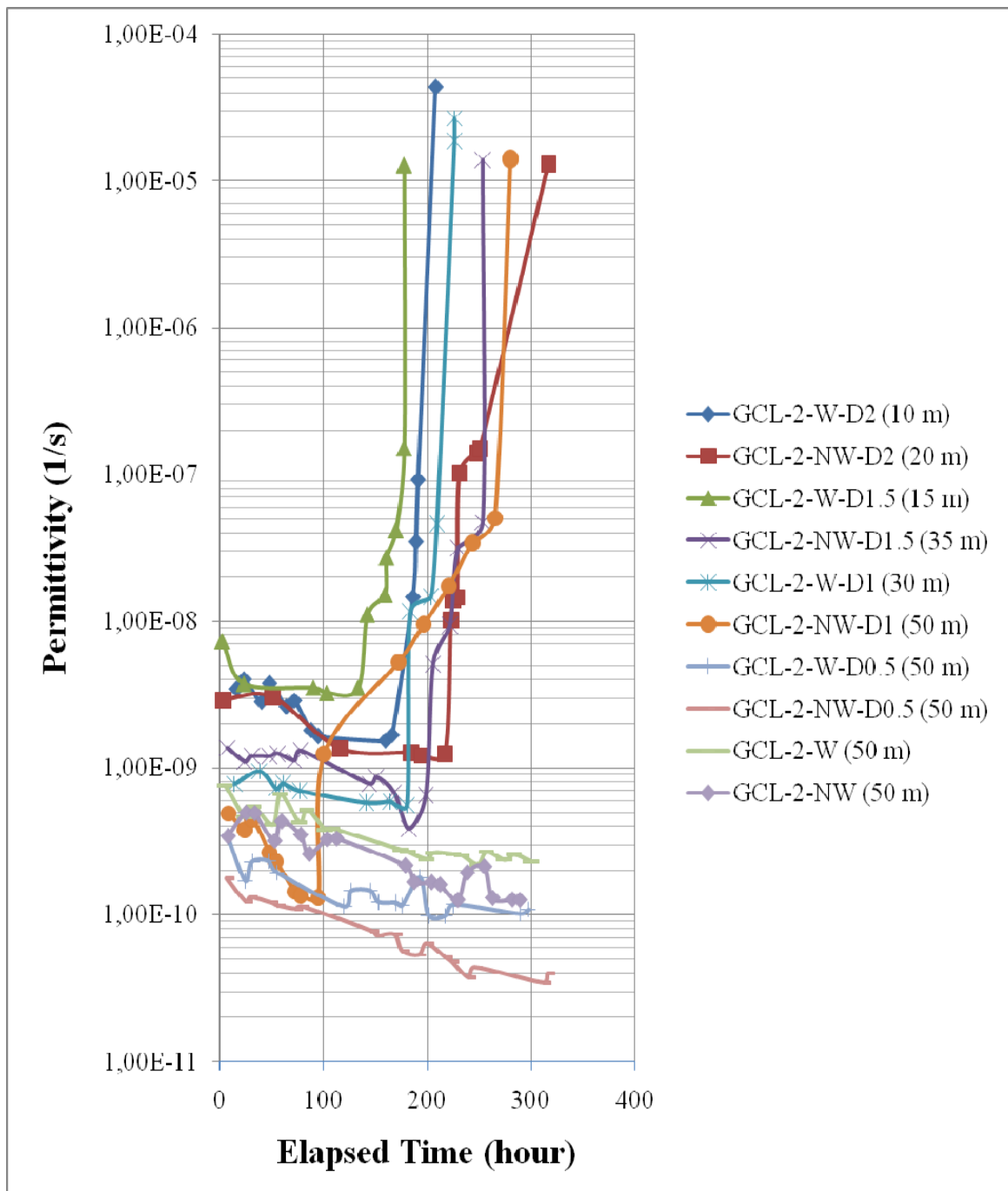


Figure 5.2. Permittivity (Ψ)-Elapsed Time (t) Graph for GCL-2 samples

As shown in figure 5.4, none of the three GCL-4 samples experienced high amount of bentonite migration and internal erosion. Permittivities of these samples decreased approximately half order of magnitude during approximately 250-hour elapsed time as seen in figure 5.4. GCL-4-W-D2 had the lowest and GCL-4-W-D1 had the highest permittivity at the end of approximately 250 hours when the hydraulic head was 50 m.

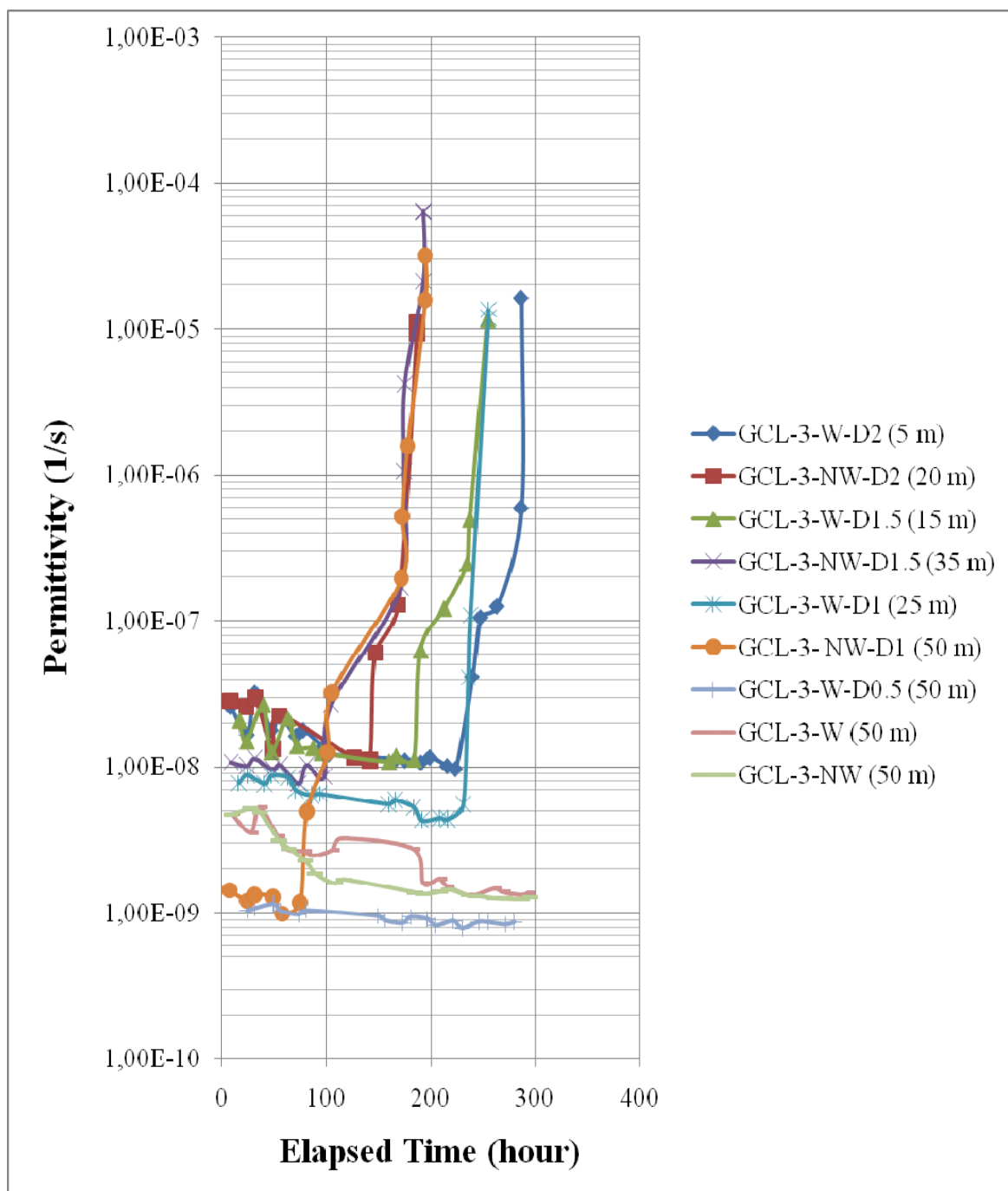


Figure 5.3. Permittivity (Ψ)-Elapsed Time (t) Graph for GCL-3 samples

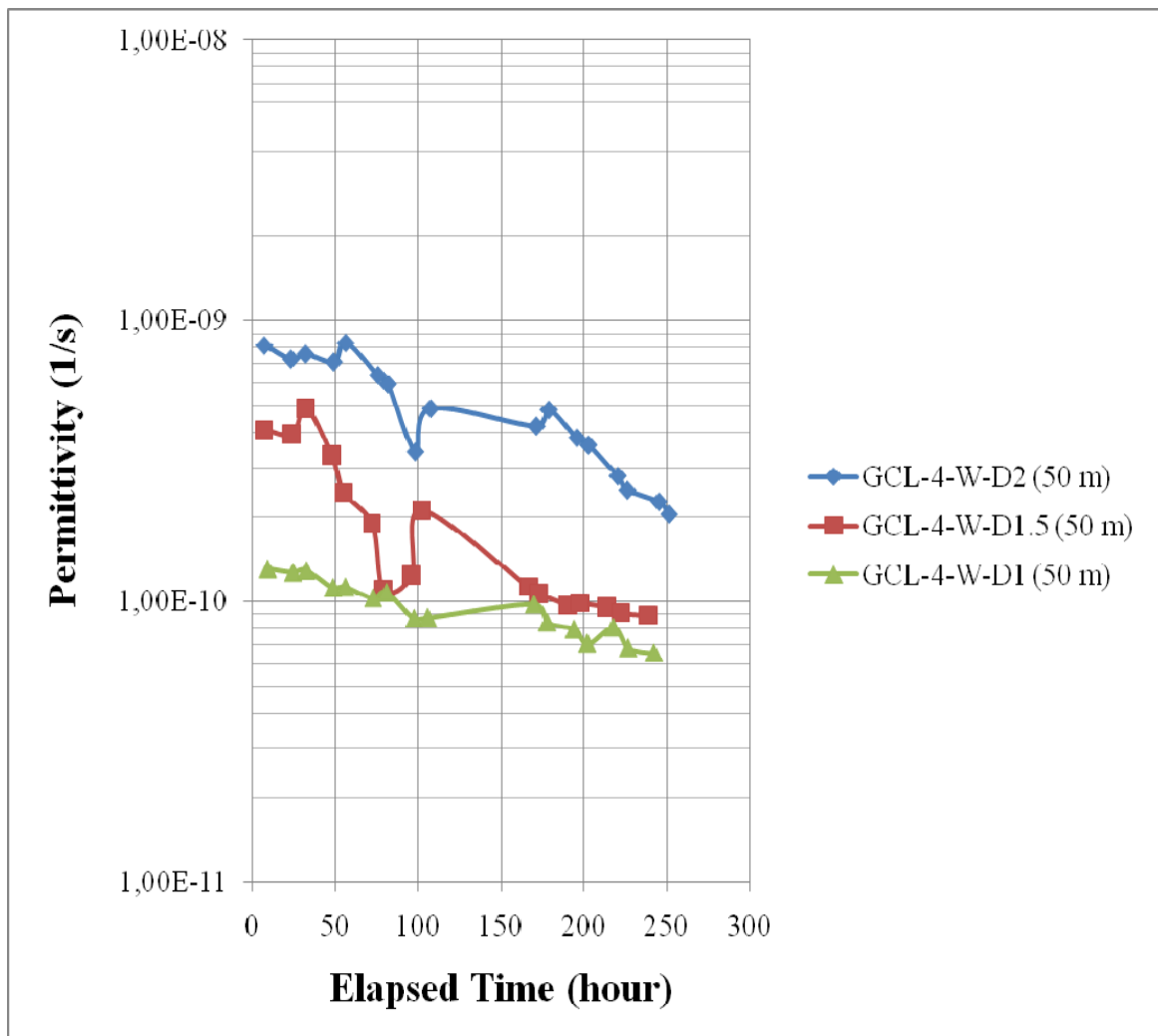


Figure 5.4. Permittivity (Ψ)-Elapsed Time (t) Graph for GCL-4 samples

The GCL samples were also evaluated according to the void diameter sizes of the bases which they were tested over. As shown in figure 5.5, only one of the seven GCL samples tested over the base with uniform voids having 2 cm diameter did not experience internal erosion and its permittivity decreased after approximately 250 hours when the hydraulic head had been increased up to 50 m. Internal erosion occurred for GCL-3-W-D2, GCL-2-W-D2, GCL-3-NW-D2, GCL-2-NW-D2, GCL-1-W-D2 and GCL-1-NW-D2 samples under 5 m, 10 m, 20 m, 20 m, 30 m and 35 m, respectively. Only GCL-4-W-D2 sample kept its low hydraulic conductivity parameters even under 50 m as seen in figure 5.5.

As shown in figure 5.6, five of the seven GCL samples tested over the base with uniform voids having 1.5 cm diameter experienced internal erosion. Internal erosion

occured for GCL-3-W-D1.5, GCL-2-W-D1.5, GCL-3-NW-D1.5, GCL-2-NW-D1.5 and GCL-1-W-D1.5 samples under 15 m, 15 m, 35 m, 35 m and 45 m, respectively. Only GCL-1-NW-D1.5 and GCL-4-W-D1.5 samples kept their low hydraulic conductivity parameters even under 50 m as seen in figure 5.6.

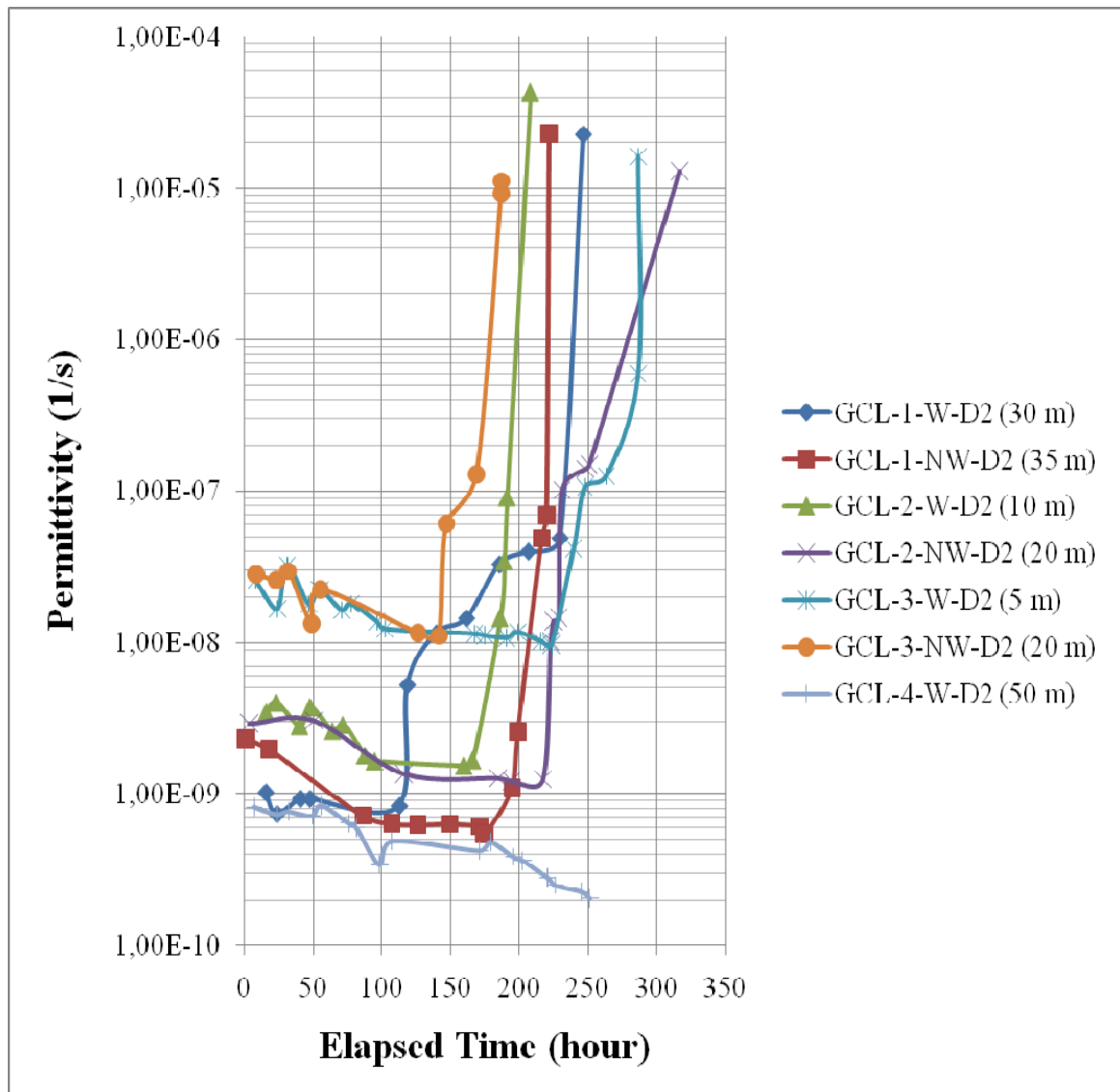


Figure 5.5. Permittivity (Ψ)-Elapsed Time (t) Graph for GCL samples tested over the base with uniform voids having 2 cm diameter

As shown in figure 5.7, only four of the seven GCL samples tested over the base with uniform voids having 1 cm diameter experienced internal erosion. Internal erosion occurred for GCL-3-W-D1, GCL-2-W-D1, GCL-3-NW-D1 and GCL-2-NW-D1 samples under 25 m, 30 m, 50 m and 50 m, respectively. GCL-1-W-D1, GCL-1-NW-D1 and GCL-

4-W-D1 samples kept their low hydraulic conductivity parameters even under 50 m as seen in figure 5.7.

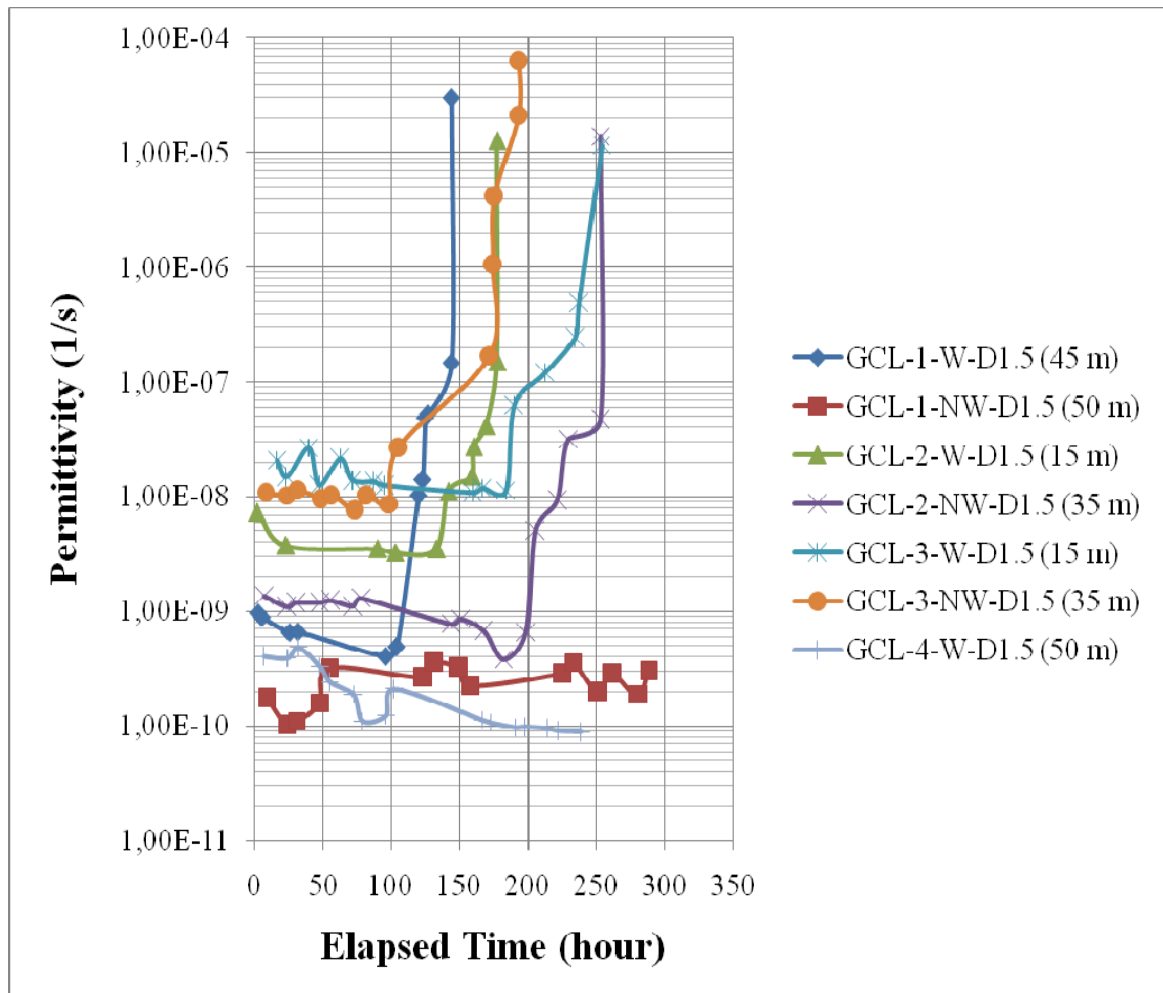


Figure 5.6. Permittivity (Ψ)-Elapsed Time (t) Graph for GCL samples tested over the base with uniform voids having 1.5 cm diameter

When the hydraulic conductivity parameters obtained from the triaxial permeability tests are investigated, it is observed that GCL-2 and GCL-3 samples are the worst in terms of internal erosion after the termination of the tests.

As shown in figures 5.5, 5.6 and 5.7, GCL-2 and GCL-3 samples experienced internal erosion when they were placed over the bases with uniform voids having 2 cm, 1.5 cm and 1 cm. Hydraulic heads which caused high amount of bentonite migration and internal erosion were almost the same for both GCL-2 and GCL-3 samples. Only GCL-3-W-D2 and GCL-3-W-D1 experienced internal erosion under hydraulic heads of 5 m and 25

m, respectively while GCL-2-W-D2 and GCL-2-W-D1 experienced it under 10 m and 30 m, respectively. Internal erosion occurred under the same hydraulic head for all of the GCL-2 and GCL-3 NW samples.

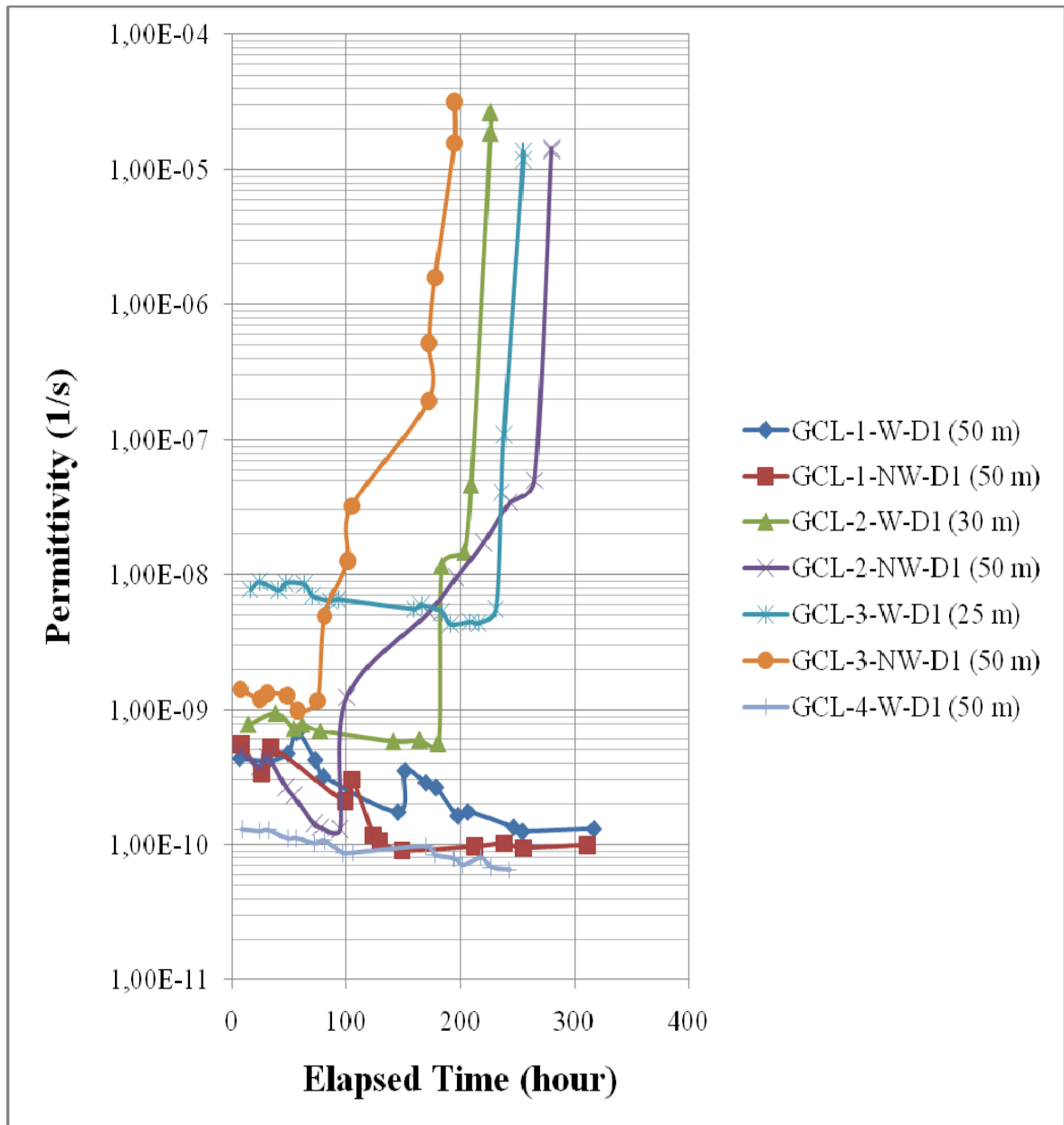


Figure 5.7. Permittivity (Ψ)-Elapsed Time (t) Graph for GCL samples tested over the base with uniform voids having 1 cm diameter

Even if the hydraulic conductivity parameters of GCL-3 samples had been approximately one order of magnitude higher than those of GCL-2 samples before internal erosion occurred, both GCL-2 and GCL-3 samples experienced internal erosion almost

under the same hydraulic heads and the hydraulic conductivity parameters increased to almost the same level for both GCL-2 and GCL-3 samples. According to the results and figures 5.5, 5.6 and 5.7, performance of GCL-2 samples against bentonite migration and internal erosion was only slightly better than that of GCL-3 samples when the GCL samples were tested over bases with circular, uniform voids having 2 cm, 1.5 cm, 1 cm diameters under high hydraulic heads.

Although calcium bentonite has higher hydraulic conductivity than sodium bentonite, both GCL-2 (SB used between woven (W1) and nonwoven (NW) geotextiles) and GCL-3 (CB used between woven (W1) and nonwoven (NW) geotextiles) samples behaved almost the same under high hydraulic heads.

As shown in figures 5.5, 5.6 and 5.7, performance of the GCL-1 samples against internal erosion was better than that of GCL-2 and GCL-3 samples. GCL-1-NW-D1.5, GCL-1-W-D1 and GCL-1-NW-D1 samples did not experience internal erosion even under 50 m of hydraulic heads while all of the GCL-2 and GCL-3 samples tested over the bases with circular, uniform voids having 2 cm, 1.5 cm and 1 cm experienced internal erosion. Hydraulic heads which caused internal erosion for GCL-1 samples were also higher than those for GCL-2 and GCL-3 samples when the bases beneath the GCL samples had the same void sizes. For instance, GCL-1-W-D2 and GCL-1-NW-D2 experienced internal erosion under hydraulic heads of 30 m and 35 m, respectively while GCL-2-W-D2 and GCL-2-NW-D2 experienced internal erosion under hydraulic heads of 10 m and 20 m, respectively as shown in figure 5.5.

Main reason for the better performance of GCL-1 samples against internal erosion than GCL-2 and GCL-3 samples and bentonite migration was the existence of the needlepunched fibres on the GCL-1 samples. These needle-punched fibres manufactured from the nonwoven geotextile component (N1) through the bentonite (SB) to the woven geotextile component (W1) of a GCL-1 sample limited the deformation of GCL-1 samples under high hydraulic heads and helped the bentonite (SB) to be distributed more uniformly inside the GCL sample. With the help of the needlepunched fibres, difference between the maximum thickness and the average thickness of a GCL-1 sample was measured lower than that of a GCL-2 or GCL-3 sample and the needlepunched fibres on the crest zones of

a GCL-1 sample prevented more bentonite to migrate out vertically from the GCL-1 sample.

The nonwoven geotextile component (N1) performed better against internal erosion than the woven geotextile component (W1) of all of GCL-1, GCL-2 and GCL-3 samples when the GCL samples were tested over the bases under high hydraulic heads as shown in figures 5.5, 5.6 and 5.7. For GCL-1 samples, difference between the hydraulic heads which caused internal erosion when W1 was in contact with the bases and the hydraulic heads which caused internal erosion when N1 was in contact with the bases was not so high. For instance, GCL-1-W-D1 experienced internal erosion under 30 m where GCL-1-NW-D1 experienced internal erosion under 35 m (the head difference was 5 m). This difference was higher for GCL-2 and GCL-3 samples. For instance, GCL-3-W-D1 experienced internal erosion under 5 m where GCL-3-NW-D1 experienced internal erosion under 20 m (the head difference was 15 m).

The difference became even higher when the diameter of the base voids became higher. For GCL-2-W-D2 and GCL-2-NW-D2, internal erosion occurred under 10 m and 20 m, respectively where for GCL-2-W-D1.5 and GCL-2-NW-D1.5, internal erosion occurred under 15 m and 35 m, respectively.

One of the main reasons for the better performance of the nonwoven geotextile (N1) against internal erosion and bentonite migration than the woven geotextile (W1) is the higher rigidity of W1 rather than N1. Because of the higher rigidity of W1, some of the slit film tapes on the crest zones of the woven geotextile component (W1) were damaged. When the slit film tapes on the woven geotextile (W1) were damaged, the openings between the slit film tapes got larger and high amount of the bentonite from the GCL sample migrated through the woven geotextile component (W1) into the effluent burette.

As shown in figure 5.4, GCL-4 samples performed the best against internal erosion among all of the tested GCL samples under high hydraulic heads. GCL-4 samples did not experience internal erosion when the woven geotextile components (W2) were placed over the bases with uniform voids having 2 cm, 1.5 cm and 1 cm diameters, respectively under even 50 m of hydraulic heads.

Main reason for the high performance of GCL-4 samples against internal erosion was the high tensile strength of the woven geotextile component (W2). The tensile strength of W2 is approximately three and a half times of that of W1. Differences between the maximum and average thicknesses of GCL-4 samples were also very low when compared with those for GCL-1, GCL-2 and GCL-3 samples. Due to these low thickness differences, high amount of bentonite extrusion from the openings on the crest zones of GCL-4 samples under high hydraulic heads was prevented and internal erosion did not occur. High tensile strength of W2 also prevented the formation of defects on the slit film tapes on the woven geotextile component (W2) of a GCL-4 sample. Low deformations of the crest zones were due to the high tensile strength and durability of the woven geotextile component (W2). When the deformations were low, the openings of the crest zones remained small which prevented high amount of vertical bentonite extrusion through the woven geotextile component (W2) of a GCL-4 sample.

Void size of the base plays an important role on the bentonite migration from a GCL sample. When the void size was larger, the amount of the migrated bentonite was also higher and internal erosion occurred on the GCL samples under lower hydraulic heads.

As shown in figure 5.5, all of the GCL samples except GCL-4-W-D2 sample experienced internal erosion when they were tested over the base with uniform circular voids having 2 cm diameter (representing uniform rounded gravel subgrade having approximately 5 cm diameter). The lowest and highest hydraulic heads which caused internal erosion were 5 m for GCL-3-W-D2 and 35 m for GCL-1-NW-D2, respectively.

As shown in figure 5.6, performance of the base with uniform circular voids having 1.5 cm diameter against internal erosion (representing uniform rounded gravel subgrade having approximately 3.75 cm diameter) was better than that of the base with uniform circular voids having 2 cm diameter. The lowest and highest hydraulic heads which caused internal erosion were 15 m for GCL-3-W-D1.5 and 45 m for GCL-1-W-D1.5, respectively.

As shown in figure 5.7, performance of the base with uniform circular voids having 1 cm diameter against internal erosion (representing uniform rounded gravel subgrade having approximately 2.5 cm diameter) was better than that of the base with uniform

circular voids having 1.5 cm diameter. The lowest and highest hydraulic heads which caused internal erosion were 25 m for GCL-3-W-D1 and 50 m for GCL-3-NW-D1 and GCL-2-NW-D1, respectively.

Performance of the base with uniform circular voids having 0.5 cm diameter against internal erosion (representing uniform rounded gravel subgrade having approximately 1.25 cm diameter) was the best among four different bases with four different void sizes. All of the GCL samples tested over the base with uniform circular voids having 0.5 cm diameter did not experience internal erosion even under 50 m of hydraulic head.

Due to the configuration of the triaxial permeability test apparatus, lower hydraulic conductivities were measured from the same GCL samples when the effective stress had been increased until internal erosion was experienced. For example, approximately one order of magnitude lower hydraulic conductivity was measured from a GCL sample that was tested under 50 m of hydraulic head when compared to the hydraulic conductivity measured from the same GCL sample that was tested under 5 m of hydraulic head.

To increase the hydraulic head, influent pressure, which was applied at the contact point between the bentonite component and the upper geotextile component of a GCL sample, where water inflowed, was kept constant while effluent pressure, which was applied at the contact point between the bentonite component and the lower geotextile component of the same GCL sample, where water outflowed, was decreased. When the hydraulic head was increased, cell pressure and influent pressure were kept constant as 550 kPa and 530 kPa, respectively while the effluent pressure was decreased to the desired level. For example, under 5 m of hydraulic head, the effluent pressure was 480 kPa. When the hydraulic head was increased to 50 m, the effluent pressure was decreased to 40 kPa. As a result, effective pressure applied at the contact point between the bentonite component and the lower geotextile component of the GCL sample became 510 kPa under 50 m of hydraulic head while it had been 70 kPa under 5 m of hydraulic head.

Higher deformation of the lower geotextile component of a GCL sample is predicted to be due to the higher effective pressure applied at the contact point between the bentonite component and the lower geotextile component of the GCL sample while lower

deformation on the upper geotextile component of the same GCL sample was due to the lower effective pressure, as 20 kPa, applied at the contact point between the bentonite component and the upper geotextile component of the GCL sample.

When the void size of a base got larger, the thickness and the area of the crest zone also got larger. Crest zones were formed at the contact points of a GCL sample and the voids of a base under high hydraulic head. High amount of bentonite could migrate from the openings and damaged regions on the crest zones of the geotextile component of a GCL sample as shown in figure 5.8.

Slightly lower increase, up to one order of magnitude in hydraulic conductivity measured from the GCL samples can be interpreted as a sign that internal erosion started. By facing high effective stress, the lower geotextile component began to deform and after an elapsed time, some bentonite particles began to migrate out of the lower geotextile which caused an increase up to one order of magnitude in hydraulic conductivity. As time passed, the lower geotextile could not resist high effective stresses which caused more bentonite particles to extrude out. Bentonite migration occurred with low amount of increase in hydraulic conductivity for GCL-1 between 25-130 hours, for GCL-2 between 40-180 hours and for GCL-3 between 25-110 hours. Finally, a very high increase, up to three orders of magnitude in hydraulic conductivity had been measured for all of the GCL samples which experienced hydraulic failure. During the last period of hydraulic failure, high amount of bentonite extruded out of the lower geotextile component as shown in figure 5.8. Then, the bentonite particles in the upper region of the crest zone began to move downwards, and extruded out through the lower geotextile which caused hydraulic failure of the GCL sample. However, GCL-4 samples did not experience internal erosion even under 50 m of hydraulic head due to high tensile strength of the lower woven geotextile component which was placed over the base with uniform voids. Lower geotextile component of GCL-4 resisted high effective stresses and it did not deform too much. Most of the GCL-1 samples did not also experience internal erosion due to the needlepunched fibres which caused high resistance against effective stresses.

In figure 5.9, the relationship between the hydraulic heads which caused internal erosion for the GCL samples and the void diameter of the base was shown. For some of the

GCL samples, internal erosion did not occur even under 50 m of hydraulic head. These GCL samples such as the GCL samples tested over the base with voids having 0,5 cm diameter were not shown in figure 5.9.

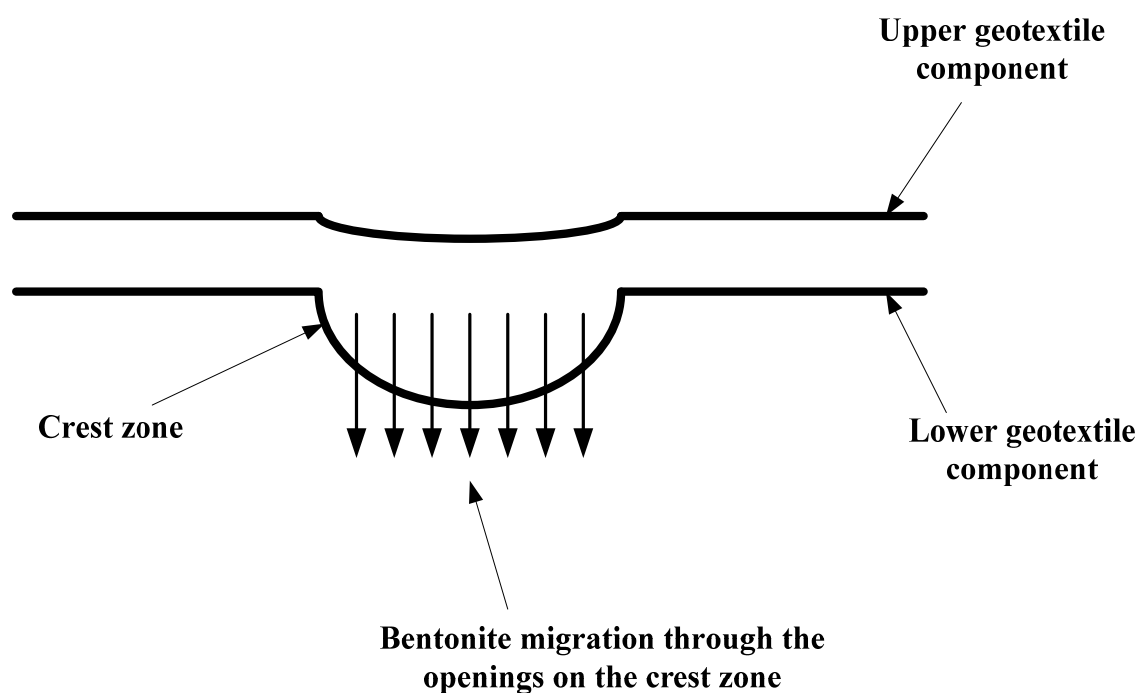


Figure 5.8. Schematic cross-sectional view of a GCL sample showing bentonite migration

According to figure 5.9, performance of GCL-2 samples against internal erosion was almost the same as that of GCL-3 samples. As shown in figure 5.9, the hydraulic heads at failure were the same for GCL-2 and GCL-3 samples when the nonwoven geotextile component of these samples was in contact with the voids of the base. Furthermore, the hydraulic heads at failure were just slightly different for GCL-2 and GCL-3 samples when the woven geotextile component of these samples was in contact with the voids of the base. This result shows that bentonite type does not play an important role on internal erosion.

According to figure 5.9, performance of GCL-1 samples against internal erosion was better than that of GCL-2 and GCL-3 samples. The only failed GCL-1 sample when the nonwoven geotextile component was in contact with the voids of the base experienced internal erosion under 35 m of hydraulic head over the base with voids having 2 cm

diameter. This result shows that the needlepunched fibres on the GCL-1 samples plays an important role on internal erosion.

According to figure 5.9, all of the GCL-1, GCL-2 and GCL-3 samples tested with their woven geotextile components (W1) over the bases with voids experienced internal erosion under lower hydraulic heads than the GCL samples tested with their nonwoven geotextile components (N1) over the bases with voids. This result shows that geotextile type plays an important role on internal erosion.

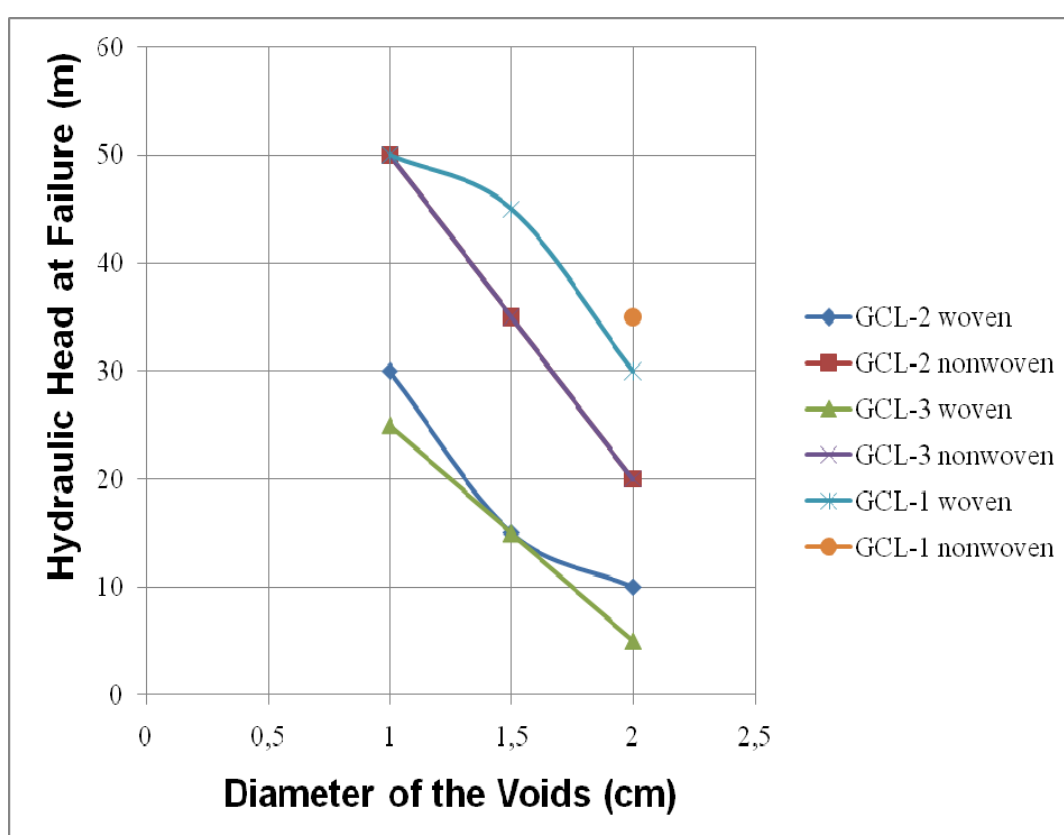


Figure 5.9. Relationship between hydraulic head at failure and diameter of the voids of the base placed beneath GCL-1, GCL-2 and GCL-3 samples

Evaluation of the test results shows that the main factors which cause high amount of bentonite migration from a GCL sample or internal erosion under a high hydraulic head are the types (woven or nonwoven) and engineering properties (tensile strength, rigidity) of the geotextile component of a GCL sample, bonding conditions (needlepunched or not) of the geotextile components to the bentonite component of a GCL sample and the size of the voids of the base placed beneath a GCL sample. However, type of the bentonite component

(sodium bentonite or calcium bentonite) of a GCL sample does not play an important role on high amount of bentonite migration from a GCL sample or internal erosion under a high hydraulic head.

5.2. Mass per Unit Area of the Bentonite Component of the GCL

The amount of bentonite migrated from a GCL sample and the level of internal erosion for a GCL sample could also be identified by measuring and comparing mass per unit area values of the bentonite component of several GCL samples.

According to the results, lower mass per unit area values were obtained from the zones where a GCL sample faced the voids of a base (lowest values were 0,20-0,25 g/cm² in this thesis). When internal erosion was observed, mass per unit area values at the zones where a GCL sample faced the voids (crest zones) were even lower. These low mass per unit area values obtained from the crest zones were due to the high amount of bentonite extrusion through the openings formed under high hydraulic heads on the crest zones as shown in figure 5.8.

GCL-4 samples did not experience internal erosion and the average mass per unit area values of the crests were 0,61-0,66 g/cm². Differences of the average mass per unit area values between the crests and the flats of GCL-4 samples were 0-0,05 g/cm². All of the GCL samples which did not experience internal erosion had higher mass per unit area values at the crest zones. Differences of mass per unit area values between the crests and the flats were very low for all of these samples due to very little amount of bentonite loss. However, a few of the zones where the GCL samples faced the solid base (flat zones) had lower mass per unit area values than the average. For example, the lowest crest and flat mass per unit area values for GCL-3-W-D2 were 0,20 and 0,45 g/cm², respectively. 0,45 g/cm² of mass per unit area was lower than 0,65 g/cm² of mass per unit area that was the average mass per unit area obtained for a GCL-3 sample when tested over a porous stone. This sample taken from the zone where GCL-3-W-D2 faced the solid base might have been taken from a region very near to a crest zone which had very low mass per unit area value due to high amount of bentonite loss. Some bentonite particles from the flat zone

might have also been removed out through the openings of the geotextile component which caused this lower mass per unit area value than the average.

Very low mass per unit area of the bentonite component of a GCL sample is an indication of bentonite migration from the GCL sample. As a result of this, mass per unit area of the bentonite component of a GCL sample reduced at the crest zones where the GCL sample faced the voids of the base. Very low differences of mass per unit area values between the crests and the flats of a GCL sample indicated uniform distribution of bentonite throughout the GCL sample. Under high hydraulic head, vertically extruded bentonite from the openings of the geotextile component of a GCL sample where the GCL sample faced a void, was the reason for lower mass per unit area value at this zone.

5.3. Moisture Content of the Bentonite Component of the GCL

Very high moisture content of the bentonite component of a GCL sample is also an indication of bentonite migration from the GCL sample. According to the results, higher water contents were obtained from the zones where a GCL sample faced the voids of a base (highest values measured at these zones were 190-205 per cent in this thesis) and lower water contents were obtained from the zones where a GCL sample faced the solid base (values measured at these zones generally ranged from 80 per cent to 100 per cent in this thesis).

Higher water contents were measured at the crest zones when the void diameter of the base was also higher because the zone with larger area faced much more water during bentonite migration. When the difference of water contents between the crests and the flats of a GCL sample was high, the amount of bentonite migrated from the GCL sample was also high (highest values of average water content differences between the crests and the flats were 90-95 per cent in this thesis).

GCL-4 samples did not experience internal erosion and the average water content values measured at the zones where the GCL samples faced the voids ranged from 83 per cent to 93 per cent. The average water content differences between the zones where GCL-4 samples faced the voids and the zones where GCL-4 samples faced the solid bases were 2-

9 per cent. These low values were due to the very low amount of bentonite migration from GCL-4 samples. This behavior was also observed on the other GCL samples which did not experience internal erosion in this thesis.

When high amount of bentonite migrated through the openings on the crest zone of a GCL sample, higher moisture content was measured at the crest zone that faced a void of the base.

6. CONCLUSIONS

- The study demonstrates that there is no indication of internal erosion for the GCL samples when they were placed between two porous stones and triaxial permeability tests were performed on these GCL samples under hydraulic heads up to 50 m. Hydraulic conductivities of the GCL samples did not increase until the termination of the tests.
- Void size of the base which was placed beneath the GCL samples plays an important role on internal erosion. When the void size was larger, the amount of migrated bentonite from the GCL sample under high hydraulic heads was also higher. All of the GCL-1, GCL-2 and GCL-3 samples experienced internal erosion at hydraulic heads ranging from 5 m to 35 m when they were tested over the base with uniform circular voids having 2 cm diameter. Most of the GCL-1, GCL-2 and GCL-3 samples experienced internal erosion at hydraulic heads ranging from 15 m to 45 m when they were tested over the base with uniform circular voids having 1.5 cm diameter. Some of the GCL-1, GCL-2 and GCL-3 samples experienced internal erosion at hydraulic heads ranging from 25 m to 50 m when they were tested over the base with uniform circular voids having 1 cm diameter. None of the GCL samples experienced internal erosion under hydraulic heads of 50 m when the GCL samples were tested over the base with uniform circular voids having 0.5 cm diameter. As a result, there is no indication of internal erosion for the GCL samples when they were placed over the base with uniform circular voids having 0.5 cm diameter and tested under hydraulic heads up to 50 m.
- Manufacturing type of the GCL samples (needlepunched or not) plays an important role on internal erosion. Performance of GCL-1 (manufactured by needlepunching from the nonwoven geotextile, N1 through the sodium bentonite to the woven geotextile, W1) against internal erosion was better than that of GCL-2 (manufactured by placing sodium bentonite between woven geotextile, W1 and nonwoven geotextile, N1 without needlepunching) and GCL-3 samples (manufactured by

placing calcium bentonite between woven geotextile, W1 and nonwoven geotextile, N1 without needlepunching). GCL-1-NW-D1.5, GCL-1-W-D1 and GCL-1-NW-D1 samples did not experience internal erosion under 50 m of hydraulic head while all of the GCL-2 and GCL-3 samples tested over the bases with circular, uniform voids having diameters of 2 cm, 1.5 cm and 1 cm experienced internal erosion. Needle punched fibres of the GCL-1 samples prevented high amount of bentonite migration under high hydraulic heads.

- Engineering properties of the geotextile component plays an important role on internal erosion. Performance of the nonwoven geotextile component (N1) against internal erosion was better than that of the woven geotextile component (W1) among all of the GCL-1, GCL-2 and GCL-3 samples under high hydraulic heads. This was observed for the GCL samples tested over the bases with uniform circular voids having diameters of 2 cm, 1.5 cm and 1 cm. Because of the higher rigidity of W1, some of the slit film tapes on the woven geotextile component (W1) of the GCL samples where the GCL samples faced the voids, were damaged. When the slit film tapes on the woven geotextile (W1) were damaged, the openings between the slit film tapes got larger and high amount of the bentonite extruded vertically through the woven geotextile component (W1) into the voids of the base.
- Performance of GCL-4 against internal erosion was the best among all of the GCL types due to the engineering properties of the woven geotextile component, W2. All of the GCL-4 samples (GCL-4-W-D2, GCL-4-W-D1.5 and GCL-4-W-D1) did not experience internal erosion under even 50 m of hydraulic head. High tensile strength of W2 prevented the formation of defects on the slit film tapes of the woven geotextile component. Low deformation of the woven geotextile (W2) where the GCL sample faced the voids was due to the high tensile strength and durability of the woven geotextile component (W2). When the deformations were low, the openings on the geotextile where the GCL sample faced the voids of the base remained small which prevented high amount of bentonite extrusion through the woven geotextile component (W2) of a GCL-4 sample.

- Type of bentonite (sodium or calcium) used in the GCL samples does not play an important role on internal erosion under high hydraulic heads. Even if the engineering properties of sodium bentonite is different than those of calcium bentonite, the performance of GCL-2 against internal erosion was almost the same as the performance of GCL-3. Calcium bentonite has approximately one order of magnitude higher hydraulic conductivity and lower swell index value than sodium bentonite used in this thesis. However, the hydraulic heads which caused internal erosion were almost the same for both GCL-2 and GCL-3. Only two of the GCL-3 samples experienced internal erosion under 5 m lower hydraulic heads than the GCL-2 samples experienced.
- Mass per unit area of the bentonite component of a GCL sample is an indication of internal erosion. When internal erosion was detected, very low mass per unit area values ($0,20-0,25 \text{ g/cm}^2$) were measured at the zones where a GCL sample faced the voids of the base due to the high amount of bentonite extrusion from the openings on the geotextile component. Very low mass per unit area differences ($0,01-0,05 \text{ g/cm}^2$) between the values measured at the zones where a GCL sample faced the voids and the values measured at the zones where a GCL sample faced the solid base, is an indication of very low amount of bentonite migration and uniform distribution of the bentonite throughout the GCL sample.
- Moisture content of the bentonite component of a GCL sample is an indication of internal erosion. When internal erosion was detected, very high moisture content values (190-195 per cent) were measured at the zones where a GCL sample faced the voids of the base. High moisture content differences (90-95 per cent) between the values measured at the zones where a GCL sample faced the voids and the values measured at the zones where a GCL sample faced the solid base, is an indication of high amount of bentonite migration.
- Lower hydraulic conductivity measured under higher hydraulic head for the same GCL sample that did not experience internal erosion is predicted to be due to higher effective pressure applied at the contact point between the bentonite component and the lower geotextile component of the GCL sample.

- After hydraulic head had been increased to the desired level, hydraulic conductivity of the GCL samples increased up to one order of magnitude in 75-225 hours which can be interpreted as a sign that internal erosion started. After internal erosion had started, bentonite loss occurred with low amount of increase in hydraulic conductivity in 25-180 hours. Bentonite extrusion through the lower geotextile component of the GCL samples caused the increase in hydraulic conductivity. Finally, the lower geotextile component of the GCL samples could not resist high effective stresses which caused high amount of bentonite migration out of the lower geotextile component. Hydraulic failure of the GCL samples occurred with high increase, up to three orders of magnitude in hydraulic conductivity.
- High amount of bentonite loss caused approximately 3-5 orders of magnitude increase in hydraulic conductivity of the GCL samples and internal erosion caused the GCL samples to lose their hydraulic barrier capabilities.

Usage of different types of GCL samples placed over bases with uniform voids representing rounded uniform gravel subgrades was investigated in this thesis. As a result, performance of some of the GCL samples against internal erosion was found to be good under high hydraulic heads up to 50 m.

For further study, it is recommended to investigate the behavior of GCL samples under high hydraulic heads by using chemical solutions instead of water as the hydration and permeation liquid.

APPENDIX A: FLEXIBLE WALL TRIAXIAL PERMEABILITY TEST RESULTS

Hydraulic Conductivity Calculations

Table A.1. Hydraulic Conductivity Calculations for GCL-1-W-D2 under 30 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
3000	14,19	14,2	14,20	0,83	55800	8,55E-10	1,03E-09	16	3,24E-06	22	0,95
3000	5,05	5	5,03	0,83	28800	6,15E-10	7,41E-10	24	2,22E-06	20	1,00
3000	13,51	13,5	13,51	0,83	61200	7,78E-10	9,37E-10	41	2,81E-06	20	1,00
3000	5,55	5,55	5,55	0,83	25200	7,76E-10	9,35E-10	48	2,81E-06	20	1,00
3000	48,49	48,48	48,49	0,83	234000	6,96E-10	8,39E-10	113	2,64E-06	22	0,95
3000	28,09	28,2	28,15	0,83	21600	4,38E-09	5,27E-09	119	1,66E-05	22	0,95
3000	52,42	52,5	52,46	0,83	18000	9,57E-09	1,15E-08	140	3,71E-05	23	0,93
3000	90,45	90,45	90,45	0,83	25200	1,21E-08	1,45E-08	162	4,57E-05	22	0,95
3000	204,86	204,81	204,84	0,83	25200	2,73E-08	3,29E-08	186	1,04E-04	22	0,95
3000	142,42	142,29	142,36	0,83	14400	3,32E-08	4,00E-08	207	1,26E-04	22	0,95
3000	332,46	332,47	332,47	0,83	28800	4,07E-08	4,90E-08	230	1,47E-04	20	1,00
3000	319	320	319,50	0,83	60	1,88E-05	2,26E-05	247	6,78E-02	20	1,00

Table A.2. Hydraulic Conductivity Calculations for GCL-1-NW-D2 under 35 m hydraulic head (Calculations after clogging of the voids of the base pedestal are also taken into account)

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ² /s)	Temperature (°C)	Temp. Correction Factor
3500	2,87	2,6	2,74	0,87	4320	2,00E-09	2,30E-09	1	8,06E-06	20	1,00
3500	1,42	1,44	1,43	0,87	2640	1,72E-09	1,97E-09	18	6,90E-06	20	1,00
3500	2,48	2,48	2,48	0,87	12600	6,23E-10	7,16E-10	86	2,51E-06	20	1,00
3500	1,94	1,7	1,82	0,87	10380	5,55E-10	6,38E-10	107	2,23E-06	20	1,00
3500	1,79	1,78	1,79	0,87	10380	5,45E-10	6,26E-10	126	2,19E-06	20	1,00
3500	4,52	4,48	4,50	0,87	25800	5,52E-10	6,35E-10	149	2,22E-06	20	1,00
3500	3,62	3,4	3,51	0,87	20880	5,32E-10	6,12E-10	171	2,14E-06	20	1,00
3500	0,9	0,9	0,90	0,87	6000	4,75E-10	5,46E-10	175	1,91E-06	20	1,00
3500	6,5	4,3	5,40	0,87	18000	9,50E-10	1,09E-09	195	3,82E-06	20	1,00
3500	5,52	5,48	5,50	0,87	7800	2,23E-09	2,57E-09	199	8,98E-06	20	1,00
3500	64,28	64,36	64,32	0,87	4800	4,24E-08	4,88E-08	216	1,71E-04	20	1,00
3500	199,2	210,8	205,00	0,87	10800	6,01E-08	6,91E-08	220	2,42E-04	20	1,00
3500	377,6	377,7	377,65	0,87	60	1,99E-05	2,29E-05	222	8,02E-02	20	1,00
3500	220,5	220	220,25	0,87	60	1,16E-05	1,34E-05	222	4,68E-02	20	1,00
3500	144,5	144,3	144,40	0,87	60	7,62E-06	8,76E-06	223	3,07E-02	20	1,00
3500	195	195	195,00	0,87	3600	1,72E-07	1,97E-07	227	6,90E-04	20	1,00
3500	185,63	186,02	185,83	0,87	9000	6,54E-08	7,51E-08	287	2,63E-04	20	1,00
3500	206,5	203,75	205,13	0,87	9780	6,64E-08	7,63E-08	294	2,67E-04	20	1,00

Table A.3. Hydraulic Conductivity Calculations for GCL-1-NW-D2 under 35 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
3500	2,87	2,6	2,74	0,87	4320	2,00E-09	2,30E-09	1	8,06E-06	20	1,00
3500	1,42	1,44	1,43	0,87	2640	1,72E-09	1,97E-09	18	6,90E-06	20	1,00
3500	2,48	2,48	2,48	0,87	12600	6,23E-10	7,16E-10	86	2,51E-06	20	1,00
3500	1,94	1,7	1,82	0,87	10380	5,55E-10	6,38E-10	107	2,23E-06	20	1,00
3500	1,79	1,78	1,79	0,87	10380	5,45E-10	6,26E-10	126	2,19E-06	20	1,00
3500	4,52	4,48	4,50	0,87	25800	5,52E-10	6,35E-10	149	2,22E-06	20	1,00
3500	3,62	3,4	3,51	0,87	20880	5,32E-10	6,12E-10	171	2,14E-06	20	1,00
3500	0,9	0,9	0,90	0,87	6000	4,75E-10	5,46E-10	175	1,91E-06	20	1,00
3500	6,5	4,3	5,40	0,87	18000	9,50E-10	1,09E-09	195	3,82E-06	20	1,00
3500	5,52	5,48	5,50	0,87	7800	2,23E-09	2,57E-09	199	8,98E-06	20	1,00
3500	64,28	64,36	64,32	0,87	4800	4,24E-08	4,88E-08	216	1,71E-04	20	1,00
3500	199,2	210,8	205,00	0,87	10800	6,01E-08	6,91E-08	220	2,42E-04	20	1,00
3500	377,6	377,7	377,65	0,87	60	1,99E-05	2,29E-05	222	8,02E-02	20	1,00

Table A.4. Hydraulic Conductivity Calculations for GCL-1-W-D1.5 under 45 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
4500	3,87	3,77	3,82	0,75	9900	7,29E-10	9,72E-10	3	4,92E-06	25	0,89
4500	3,42	3,35	3,39	0,75	9600	6,66E-10	8,88E-10	5	4,49E-06	25	0,89
4500	4,87	4,92	4,90	0,75	19200	4,92E-10	6,56E-10	26	3,25E-06	24	0,91
4500	5,57	5,59	5,58	0,75	21600	4,99E-10	6,65E-10	32	3,29E-06	24	0,91
4500	37,4	37,38	37,39	0,75	231600	3,05E-10	4,07E-10	96	2,06E-06	25	0,89
4500	5,38	5,37	5,38	0,75	28800	3,69E-10	4,92E-10	104	2,38E-06	23	0,93
4500	224,57	224,55	224,56	0,75	57600	7,71E-09	1,03E-08	120	4,97E-05	23	0,93
4500	59,09	59,07	59,08	0,75	10800	1,06E-08	1,41E-08	123	6,97E-05	24	0,91
4500	139,09	139,1	139,10	0,75	7200	3,65E-08	4,86E-08	125	2,46E-04	25	0,89
4500	151,25	151,26	151,26	0,75	7200	3,97E-08	5,29E-08	127	2,68E-04	25	0,89
4500	440	440	440,00	0,75	8100	1,10E-07	1,47E-07	144	6,92E-04	22	0,95
4500	443	444,5	443,75	0,75	40	2,25E-05	2,99E-05	144	1,41E-01	22	0,95

Table A.5. Hydraulic Conductivity Calculations for GCL-1-NW-D1.5 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	2,38	2,56	2,47	0,77	33300	1,36E-10	1,76E-10	9	9,45E-07	23	0,93
5000	2,27	2,35	2,31	0,77	53400	7,90E-11	1,03E-10	24	5,51E-07	23	0,93
5000	1,15	1,18	1,17	0,77	25200	8,45E-11	1,10E-10	31	5,89E-07	23	0,93
5000	3,9	3,96	3,93	0,77	60000	1,22E-10	1,59E-10	48	8,34E-07	22	0,95
5000	3,57	3,63	3,60	0,77	27000	2,49E-10	3,24E-10	55	1,70E-06	22	0,95
5000	27,11	27,08	27,10	0,77	244800	2,07E-10	2,69E-10	123	1,41E-06	22	0,95
5000	4,23	4,15	4,19	0,77	28080	2,79E-10	3,62E-10	131	1,90E-06	22	0,95
5000	8,75	8,66	8,71	0,77	64800	2,51E-10	3,26E-10	149	1,71E-06	22	0,95
5000	3,01	3,03	3,02	0,77	32400	1,74E-10	2,26E-10	158	1,19E-06	22	0,95
5000	28,77	28,86	28,82	0,77	241200	2,23E-10	2,90E-10	225	1,52E-06	22	0,95
5000	4,4	4,43	4,42	0,77	30000	2,75E-10	3,57E-10	233	1,87E-06	22	0,95
5000	5,24	5,34	5,29	0,77	64200	1,54E-10	2,00E-10	251	1,05E-06	22	0,95
5000	4,23	4,3	4,27	0,77	36000	2,22E-10	2,88E-10	261	1,51E-06	22	0,95
5000	5,36	5,26	5,31	0,77	68400	1,45E-10	1,89E-10	280	9,89E-07	22	0,95
5000	3,71	3,73	3,72	0,77	29700	2,34E-10	3,04E-10	288	1,60E-06	22	0,95

Table A.6. Hydraulic Conductivity Calculations for GCL-1-W-D1 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	4,29	4,2	4,25	0,68	24900	2,95E-10	4,34E-10	7	2,17E-06	20	1,00
5000	4,42	4,46	4,44	0,68	27300	2,82E-10	4,14E-10	32	2,07E-06	20	1,00
5000	11,67	11,64	11,66	0,68	63000	3,21E-10	4,71E-10	49	2,36E-06	20	1,00
5000	7,54	7,61	7,58	0,68	28800	4,56E-10	6,70E-10	57	3,35E-06	20	1,00
5000	9,79	9,78	9,79	0,68	57600	2,87E-10	4,22E-10	73	2,16E-06	21	0,98
5000	3,4	3,39	3,40	0,68	26400	2,17E-10	3,20E-10	80	1,64E-06	21	0,98
5000	16,55	16,58	16,57	0,68	234600	1,19E-10	1,76E-10	146	8,99E-07	21	0,98
5000	3,06	3,05	3,06	0,68	21600	2,39E-10	3,52E-10	152	1,80E-06	21	0,98
5000	7,57	7,64	7,61	0,68	65700	1,96E-10	2,88E-10	170	1,47E-06	21	0,98
5000	3,43	3,43	3,43	0,68	32100	1,81E-10	2,66E-10	179	1,36E-06	21	0,98
5000	4,42	4,41	4,42	0,68	68400	1,12E-10	1,64E-10	198	8,22E-07	20	1,00
5000	2,27	2,2	2,24	0,68	32400	1,20E-10	1,76E-10	207	8,79E-07	20	1,00
5000	7,7	7,68	7,69	0,68	144000	9,25E-11	1,36E-10	247	6,80E-07	20	1,00
5000	1,38	1,36	1,37	0,68	27600	8,60E-11	1,26E-10	254	6,32E-07	20	1,00
5000	11,65	11,7	11,68	0,68	225000	8,99E-11	1,32E-10	317	6,61E-07	20	1,00

Table A.7. Hydraulic Conductivity Calculations for GCL-1-NW-D1 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm³)	Outflow (cm³)	Average of Inflow and Outflow (cm³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm³/cm²)/s	Temperature (°C)	Temp. Correction Factor
5000	6,25	6,24	6,25	0,65	28800	3,59E-10	5,52E-10	8	2,76E-06	20	1,00
5000	8,65	8,55	8,60	0,65	64800	2,20E-10	3,38E-10	26	1,69E-06	20	1,00
5000	5,39	6,38	5,89	0,65	28800	3,38E-10	5,21E-10	34	2,60E-06	20	1,00
5000	19,23	19,25	19,24	0,65	234000	1,36E-10	2,09E-10	99	1,05E-06	20	1,00
5000	2,54	2,57	2,56	0,65	21600	1,96E-10	3,01E-10	105	1,51E-06	20	1,00
5000	3,14	3,15	3,15	0,65	68400	7,61E-11	1,17E-10	124	5,86E-07	20	1,00
5000	0,69	0,8	0,75	0,65	18000	6,85E-11	1,05E-10	129	5,27E-07	20	1,00
5000	2,58	2,55	2,57	0,65	72000	5,90E-11	9,08E-11	149	4,54E-07	20	1,00
5000	8,77	8,78	8,78	0,65	230400	6,31E-11	9,70E-11	213	4,85E-07	20	1,00
5000	1,31	1,29	1,30	0,65	32400	6,64E-11	1,02E-10	238	5,11E-07	20	1,00
5000	2,28	2,28	2,28	0,65	61200	6,17E-11	9,49E-11	255	4,75E-07	20	1,00
5000	2,25	2,25	2,25	0,65	57600	6,47E-11	9,95E-11	311	4,98E-07	20	1,00

Table A.8. Hydraulic Conductivity Calculations for GCL-1 W under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	6,16	6,14	6,15	0,78	29700	3,92E-10	5,03E-10	8	2,64E-06	22	0,95
5000	9,84	9,83	9,84	0,78	61800	3,01E-10	3,86E-10	25	2,03E-06	22	0,95
5000	3,99	3,97	3,98	0,78	18600	4,05E-10	5,20E-10	31	2,73E-06	22	0,95
5000	12	11,68	11,84	0,78	62700	3,58E-10	4,59E-10	48	2,41E-06	22	0,95
5000	4,51	4,56	4,54	0,78	27000	3,18E-10	4,08E-10	56	2,14E-06	22	0,95
5000	7,66	7,66	7,66	0,78	67500	2,15E-10	2,76E-10	74	1,45E-06	22	0,95
5000	2,83	2,85	2,84	0,78	26400	2,04E-10	2,61E-10	82	1,37E-06	22	0,95
5000	6,4	6,37	6,39	0,78	60900	1,99E-10	2,55E-10	99	1,34E-06	22	0,95
5000	3,06	3,03	3,05	0,78	22500	2,56E-10	3,29E-10	105	1,72E-06	22	0,95
5000	12	12,5	12,25	0,78	238500	9,73E-11	1,25E-10	171	6,54E-07	22	0,95
5000	1,72	1,74	1,73	0,78	21300	1,54E-10	1,97E-10	177	1,03E-06	22	0,95
5000	4,66	4,67	4,67	0,78	64800	1,36E-10	1,75E-10	195	9,17E-07	22	0,95
5000	1,3	1,27	1,29	0,78	25800	9,43E-11	1,21E-10	202	6,34E-07	22	0,95
5000	3,04	3,01	3,03	0,78	62400	9,18E-11	1,18E-10	219	6,18E-07	22	0,95
5000	1,47	1,46	1,47	0,78	29700	9,80E-11	1,26E-10	228	6,28E-07	20	1,00
5000	3,17	3,16	3,17	0,78	65700	9,57E-11	1,23E-10	246	6,14E-07	20	1,00
5000	1,12	1,13	1,13	0,78	23700	9,43E-11	1,21E-10	253	6,05E-07	20	1,00
5000	2,91	2,93	2,92	0,78	61800	9,39E-11	1,20E-10	270	6,02E-07	20	1,00
5000	1,22	1,24	1,23	0,78	26400	9,26E-11	1,19E-10	277	5,94E-07	20	1,00

Table A.9. Hydraulic Conductivity Calculations for GCL-1 NW under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	3,19	3,15	3,17	0,78	23400	2,69E-10	3,45E-10	7	1,73E-06	20	1,00
5000	8,66	8,67	8,67	0,78	65100	2,65E-10	3,39E-10	25	1,70E-06	20	1,00
5000	3,11	3,1	3,11	0,78	27900	2,21E-10	2,84E-10	32	1,42E-06	20	1,00
5000	6,26	6,18	6,22	0,78	65400	1,89E-10	2,42E-10	51	1,21E-06	20	1,00
5000	2,18	2,22	2,20	0,78	24900	1,76E-10	2,25E-10	57	1,13E-06	20	1,00
5000	6,03	6,05	6,04	0,78	62700	1,91E-10	2,45E-10	75	1,23E-06	20	1,00
5000	2,54	2,5	2,52	0,78	29400	1,70E-10	2,18E-10	83	1,09E-06	20	1,00
5000	4,18	4,2	4,19	0,78	61800	1,35E-10	1,73E-10	100	8,64E-07	20	1,00
5000	2,39	2,33	2,36	0,78	26700	1,76E-10	2,25E-10	108	1,13E-06	20	1,00
5000	10,4	10,5	10,45	0,78	235200	8,83E-11	1,13E-10	173	5,66E-07	20	1,00
5000	1,15	1,18	1,17	0,78	24000	9,65E-11	1,24E-10	180	6,18E-07	20	1,00
5000	2,62	2,63	2,63	0,78	63000	8,28E-11	1,06E-10	197	5,31E-07	20	1,00
5000	1,35	1,35	1,35	0,78	27900	9,62E-11	1,23E-10	205	6,16E-07	20	1,00
5000	2,74	2,77	2,76	0,78	67800	8,08E-11	1,04E-10	224	5,18E-07	20	1,00
5000	1,3	1,31	1,31	0,78	31200	8,31E-11	1,07E-10	232	5,33E-07	20	1,00
5000	2,63	2,62	2,63	0,78	65700	7,94E-11	1,02E-10	251	5,09E-07	20	1,00
5000	1,04	1,04	1,04	0,78	25200	8,20E-11	1,05E-10	258	5,26E-07	20	1,00
5000	2,55	2,54	2,55	0,78	62100	8,14E-11	1,04E-10	275	5,22E-07	20	1,00
5000	1,2	1,23	1,22	0,78	30000	8,05E-11	1,03E-10	283	5,16E-07	20	1,00

Table A.10. Hydraulic Conductivity Calculations for GCL-2-W-D2 under 10 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
1000	16,8	16,7	16,75	0,81	57600	2,79E-09	3,45E-09	16	3,70E-06	23	0,93
1000	8,83	8,83	8,83	0,81	26100	3,25E-09	4,01E-09	23	4,31E-06	23	0,93
1000	14,55	14,5	14,53	0,81	61200	2,28E-09	2,82E-09	40	3,02E-06	23	0,93
1000	8,55	8,56	8,56	0,81	27600	3,05E-09	3,76E-09	48	3,95E-06	22	0,95
1000	12,6	12,7	12,65	0,81	58800	2,12E-09	2,61E-09	64	2,74E-06	22	0,95
1000	6,44	6,46	6,45	0,81	27300	2,32E-09	2,87E-09	72	3,01E-06	22	0,95
1000	8,55	8,55	8,55	0,81	57600	1,46E-09	1,80E-09	88	1,89E-06	22	0,95
1000	3,43	3,41	3,42	0,81	25200	1,33E-09	1,65E-09	95	1,73E-06	22	0,95
1000	30	30,5	30,25	0,81	234000	1,24E-09	1,53E-09	160	1,65E-06	23	0,93
1000	3,2	3,23	3,22	0,81	22800	1,36E-09	1,67E-09	166	1,80E-06	23	0,93
1000	17,7	17,6	17,65	0,81	14400	1,18E-08	1,45E-08	186	1,56E-05	23	0,93
1000	31,6	31,5	31,55	0,81	10800	2,81E-08	3,47E-08	189	3,72E-05	23	0,93
1000	55,5	55,5	55,50	0,81	7200	7,41E-08	9,15E-08	191	9,82E-05	23	0,93
1000	214	215	214,50	0,81	60	3,52E-05	4,34E-05	208	4,55E-02	22	0,95

Table A.11. Hydraulic Conductivity Calculations for GCL-2-NW-D2 under 20 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
2000	6,5	6,47	6,49	0,67	12600	1,95E-09	2,92E-09	4	6,56E-06	25	0,89
2000	29,07	29,08	29,08	0,67	54000	2,04E-09	3,05E-09	51	6,86E-06	25	0,89
2000	1,44	1,43	1,44	0,67	6000	9,08E-10	1,36E-09	116	3,05E-06	25	0,89
2000	3,37	3,35	3,36	0,67	15000	8,50E-10	1,27E-09	184	2,85E-06	25	0,89
2000	7,75	7,75	7,75	0,67	36000	8,17E-10	1,22E-09	194	2,74E-06	25	0,89
2000	5,55	5,56	5,56	0,67	25200	8,37E-10	1,25E-09	217	2,81E-06	25	0,89
2000	9,77	9,78	9,78	0,67	5400	6,87E-09	1,03E-08	223	2,31E-05	25	0,89
2000	17,65	17,65	17,65	0,67	7200	9,31E-09	1,39E-08	225	3,12E-05	25	0,89
2000	18,57	18,58	18,58	0,67	7200	9,79E-09	1,46E-08	229	3,29E-05	25	0,89
2000	150,71	150,76	150,74	0,67	8400	6,81E-08	1,02E-07	231	2,29E-04	25	0,89
2000	89,05	89,02	89,04	0,67	3600	9,39E-08	1,40E-07	248	3,15E-04	25	0,89
2000	70,75	70,75	70,75	0,67	2700	9,95E-08	1,48E-07	251	3,34E-04	25	0,89
2000	137	138	137,50	0,67	60	8,70E-06	1,30E-05	317	2,92E-02	25	0,89

Table. A.12. Hydraulic Conductivity Calculations for GCL-2-W-D1.5 under 15 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
1500	6,54	6,57	6,56	0,73	6600	5,35E-09	7,34E-09	2	1,27E-05	26	0,87
1500	9,13	9,15	9,14	0,73	18000	2,74E-09	3,75E-09	23	6,47E-06	26	0,87
1500	5,14	5,14	5,14	0,73	10800	2,57E-09	3,51E-09	90	6,06E-06	26	0,87
1500	20,57	20,56	20,57	0,73	46800	2,37E-09	3,25E-09	103	5,60E-06	26	0,87
1500	25,6	25,56	25,58	0,73	54000	2,55E-09	3,50E-09	133	6,03E-06	26	0,87
1500	27,15	27,16	27,16	0,73	18000	8,13E-09	1,11E-08	142	1,92E-05	26	0,87
1500	14,4	14,46	14,43	0,73	7200	1,11E-08	1,51E-08	159	2,55E-05	25	0,89
1500	19,48	19,51	19,50	0,73	5400	1,99E-08	2,73E-08	160	4,60E-05	25	0,89
1500	20,28	20,32	20,30	0,73	3600	3,04E-08	4,16E-08	169	7,18E-05	26	0,87
1500	589,06	589	589,03	0,73	28800	1,10E-07	1,51E-07	177	2,61E-04	26	0,87
1500	210	209	209,50	0,73	120	9,41E-06	1,29E-05	177	2,22E-02	26	0,87

Table A.13. Hydraulic Conductivity Calculations for GCL-2-NW-D1.5 under 35 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
3500	9,24	9,19	9,22	0,67	25800	9,15E-10	1,37E-09	7	4,55E-06	18	1,05
3500	17,68	17,58	17,63	0,67	59400	7,42E-10	1,11E-09	24	3,78E-06	19	1,02
3500	7,95	7,92	7,94	0,67	25200	8,07E-10	1,20E-09	31	4,01E-06	18	1,05
3500	19,27	19,3	19,29	0,67	61200	8,07E-10	1,21E-09	48	4,01E-06	18	1,05
3500	9,44	9,42	9,43	0,67	28800	8,39E-10	1,25E-09	56	4,17E-06	18	1,05
3500	17,7	17,65	17,68	0,67	58800	7,51E-10	1,12E-09	72	3,83E-06	19	1,02
3500	7,57	7,58	7,58	0,67	21600	8,76E-10	1,31E-09	78	4,47E-06	19	1,02
3500	49,6	49,5	49,55	0,67	237600	5,21E-10	7,78E-10	144	2,66E-06	19	1,02
3500	5,66	5,59	5,63	0,67	23700	5,79E-10	8,64E-10	151	3,02E-06	20	1,00
3500	11,45	11,5	11,48	0,67	61200	4,57E-10	6,82E-10	168	2,39E-06	20	1,00
3500	5,55	5,48	5,52	0,67	52200	2,58E-10	3,85E-10	182	1,35E-06	20	1,00
3500	10,6	10,6	10,60	0,67	58800	4,40E-10	6,56E-10	198	2,30E-06	20	1,00
3500	35,5	35,4	35,45	0,67	25200	3,43E-09	5,12E-09	205	1,79E-05	20	1,00
3500	149,1	149,1	149,10	0,67	57600	6,31E-09	9,42E-09	221	3,30E-05	20	1,00
3500	249,4	249,5	249,45	0,67	28800	2,11E-08	3,15E-08	229	1,10E-04	20	1,00
3500	359,2	359,1	359,15	0,67	27600	3,17E-08	4,74E-08	253	1,66E-04	20	1,00
3500	228	230	229,00	0,67	60	9,31E-06	1,39E-05	253	4,86E-02	20	1,00

Table A.14. Hydraulic Conductivity Calculations for GCL-2-W-D1 under 30 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
3000	9,24	9,26	9,25	0,7	50400	5,46E-10	7,79E-10	14	2,34E-06	20	1,00
3000	6,44	6,46	6,45	0,7	28800	6,66E-10	9,51E-10	38	2,85E-06	20	1,00
3000	9,87	9,87	9,87	0,7	57600	5,09E-10	7,28E-10	54	2,18E-06	20	1,00
3000	4,65	4,66	4,66	0,7	25200	5,49E-10	7,84E-10	61	2,35E-06	20	1,00
3000	9,5	9,49	9,50	0,7	57600	4,90E-10	7,00E-10	77	2,10E-06	20	1,00
3000	31,5	31,5	31,50	0,7	230400	4,06E-10	5,81E-10	141	1,74E-06	20	1,00
3000	4,02	4	4,01	0,7	28800	4,14E-10	5,91E-10	164	1,77E-06	20	1,00
3000	7,73	7,75	7,74	0,7	58800	3,91E-10	5,59E-10	180	1,68E-06	20	1,00
3000	29,5	29,6	29,55	0,7	10800	8,13E-09	1,16E-08	183	3,49E-05	20	1,00
3000	49,8	50	49,90	0,7	14400	1,03E-08	1,47E-08	203	4,41E-05	20	1,00
3000	68,5	68,5	68,50	0,7	6300	3,23E-08	4,62E-08	209	1,39E-04	20	1,00
3000	265	265,5	265,25	0,7	60	1,31E-05	1,88E-05	226	5,63E-02	20	1,00
3000	377	378	377,50	0,7	60	1,87E-05	2,67E-05	226	8,01E-02	20	1,00

Table A.15. Hydraulic Conductivity Calculations for GCL-2-NW-D1 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	5,37	5,44	5,41	0,69	28800	3,38E-10	4,90E-10	8	2,39E-06	19	1,02
5000	8,35	8,3	8,33	0,69	57600	2,60E-10	3,77E-10	24	1,84E-06	19	1,02
5000	4,31	4,32	4,32	0,69	25200	3,09E-10	4,47E-10	31	2,18E-06	19	1,02
5000	6,1	6,11	6,11	0,69	60000	1,83E-10	2,66E-10	48	1,30E-06	19	1,02
5000	1,96	2,01	1,99	0,69	22500	1,59E-10	2,30E-10	54	1,12E-06	19	1,02
5000	3,57	3,58	3,58	0,69	64800	9,94E-11	1,44E-10	72	7,03E-07	19	1,02
5000	1,1	1,13	1,12	0,69	21000	9,33E-11	1,35E-10	78	6,76E-07	20	1,00
5000	3,19	3,13	3,16	0,69	61200	9,08E-11	1,32E-10	95	6,58E-07	20	1,00
5000	9,82	9,79	9,81	0,69	20100	8,58E-10	1,24E-09	100	6,21E-06	20	1,00
5000	52,3	52,22	52,26	0,69	25200	3,65E-09	5,28E-09	172	2,64E-05	20	1,00
5000	107,5	108	107,75	0,69	28800	6,58E-09	9,53E-09	196	4,77E-05	20	1,00
5000	175,5	174,5	175,00	0,69	25800	1,19E-08	1,73E-08	221	8,64E-05	20	1,00
5000	339,5	340	339,75	0,69	25200	2,37E-08	3,43E-08	244	1,72E-04	20	1,00
5000	379	380	379,50	0,69	19200	3,47E-08	5,04E-08	265	2,52E-04	20	1,00
5000	328	330	329,00	0,69	60	9,64E-06	1,40E-05	280	6,99E-02	20	1,00
5000	339,9	340	339,95	0,69	60	9,96E-06	1,44E-05	280	7,22E-02	20	1,00

Table A.16. Hydraulic Conductivity Calculations for GCL-2-W-D0.5 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	3,82	3,8	3,81	0,65	27600	2,23E-10	3,43E-10	8	1,76E-06	21	0,98
5000	4,22	4,19	4,21	0,65	61200	1,11E-10	1,71E-10	25	8,75E-07	21	0,98
5000	2,09	2,07	2,08	0,65	22500	1,49E-10	2,30E-10	31	1,18E-06	21	0,98
5000	5,38	5,43	5,41	0,65	57600	1,52E-10	2,33E-10	47	1,20E-06	21	0,98
5000	2,24	2,28	2,26	0,65	29700	1,26E-10	1,94E-10	55	9,69E-07	20	1,00
5000	10,39	10,36	10,38	0,65	231900	7,41E-11	1,14E-10	120	5,70E-07	20	1,00
5000	1,35	1,32	1,34	0,65	23400	9,45E-11	1,45E-10	126	7,27E-07	20	1,00
5000	4,06	4,08	4,07	0,65	67800	9,48E-11	1,46E-10	145	7,65E-07	22	0,95
5000	1,44	1,43	1,44	0,65	28500	7,95E-11	1,22E-10	153	6,41E-07	22	0,95
5000	2,97	3	2,99	0,65	60000	7,85E-11	1,21E-10	170	6,34E-07	22	0,95
5000	1,12	1,06	1,09	0,65	22800	7,55E-11	1,16E-10	176	6,09E-07	22	0,95
5000	4,54	4,51	4,53	0,65	61200	1,17E-10	1,80E-10	193	9,42E-07	22	0,95
5000	1,19	1,15	1,17	0,65	29400	6,43E-11	9,90E-11	201	5,07E-07	21	0,98
5000	2,39	2,34	2,37	0,65	58500	6,38E-11	9,82E-11	217	5,15E-07	22	0,95
5000	1,39	1,39	1,39	0,65	28800	7,62E-11	1,17E-10	225	6,15E-07	22	0,95
5000	9,43	9,43	9,43	0,65	231300	6,59E-11	1,01E-10	290	5,19E-07	21	0,98
5000	1,21	1,19	1,20	0,65	28200	7,05E-11	1,08E-10	297	5,42E-07	20	1,00

Table A.17. Hydraulic Conductivity Calculations for GCL-2-NW-0.5 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval Δt (s)	Permeability coefficient k (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	1,53	1,58	1,56	0,65	21900	1,15E-10	1,77E-10	6	9,05E-07	21	0,98
5000	3,29	3,34	3,32	0,65	66900	8,01E-11	1,23E-10	25	6,31E-07	21	0,98
5000	0,94	0,87	0,91	0,65	17100	8,56E-11	1,32E-10	29	6,74E-07	21	0,98
5000	3,41	3,38	3,40	0,65	69600	7,89E-11	1,21E-10	49	6,21E-07	21	0,98
5000	1,09	1,12	1,11	0,65	24300	7,53E-11	1,16E-10	56	5,79E-07	20	1,00
5000	2,62	2,66	2,64	0,65	61200	7,14E-11	1,10E-10	73	5,50E-07	20	1,00
5000	1,05	1,04	1,05	0,65	23400	7,40E-11	1,14E-10	79	5,69E-07	20	1,00
5000	7,69	7,64	7,67	0,65	238800	5,07E-11	7,80E-11	145	4,09E-07	22	0,95
5000	0,59	0,62	0,61	0,65	20400	4,68E-11	7,20E-11	151	3,78E-07	22	0,95
5000	1,85	1,84	1,85	0,65	61200	4,76E-11	7,32E-11	168	3,84E-07	22	0,95
5000	0,6	0,67	0,64	0,65	27300	3,67E-11	5,65E-11	176	2,96E-07	22	0,95
5000	1,25	1,28	1,27	0,65	57600	3,47E-11	5,33E-11	192	2,80E-07	22	0,95
5000	0,69	0,72	0,71	0,65	27600	4,13E-11	6,35E-11	199	3,25E-07	21	0,98
5000	1,36	1,35	1,36	0,65	64200	3,33E-11	5,13E-11	217	2,69E-07	22	0,95
5000	0,45	0,4	0,43	0,65	21600	3,11E-11	4,78E-11	223	2,51E-07	22	0,95
5000	0,91	0,89	0,90	0,65	60300	2,41E-11	3,71E-11	240	1,90E-07	21	0,98
5000	0,36	0,34	0,35	0,65	20400	2,84E-11	4,37E-11	246	2,19E-07	20	1,00
5000	3,21	3,23	3,22	0,65	238800	2,23E-11	3,44E-11	312	1,72E-07	20	1,00
5000	0,21	0,22	0,22	0,65	13800	2,58E-11	3,97E-11	316	1,98E-07	20	1,00

Table A.18. Hydraulic Conductivity Calculations for GCL-2-W under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	5,44	5,43	5,44	0,73	17400	5,54E-10	7,59E-10	5	3,98E-06	22	0,95
5000	13	13,5	13,25	0,73	69600	3,38E-10	4,62E-10	24	2,43E-06	22	0,95
5000	6,65	6,65	6,65	0,73	29700	3,97E-10	5,44E-10	32	2,85E-06	22	0,95
5000	11,2	11	11,10	0,73	65700	3,00E-10	4,10E-10	51	2,15E-06	22	0,95
5000	7,34	7,35	7,35	0,73	27000	4,82E-10	6,61E-10	58	3,47E-06	22	0,95
5000	11,4	11,5	11,45	0,73	65100	3,12E-10	4,27E-10	76	2,24E-06	22	0,95
5000	5,8	5,83	5,82	0,73	27300	3,78E-10	5,17E-10	84	2,71E-06	22	0,95
5000	9,7	9,73	9,72	0,73	61800	2,79E-10	3,82E-10	101	2,00E-06	22	0,95
5000	3,83	3,91	3,87	0,73	24300	2,82E-10	3,87E-10	108	2,03E-06	22	0,95
5000	27	27,5	27,25	0,73	238200	2,03E-10	2,78E-10	174	1,46E-06	22	0,95
5000	2,93	2,93	2,93	0,73	26700	1,95E-10	2,67E-10	181	1,40E-06	22	0,95
5000	6,26	6,26	6,26	0,73	63300	1,75E-10	2,40E-10	199	1,26E-06	22	0,95
5000	2,8	2,69	2,75	0,73	25200	1,93E-10	2,65E-10	206	1,39E-06	22	0,95
5000	7,32	7,34	7,33	0,73	68700	1,89E-10	2,59E-10	225	1,36E-06	22	0,95
5000	3,04	3,05	3,05	0,73	29100	1,86E-10	2,54E-10	233	1,33E-06	22	0,95
5000	4,93	4,95	4,94	0,73	54300	1,61E-10	2,21E-10	248	1,16E-06	22	0,95
5000	3,5	3,44	3,47	0,73	31500	1,95E-10	2,68E-10	257	1,40E-06	22	0,95
5000	6,1	6,07	6,09	0,73	62400	1,73E-10	2,37E-10	274	1,24E-06	22	0,95
5000	3,51	3,49	3,50	0,73	33000	1,88E-10	2,58E-10	283	1,35E-06	22	0,95
5000	5,53	5,52	5,53	0,73	57900	1,69E-10	2,32E-10	300	1,22E-06	22	0,95

Table. A.19. Hydraulic Conductivity Calculations for GCL-2-NW under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	3,67	3,69	3,68	0,75	27300	2,58E-10	3,43E-10	8	1,72E-06	20	1,00
5000	12,2	12	12,10	0,75	62100	3,72E-10	4,96E-10	25	2,48E-06	20	1,00
5000	5,88	5,87	5,88	0,75	30300	3,70E-10	4,94E-10	33	2,47E-06	20	1,00
5000	8,7	8,6	8,65	0,75	69000	2,40E-10	3,19E-10	52	1,60E-06	20	1,00
5000	4,35	4,33	4,34	0,75	24300	3,25E-10	4,34E-10	59	2,28E-06	22	0,95
5000	9,7	9,6	9,65	0,75	66600	2,64E-10	3,52E-10	78	1,85E-06	22	0,95
5000	3,17	3,19	3,18	0,75	29700	1,95E-10	2,60E-10	86	1,36E-06	22	0,95
5000	8,3	8,3	8,30	0,75	61500	2,46E-10	3,28E-10	103	1,72E-06	22	0,95
5000	4,54	4,63	4,59	0,75	33600	2,49E-10	3,31E-10	112	1,74E-06	22	0,95
5000	21,35	21,3	21,33	0,75	238800	1,63E-10	2,17E-10	179	1,14E-06	22	0,95
5000	2,05	2,07	2,06	0,75	30000	1,25E-10	1,67E-10	187	8,75E-07	22	0,95
5000	4,11	4,1	4,11	0,75	60000	1,25E-10	1,66E-10	204	8,72E-07	22	0,95
5000	1,96	1,96	1,96	0,75	29700	1,20E-10	1,60E-10	212	8,41E-07	22	0,95
5000	3,03	3,09	3,06	0,75	61800	9,46E-11	1,26E-10	229	6,31E-07	20	1,00
5000	2,48	2,53	2,51	0,75	33000	1,45E-10	1,93E-10	238	9,67E-07	20	1,00
5000	4,93	4,95	4,94	0,75	59100	1,60E-10	2,13E-10	255	1,06E-06	20	1,00
5000	1,45	1,49	1,47	0,75	28800	9,75E-11	1,30E-10	263	6,50E-07	20	1,00
5000	3,4	3,38	3,39	0,75	68100	9,51E-11	1,27E-10	282	6,34E-07	20	1,00
5000	1,28	1,3	1,29	0,75	26100	9,44E-11	1,26E-10	289	6,30E-07	20	1,00

Table A.20. Hydraulic Conductivity Calculations for GCL-3-W-D2 under 5 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
500	30,69	30,66	30,68	0,83	28800	2,15E-08	2,59E-08	8	1,36E-05	22	0,95
500	39,5	39,6	39,55	0,83	57600	1,38E-08	1,67E-08	24	8,75E-06	22	0,95
500	35	35,05	35,03	0,83	26400	2,68E-08	3,22E-08	31	1,69E-05	22	0,95
500	40,2	40,2	40,20	0,83	55800	1,49E-08	1,79E-08	47	9,18E-06	21	0,98
500	25,7	25,75	25,73	0,83	28800	1,84E-08	2,22E-08	55	1,14E-05	21	0,98
500	38,75	38,8	38,78	0,83	57600	1,36E-08	1,64E-08	71	8,58E-06	22	0,95
500	18	18,2	18,10	0,83	24600	1,48E-08	1,79E-08	78	9,37E-06	22	0,95
500	38,5	38,6	38,55	0,83	68400	1,14E-08	1,37E-08	97	7,18E-06	22	0,95
500	10,5	10,4	10,45	0,83	20700	1,02E-08	1,23E-08	102	6,43E-06	22	0,95
500	109,3	109,5	109,40	0,83	233400	9,45E-09	1,14E-08	167	5,97E-06	22	0,95
500	13,15	13,2	13,18	0,83	28800	9,23E-09	1,11E-08	175	5,83E-06	22	0,95
500	23,8	23,8	23,80	0,83	55200	8,90E-09	1,07E-08	191	5,49E-06	21	0,98
500	14,3	14,4	14,35	0,83	30600	9,68E-09	1,17E-08	199	5,97E-06	21	0,98
500	24,7	24,6	24,65	0,83	60300	8,44E-09	1,02E-08	216	5,21E-06	21	0,98
500	10,9	10,9	10,90	0,83	27900	8,06E-09	9,72E-09	224	4,98E-06	21	0,98
500	96,4	96,6	96,50	0,83	57600	3,46E-08	4,17E-08	240	2,13E-05	21	0,98
500	126	127	126,50	0,83	29700	8,79E-08	1,06E-07	248	5,43E-05	21	0,98
500	284,5	284,4	284,45	0,83	56100	1,05E-07	1,26E-07	263	6,46E-05	21	0,98
500	439	438,8	438,90	0,83	18300	4,95E-07	5,96E-07	287	3,06E-04	21	0,98

Table A.21. Hydraulic Conductivity Calculations for GCL-3-NW-D2 under 20 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
2000	140	139,5	139,75	0,72	30000	2,04E-08	2,83E-08	8	5,93E-05	22	0,95
2000	230	230	230,00	0,72	54000	1,86E-08	2,59E-08	23	5,43E-05	22	0,95
2000	147,4	147,5	147,45	0,72	30300	2,13E-08	2,96E-08	32	6,20E-05	22	0,95
2000	135	134,5	134,75	0,72	61200	9,63E-09	1,34E-08	49	2,80E-05	22	0,95
2000	90,5	91,5	91,00	0,72	23100	1,61E-08	2,23E-08	55	5,02E-05	21	0,89
2000	43,5	45	44,25	0,72	21600	8,36E-09	1,16E-08	126	2,61E-05	21	0,89
2000	99,5	99,5	99,50	0,72	54600	7,97E-09	1,11E-08	141	2,32E-05	22	0,95
2000	189	188,7	188,85	0,72	19800	4,37E-08	6,08E-08	147	1,22E-04	20	1,00
2000	437,8	437,7	437,75	0,72	21600	9,29E-08	1,29E-07	169	2,58E-04	20	1,00
2000	87	88	87,50	0,72	60	6,69E-06	9,29E-06	187	1,86E-02	20	1,00
2000	105	105	105,00	0,72	60	8,03E-06	1,11E-05	187	2,23E-02	20	1,00

Table A.22. Hydraulic Conductivity Calculations for GCL-3-W-D1.5 under 15 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
1500	148,66	149,16	148,91	0,76	59400	1,58E-08	2,08E-08	17	3,19E-05	21	0,98
1500	45,4	45,5	45,45	0,76	25200	1,14E-08	1,50E-08	24	2,30E-05	21	0,98
1500	184	185	184,50	0,76	57600	2,02E-08	2,66E-08	40	4,08E-05	21	0,98
1500	41,25	41,3	41,28	0,76	27000	9,63E-09	1,27E-08	47	1,95E-05	21	0,98
1500	146,5	146,5	146,50	0,76	56400	1,64E-08	2,15E-08	63	3,31E-05	21	0,98
1500	54,4	54,5	54,45	0,76	32400	1,06E-08	1,39E-08	72	2,14E-05	21	0,98
1500	90,15	90	90,08	0,76	55200	1,03E-08	1,35E-08	87	2,08E-05	21	0,98
1500	44,5	44,5	44,50	0,76	29400	9,54E-09	1,25E-08	95	1,93E-05	21	0,98
1500	304	305	304,50	0,76	231900	8,27E-09	1,09E-08	160	1,67E-05	21	0,98
1500	35	34,8	34,90	0,76	24300	9,05E-09	1,19E-08	166	1,83E-05	21	0,98
1500	85	84,5	84,75	0,76	62400	8,56E-09	1,13E-08	184	1,73E-05	21	0,98
1500	168,5	168,4	168,45	0,76	22200	4,78E-08	6,29E-08	190	9,67E-05	21	0,98
1500	290	290	290,00	0,76	19800	9,23E-08	1,21E-07	212	1,87E-04	21	0,98
1500	428	427	427,50	0,76	14400	1,87E-07	2,46E-07	234	3,78E-04	21	0,98
1500	376	377	376,50	0,76	6300	3,77E-07	4,95E-07	237	7,61E-04	21	0,98
1500	83,5	85	84,25	0,76	60	8,85E-06	1,16E-05	254	1,79E-02	21	0,98

Table A.23. Hydraulic Conductivity Calculations for GCL-3-NW-D1.5 under 35 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
3500	102,4	102,5	102,45	0,66	30600	7,15E-09	1,08E-08	9	4,27E-05	25	0,89
3500	174,5	175	174,75	0,66	55200	6,76E-09	1,02E-08	24	4,03E-05	25	0,89
3500	99	98,8	98,90	0,66	27900	7,57E-09	1,15E-08	32	4,52E-05	25	0,89
3500	177,6	177,7	177,65	0,66	59400	6,39E-09	9,68E-09	48	3,81E-05	25	0,89
3500	92,3	92,2	92,25	0,66	28800	6,84E-09	1,04E-08	56	4,08E-05	25	0,89
3500	141,5	141,5	141,50	0,66	62100	5,10E-09	7,72E-09	73	2,90E-05	23	0,93
3500	88	88,8	88,40	0,66	28800	6,87E-09	1,04E-08	81	3,91E-05	23	0,93
3500	152	154,4	153,20	0,66	60300	5,68E-09	8,61E-09	98	3,24E-05	23	0,93
3500	188	187,7	187,85	0,66	23700	1,77E-08	2,69E-08	105	1,01E-04	23	0,93
3500	380	380	380,00	0,66	7200	1,13E-07	1,71E-07	172	6,72E-04	25	0,89
3500	396	394,5	395,25	0,66	1200	7,04E-07	1,07E-06	174	4,20E-03	25	0,89
3500	389	389	389,00	0,66	300	2,77E-06	4,20E-06	175	1,65E-02	25	0,89
3500	394,5	395,5	395,00	0,66	60	1,41E-05	2,13E-05	193	8,39E-02	25	0,89
3500	390	388	389,00	0,66	20	4,16E-05	6,30E-05	193	2,48E-01	25	0,89
3500	398	398	398,00	0,66	20	4,25E-05	6,44E-05	193	2,54E-01	25	0,89

Table A.24. Hydraulic Conductivity Calculations for GCL-3-W-D1 under 25 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
2500	87,5	88	87,75	0,75	57600	5,82E-09	7,76E-09	16	1,94E-05	20	1,00
2500	49,75	49,8	49,78	0,75	28800	6,60E-09	8,81E-09	24	2,20E-05	20	1,00
2500	90	90,25	90,13	0,75	60000	5,74E-09	7,65E-09	41	1,91E-05	20	1,00
2500	40	40	40,00	0,75	23400	6,53E-09	8,71E-09	47	2,18E-05	20	1,00
2500	96,5	96,6	96,55	0,75	58200	6,34E-09	8,45E-09	63	2,11E-05	20	1,00
2500	34,4	34,5	34,45	0,75	25200	5,22E-09	6,97E-09	70	1,74E-05	20	1,00
2500	70	70	70,00	0,75	55800	4,79E-09	6,39E-09	86	1,60E-05	20	1,00
2500	35,05	35,15	35,10	0,75	27300	4,91E-09	6,55E-09	93	1,64E-05	20	1,00
2500	260	260	260,00	0,75	237600	4,18E-09	5,58E-09	159	1,39E-05	20	1,00
2500	26,2	26,3	26,25	0,75	22500	4,46E-09	5,94E-09	166	1,49E-05	20	1,00
2500	67,8	67,7	67,75	0,75	65100	3,98E-09	5,30E-09	184	1,33E-05	20	1,00
2500	22,9	22,7	22,80	0,75	27000	3,23E-09	4,30E-09	191	1,08E-05	20	1,00
2500	55	54,5	54,75	0,75	62400	3,35E-09	4,47E-09	209	1,12E-05	20	1,00
2500	23,85	23,8	23,83	0,75	27600	3,30E-09	4,40E-09	216	1,10E-05	20	1,00
2500	57,8	57,7	57,75	0,75	53100	4,16E-09	5,54E-09	231	1,39E-05	20	1,00
2500	145	145	145,00	0,75	18000	3,08E-08	4,10E-08	236	1,03E-04	20	1,00
2500	154	155	154,50	0,75	7200	8,20E-08	1,09E-07	238	2,73E-04	20	1,00
2500	140	140	140,00	0,75	60	8,92E-06	1,19E-05	255	2,97E-02	20	1,00
2500	159,5	160	159,75	0,75	60	1,02E-05	1,36E-05	255	3,39E-02	20	1,00

Table A.25. Hydraulic Conductivity Calculations for GCL-3-NW-D1 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	16,4	17	16,70	0,64	26400	9,18E-10	1,43E-09	7	8,06E-06	25	0,89
5000	32	32,7	32,35	0,64	60600	7,74E-10	1,21E-09	24	6,80E-06	25	0,89
5000	14	14,5	14,25	0,64	24300	8,51E-10	1,33E-09	31	7,47E-06	25	0,89
5000	35,8	35,7	35,75	0,64	63000	8,23E-10	1,29E-09	48	7,23E-06	25	0,89
5000	14	14	14,00	0,64	32100	6,33E-10	9,88E-10	57	5,56E-06	25	0,89
5000	30,2	30,3	30,25	0,64	62400	7,54E-10	1,18E-09	75	6,18E-06	22	0,95
5000	47,5	47,7	47,60	0,64	23400	3,16E-09	4,94E-09	81	2,59E-05	22	0,95
5000	75	74,4	74,70	0,64	14400	8,07E-09	1,26E-08	101	6,61E-05	22	0,95
5000	177,8	178,8	178,30	0,64	13500	2,05E-08	3,21E-08	105	1,68E-04	22	0,95
5000	289	288	288,50	0,64	3600	1,25E-07	1,95E-07	172	1,02E-03	22	0,95
5000	385	385	385,00	0,64	1800	3,33E-07	5,20E-07	172	2,72E-03	22	0,95
5000	389	390	389,50	0,64	600	1,01E-06	1,58E-06	178	8,27E-03	22	0,95
5000	390	390	390,00	0,64	60	1,01E-05	1,58E-05	195	8,28E-02	22	0,95
5000	395	394,5	394,75	0,64	30	2,05E-05	3,20E-05	195	1,68E-01	22	0,95

Table A.26. Hydraulic Conductivity Calculations for GCL-3-W-D0.5 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	11,7	11,73	11,72	0,76	26100	8,48E-10	1,12E-09	7	5,72E-06	21	0,98
5000	25,6	25,4	25,50	0,76	61200	7,88E-10	1,04E-09	24	5,31E-06	21	0,98
5000	10,55	10,5	10,53	0,76	24300	8,19E-10	1,08E-09	31	5,52E-06	21	0,98
5000	30,7	30,6	30,65	0,76	66000	8,78E-10	1,15E-09	49	5,92E-06	21	0,98
5000	10,55	10,35	10,45	0,76	25200	7,84E-10	1,03E-09	56	5,28E-06	21	0,98
5000	24,6	24,65	24,63	0,76	62700	7,42E-10	9,77E-10	74	5,00E-06	21	0,98
5000	10,2	10,2	10,20	0,76	24300	7,93E-10	1,04E-09	81	5,35E-06	21	0,98
5000	94,3	94,4	94,35	0,76	245700	7,26E-10	9,55E-10	149	4,89E-06	21	0,98
5000	9,3	9,4	9,35	0,76	26100	6,77E-10	8,91E-10	156	4,56E-06	21	0,98
5000	20,8	20,8	20,80	0,76	60600	6,49E-10	8,54E-10	173	4,37E-06	21	0,98
5000	11,1	11,1	11,10	0,76	29400	7,14E-10	9,39E-10	181	4,81E-06	21	0,98
5000	21,5	21,4	21,45	0,76	57300	6,91E-10	9,09E-10	197	4,77E-06	22	0,95
5000	9,5	9,6	9,55	0,76	28200	6,25E-10	8,22E-10	205	4,31E-06	22	0,95
5000	21,8	22	21,90	0,76	60300	6,70E-10	8,82E-10	222	4,63E-06	22	0,95
5000	9,9	9,9	9,90	0,76	30600	5,97E-10	7,86E-10	230	4,12E-06	22	0,95
5000	19,95	20	19,98	0,76	55800	6,61E-10	8,69E-10	246	4,56E-06	22	0,95
5000	11,55	11,45	11,50	0,76	33900	6,57E-10	8,64E-10	255	4,32E-06	20	1,00
5000	19,85	19,9	19,88	0,76	60600	6,35E-10	8,36E-10	272	4,18E-06	20	1,00
5000	10	10,05	10,03	0,76	29400	6,60E-10	8,69E-10	280	4,34E-06	20	1,00

Table A.27. Hydraulic Conductivity Calculations for GCL-3-W under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	64,5	64,4	64,45	0,71	33000	3,37E-09	4,74E-09	9	2,49E-05	22	0,95
5000	95,6	96,6	96,10	0,71	65700	2,52E-09	3,55E-09	27	1,86E-05	22	0,95
5000	65	65	65,00	0,71	29700	3,77E-09	5,32E-09	36	2,79E-05	22	0,95
5000	86,5	85,5	86,00	0,71	62400	2,38E-09	3,35E-09	53	1,76E-05	22	0,95
5000	36,6	37	36,80	0,71	32700	1,94E-09	2,73E-09	62	1,43E-05	22	0,95
5000	65,8	65,7	65,75	0,71	60600	1,87E-09	2,64E-09	79	1,38E-05	22	0,95
5000	32,1	31,9	32,00	0,71	31500	1,75E-09	2,47E-09	88	1,29E-05	22	0,95
5000	71	71,3	71,15	0,71	63900	1,92E-09	2,70E-09	105	1,42E-05	22	0,95
5000	41,6	41,6	41,60	0,71	31200	2,30E-09	3,24E-09	114	1,70E-05	22	0,95
5000	280	278	279,00	0,71	246000	1,96E-09	2,75E-09	182	1,44E-05	22	0,95
5000	24	24	24,00	0,71	36600	1,13E-09	1,59E-09	193	8,35E-06	22	0,95
5000	38	38,1	38,05	0,71	54020	1,21E-09	1,71E-09	208	8,97E-06	22	0,95
5000	18	17	17,50	0,71	27900	1,08E-09	1,52E-09	215	7,99E-06	22	0,95
5000	36,5	36,4	36,45	0,71	66300	9,48E-10	1,34E-09	234	7,00E-06	22	0,95
5000	17,47	17,44	17,46	0,71	31800	9,46E-10	1,33E-09	243	6,99E-06	22	0,95
5000	38,7	38,7	38,70	0,71	63900	1,04E-09	1,47E-09	260	7,72E-06	22	0,95
5000	18,1	18	18,05	0,71	31500	9,88E-10	1,39E-09	269	7,30E-06	22	0,95
5000	33,3	33,35	33,33	0,71	60600	9,48E-10	1,34E-09	286	7,01E-06	22	0,95
5000	13,15	13,2	13,18	0,71	23400	9,71E-10	1,37E-09	292	7,17E-06	22	0,95

Table A.28. Hydraulic Conductivity Calculations for GCL-3-NW under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	60,2	60	60,10	0,69	31800	3,24E-09	4,70E-09	9	2,41E-05	21	0,98
5000	133,5	134,5	134,00	0,69	64500	3,56E-09	5,17E-09	27	2,65E-05	21	0,98
5000	66	67	66,50	0,69	33900	3,37E-09	4,88E-09	36	2,50E-05	21	0,98
5000	83	82	82,50	0,69	65700	2,15E-09	3,12E-09	54	1,60E-05	21	0,98
5000	38,8	39	38,90	0,69	35100	1,90E-09	2,76E-09	64	1,41E-05	21	0,98
5000	51,5	51,5	51,50	0,69	56400	1,57E-09	2,27E-09	80	1,16E-05	21	0,98
5000	25,3	25,7	25,50	0,69	34200	1,28E-09	1,85E-09	89	9,50E-06	21	0,98
5000	43	42	42,50	0,69	66600	1,10E-09	1,59E-09	108	8,13E-06	21	0,98
5000	22,8	23	22,90	0,69	33600	1,17E-09	1,69E-09	117	8,68E-06	21	0,98
5000	135	136	135,50	0,69	243900	9,53E-10	1,38E-09	185	7,08E-06	21	0,98
5000	15	15,3	15,15	0,69	27900	9,32E-10	1,35E-09	193	6,92E-06	21	0,98
5000	32,5	32,2	32,35	0,69	57650	9,63E-10	1,40E-09	209	7,15E-06	21	0,98
5000	17,4	17,5	17,45	0,69	30000	9,98E-10	1,45E-09	217	7,41E-06	21	0,98
5000	37	37	37,00	0,69	69900	9,08E-10	1,32E-09	236	6,74E-06	21	0,98
5000	14,2	14,35	14,28	0,69	27000	9,07E-10	1,31E-09	244	6,74E-06	21	0,98
5000	32	31,1	31,55	0,69	62100	8,72E-10	1,26E-09	261	6,47E-06	21	0,98
5000	17,2	17	17,10	0,69	33900	8,66E-10	1,25E-09	271	6,43E-06	21	0,98
5000	29,6	29,6	29,60	0,69	59100	8,59E-10	1,25E-09	287	6,38E-06	21	0,98
5000	14,15	14,1	14,13	0,69	27300	8,88E-10	1,29E-09	295	6,59E-06	21	0,98

Table A.29. Hydraulic Conductivity Calculations for GCL-4-W-D2 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	8,8	8,79	8,80	0,78	26100	6,39E-10	8,19E-10	7	4,29E-06	22	0,95
5000	17,5	17,65	17,58	0,78	58320	5,71E-10	7,32E-10	23	3,84E-06	22	0,95
5000	9,78	9,8	9,79	0,78	31200	5,95E-10	7,62E-10	32	4,00E-06	22	0,95
5000	18,05	18	18,03	0,78	61200	5,58E-10	7,16E-10	49	3,75E-06	22	0,95
5000	8,99	8,96	8,98	0,78	26100	6,52E-10	8,35E-10	56	4,38E-06	22	0,95
5000	18,5	18,55	18,53	0,78	70200	5,00E-10	6,41E-10	76	3,36E-06	22	0,95
5000	5,15	5,15	5,15	0,78	21000	4,65E-10	5,96E-10	82	3,12E-06	22	0,95
5000	8,43	8,45	8,44	0,78	60000	2,67E-10	3,42E-10	98	1,79E-06	22	0,95
5000	6,68	6,68	6,68	0,78	33300	3,80E-10	4,87E-10	108	2,56E-06	22	0,95
5000	39,8	39,85	39,83	0,78	229200	3,29E-10	4,22E-10	171	2,21E-06	22	0,95
5000	5,35	5,37	5,36	0,78	27000	3,76E-10	4,82E-10	179	2,53E-06	22	0,95
5000	9,68	9,65	9,67	0,78	61200	2,99E-10	3,84E-10	196	2,01E-06	22	0,95
5000	3,69	3,63	3,66	0,78	24600	2,82E-10	3,61E-10	203	1,90E-06	22	0,95
5000	7,38	7,43	7,41	0,78	64200	2,19E-10	2,80E-10	220	1,47E-06	22	0,95
5000	2,13	2,12	2,13	0,78	20700	1,95E-10	2,49E-10	226	1,31E-06	22	0,95
5000	6,39	6,37	6,38	0,78	68400	1,77E-10	2,27E-10	245	1,19E-06	22	0,95
5000	1,89	1,9	1,90	0,78	22500	1,60E-10	2,05E-10	251	1,07E-06	22	0,95

Table A.30. Hydraulic Conductivity Calculations for GCL-4-W-D1.5 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	4,2	4,25	4,23	0,82	25200	3,34E-10	4,07E-10	7	2,14E-06	22	0,95
5000	9,55	9,52	9,54	0,82	60300	3,22E-10	3,93E-10	24	2,01E-06	21	0,98
5000	5,89	5,84	5,87	0,82	30000	3,99E-10	4,86E-10	32	2,49E-06	21	0,98
5000	7,52	7,47	7,50	0,82	56100	2,72E-10	3,32E-10	48	1,70E-06	21	0,98
5000	2,67	2,72	2,70	0,82	27000	1,99E-10	2,43E-10	55	1,27E-06	22	0,95
5000	4,75	4,75	4,75	0,82	61200	1,55E-10	1,89E-10	72	9,89E-07	22	0,95
5000	1,1	1,08	1,09	0,82	24000	9,05E-11	1,10E-10	79	5,79E-07	22	0,95
5000	3,15	3,16	3,16	0,82	61800	1,02E-10	1,24E-10	96	6,50E-07	22	0,95
5000	1,92	1,88	1,90	0,82	21900	1,73E-10	2,11E-10	102	1,11E-06	22	0,95
5000	10	10,6	10,30	0,82	232800	9,24E-11	1,13E-10	167	5,64E-07	20	1,00
5000	0,9	0,91	0,91	0,82	21600	8,75E-11	1,07E-10	173	5,34E-07	20	1,00
5000	2,44	2,45	2,45	0,82	63900	7,99E-11	9,75E-11	191	4,87E-07	20	1,00
5000	0,97	0,98	0,98	0,82	25200	8,08E-11	9,86E-11	198	4,93E-07	20	1,00
5000	2,31	2,34	2,33	0,82	59100	7,84E-11	9,56E-11	214	5,01E-07	22	0,95
5000	1,11	1,12	1,12	0,82	29700	7,48E-11	9,12E-11	222	4,78E-07	22	0,95
5000	2,17	2,19	2,18	0,82	59400	7,31E-11	8,92E-11	239	4,68E-07	22	0,95

Table A.31. Hydraulic Conductivity Calculations for GCL-4-W-D1 under 50 m hydraulic head

Max. Hydraulic Head (cm)	Inflow (cm ³)	Outflow (cm ³)	Average of Inflow and Outflow (cm ³)	GCL thickness (cm)	Time Interval (s)	Permeability coefficient (cm/s)	Permittivity (1/s)	Elapsed Time (hour)	Index Flux (cm ³ /cm ²)/s	Temperature (°C)	Temp. Correction Factor
5000	1,68	1,64	1,66	0,73	32400	9,53E-11	1,31E-10	9	6,53E-07	20	1,00
5000	2,75	2,74	2,75	0,73	55200	9,25E-11	1,27E-10	24	6,33E-07	20	1,00
5000	1,44	1,47	1,46	0,73	28800	9,40E-11	1,29E-10	32	6,44E-07	20	1,00
5000	2,56	2,55	2,56	0,73	58200	8,16E-11	1,12E-10	49	5,59E-07	20	1,00
5000	1,17	1,21	1,19	0,73	27000	8,20E-11	1,12E-10	56	5,61E-07	20	1,00
5000	2,44	2,42	2,43	0,73	60300	7,50E-11	1,03E-10	73	5,13E-07	20	1,00
5000	1,2	1,23	1,22	0,73	28800	7,85E-11	1,07E-10	81	5,37E-07	20	1,00
5000	2,06	2,05	2,06	0,73	60300	6,34E-11	8,68E-11	98	4,34E-07	20	1,00
5000	1	1,04	1,02	0,73	29700	6,39E-11	8,75E-11	106	4,37E-07	20	1,00
5000	8,7	9	8,85	0,73	231000	7,13E-11	9,76E-11	170	4,88E-07	20	1,00
5000	0,96	0,94	0,95	0,73	28800	6,13E-11	8,40E-11	178	4,20E-07	20	1,00
5000	1,83	1,82	1,83	0,73	58500	5,80E-11	7,95E-11	194	3,97E-07	20	1,00
5000	0,79	0,81	0,80	0,73	28800	5,17E-11	7,08E-11	202	3,54E-07	20	1,00
5000	1,8	1,77	1,79	0,73	56400	5,89E-11	8,06E-11	218	4,03E-07	20	1,00
5000	0,87	0,88	0,88	0,73	32700	4,98E-11	6,82E-11	227	3,41E-07	20	1,00
5000	1,46	1,43	1,45	0,73	56400	4,77E-11	6,53E-11	243	3,26E-07	20	1,00

Mass/Unit Area and Moisture Content Calculations

Table A.32. Moisture Content Calculations for GCL-1-W-D2 under 30 m hydraulic head

Can no.	Y20 (flat)	H5 (crest)	A12 (crest)	H15 (crest)	Y15 (flat)	Y18 (flat)	Y16 (crest)	Y17 (flat)
Can (gr)	6,54	9,45	9,11	6,59	9,37	6,67	6,54	6,65
GCL+can (gr)	10,91	15,98	14,49	10,22	13,29	9,71	12,9	11,83
Dry GCL+can (gr)	8,80	12,03	11,21	7,97	11,38	8,16	9,06	9,29
Dry GCL (gr)	2,26	2,58	2,10	1,38	2,01	1,49	2,52	2,64
initial mass of GCL (gr)	4,37	6,53	5,38	3,63	3,92	3,04	6,36	5,18
initial water content (%) of GCL	93,36	153,10	156,19	163,04	95,02	104,03	152,38	96,21

Table A.33. Moisture Content Calculations for GCL-1-NW-D2 under 35 m hydraulic head

Can no.	H5 (flat)	K7 (crest)	Y23 (crest)	Z1 (crest)	S22 (flat)	Y18 (flat)	Y16 (crest)	S12 (flat)
Can (gr)	6,59	9,35	6,59	6,63	6,7	6,64	6,53	6,26
GCL+can (gr)	11,02	16,67	14,25	14,27	10,33	10,62	14,61	9,43
Dry GCL+can (gr)	8,84	12,39	9,72	9,66	8,55	8,58	9,75	7,92
Dry GCL (gr)	2,25	3,04	3,13	3,03	1,85	1,94	3,22	1,66
initial mass of GCL (gr)	4,43	7,32	7,66	7,64	3,63	3,98	8,08	3,17
initial water content (%) of GCL	96,89	140,79	144,73	152,15	96,22	105,15	150,93	90,96

Table A.34. Moisture Content Calculations for GCL-1-W-D1.5 under 45 m hydraulic head

Can no.	A21 (flat)	B15 (crest)	A8 (flat)	B50 (crest)	A12 (flat)	A13 (crest)	B4 (flat)	B5 (crest)
Can (gr)	10,21	10,67	9,9	11,21	11,87	10,88	12,23	12,29
GCL+can (gr)	13,72	14,98	12,88	15,04	14,99	15,18	15,29	16,54
Dry GCL+can (gr)	12,02	12,36	11,45	12,73	13,51	12,62	13,86	14,03
Dry GCL (gr)	1,81	1,69	1,55	1,52	1,64	1,74	1,63	1,74
initial mass of GCL (gr)	3,51	4,31	2,98	3,83	3,12	4,30	3,06	4,25
initial water content (%) of GCL	93,92	155,03	92,26	151,97	90,24	147,13	87,73	144,25

Table A.35. Moisture Content Calculations for GCL-1-NW-D1.5 under 50 m hydraulic head

Can no.	Y24 (flat)	S21 (crest)	K12 (crest)	Y20 (flat)	K14 (crest)	H15 (flat)	Y25 (crest)	K17 (flat)
Can (gr)	6,57	9,55	6,53	6,59	9,41	9,39	6,72	6,66
GCL+can (gr)	8,05	15,45	12,04	8,74	15,73	10,43	12,59	8,73
Dry GCL+can (gr)	7,38	12,45	9,3	7,7	12,72	9,94	9,62	7,78
Dry GCL (gr)	0,81	2,90	2,77	1,11	3,31	0,55	2,90	1,12
initial mass of GCL (gr)	1,48	5,90	5,51	2,15	6,32	1,04	5,87	2,07
initial water content (%) of GCL	82,72	103,45	98,92	93,69	90,94	89,09	102,41	84,82

Table A.36. Moisture Content Calculations for GCL-1-W-D1 under 50 m hydraulic head

Can no.	Y20 (flat)	H5 (crest)	S21 (flat)	K12 (crest)	K14 (flat)	Y24 (crest)	H14 (flat)	K17 (crest)
Can (gr)	6,62	6,62	9,55	6,54	9,46	6,58	9,4	6,66
GCL+can (gr)	8,43	8,27	11,03	8,35	11,23	8,66	11,4	9,17
Dry GCL+can (gr)	7,59	7,48	10,38	7,47	10,42	7,68	10,46	7,98
Dry GCL (gr)	0,97	0,86	0,83	0,93	0,96	1,10	1,06	1,32
initial mass of GCL (gr)	1,81	1,65	1,48	1,81	1,77	2,08	2,00	2,51
initial water content (%) of GCL	86,60	91,86	78,31	94,62	84,38	89,09	88,68	90,15

Table A.37. Moisture Content Calculations for GCL-1-NW-D1 under 50 m hydraulic head

Can no.	K37 (flat)	Y24 (crest)	212 (flat)	K14 (crest)	525 (flat)	M11 (crest)	107 (flat)	M8 (crest)
Can (gr)	14,03	13,75	14,03	14,05	46,28	53,77	53,81	53,72
GCL+can (gr)	15,57	16,19	15,65	16,06	48,62	55,63	56,32	56,79
Dry GCL+can (gr)	14,86	15,04	14,92	15,1	47,57	54,76	55,15	55,34
Dry GCL (gr)	0,83	1,29	0,89	1,05	1,29	0,99	1,34	1,62
initial mass of GCL (gr)	1,54	2,44	1,62	2,01	2,34	1,86	2,51	3,07
initial water content (%) of GCL	85,54	89,15	82,02	91,43	81,40	87,88	87,31	89,51

Table A.38. Moisture Content Calculations for GCL-1-W under 50 m hydraulic head

Can no.	Y15	K12	G4	H5	K5	Y20	K14	K17
Can (gr)	14,05	11,28	14,12	13,88	13,85	11,22	13,89	12,01
GCL+can (gr)	14,58	11,86	14,69	14,44	14,44	11,77	14,44	12,52
Dry GCL+can (gr)	14,32	11,58	14,42	14,17	14,15	11,51	14,17	12,28
Dry GCL (gr)	0,27	0,30	0,30	0,29	0,30	0,29	0,28	0,27
initial mass of GCL (gr)	0,53	0,58	0,57	0,56	0,59	0,55	0,55	0,51
initial water content (%) of GCL	96,30	93,33	90,00	93,10	96,67	89,66	96,43	88,89

Table A.39. Moisture Content Calculations for GCL-1-NW under 50 m hydraulic head

Can no.	Y15	K12	G4	H5	K5	Y20	K14	K17
Can (gr)	14,01	11,29	14,15	13,85	13,89	11,22	13,89	11,97
GCL+can (gr)	14,58	11,80	14,69	14,46	14,38	11,79	14,42	12,56
Dry GCL+can (gr)	14,31	11,56	14,43	14,18	14,14	11,53	14,17	12,28
Dry GCL (gr)	0,30	0,27	0,28	0,33	0,25	0,31	0,28	0,31
initial mass of GCL (gr)	0,57	0,51	0,54	0,61	0,49	0,57	0,53	0,59
initial water content (%) of GCL	90,00	88,89	92,86	84,85	96,00	83,87	89,29	90,32

Table A.40. Mass/Unit Area and Moisture Content Calculations for GCL-2-W-D2 under 10 m hydraulic head

Can no.	K7 (flat)	G4 (crest)	E4 (flat)	Y25 (crest)	A4 (flat)	Y15 (crest)	K17 (flat)	H5 (crest)
Can+cylinder (gr)	13,99	13,95	36,69	11,33	33,48	14,18	11,98	14,14
GCL+can+cylinder (gr)	14,47	14,21	37,15	11,7	33,92	14,48	12,49	14,46
Dry GCL+can (gr)	14,22	14,04	36,93	11,46	33,69	14,28	12,25	14,25
Dry GCL (gr)	0,23	0,09	0,24	0,13	0,21	0,10	0,27	0,11
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,52	0,20	0,55	0,30	0,48	0,23	0,61	0,25
initial mass of GCL (gr)	0,48	0,26	0,46	0,37	0,44	0,30	0,51	0,32
initial water content (%) of clay	108,70	188,89	91,67	184,62	109,52	200,00	88,89	190,91

Table A.41. Mass/Unit Area and Moisture Content Calculations for GCL-2-NW-D2 under 20 m hydraulic head

Can no.	Y15 (flat)	H15 (crest)	K5 (flat)	H3 (crest)	K17 (flat)	S14 (crest)	Y20 (flat)	T13 (crest)
Can+cylinder (gr)	14,71	13,95	14,17	14,23	11,12	14	11,37	11,33
GCL+can+cylinder (gr)	15,17	14,24	14,64	14,58	11,56	14,35	11,85	11,64
Dry GCL+can (gr)	14,95	14,06	14,43	14,37	11,35	14,13	11,63	11,45
Dry GCL (gr)	0,24	0,11	0,26	0,14	0,23	0,13	0,26	0,12
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,55	0,25	0,59	0,32	0,52	0,30	0,59	0,27
initial mass of GCL (gr)	0,46	0,29	0,47	0,35	0,44	0,35	0,48	0,31
initial water content (%) of clay	91,67	163,64	80,77	150,00	91,30	169,23	84,62	158,33

Table A.42. Mass/Unit Area and Moisture Content Calculations for GCL-2-W-D1.5 under 15 m hydraulic head

Can no.	Y20 (flat)	Y23 (crest)	T13 (flat)	K7 (crest)	K5 (flat)	H5 (crest)	K17 (flat)	Y25 (crest)
Can+cylinder (gr)	11,10	11,34	11,21	14,67	13,93	11,25	11,15	11,14
GCL+can+cylinder (gr)	11,60	11,64	11,71	15,04	14,42	11,56	11,59	11,53
Dry GCL+can (gr)	11,37	11,45	11,46	14,8	14,18	11,36	11,38	11,29
Dry GCL (gr)	0,27	0,11	0,25	0,13	0,25	0,11	0,23	0,15
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,61	0,25	0,57	0,30	0,57	0,25	0,52	0,34
initial mass of GCL (gr)	0,50	0,30	0,50	0,37	0,49	0,31	0,44	0,39
initial water content (%) of clay	85,19	172,73	100,00	184,62	96,00	181,82	91,30	160,00

Table A.43. Mass/Unit Area and Moisture Content Calculations for GCL-2-NW-D1.5 under 35 m hydraulic head

Can no.	K16 (flat)	Y22 (crest)	K18 (flat)	K7 (crest)	G6 (flat)	Y11 (crest)	H8 (flat)	K17 (crest)
Can+cylinder (gr)	11,18	13,76	37,46	13,85	13,9	14,71	11,37	14,21
GCL+can+cylinder (gr)	11,64	14,04	37,93	14,19	14,4	15,13	11,81	14,54
Dry GCL+can (gr)	11,41	13,87	37,71	13,99	14,17	14,88	11,6	14,34
Dry GCL (gr)	0,23	0,11	0,25	0,14	0,27	0,17	0,23	0,13
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,52	0,25	0,57	0,32	0,61	0,39	0,52	0,30
initial mass of GCL (gr)	0,46	0,28	0,47	0,34	0,50	0,42	0,44	0,33
initial water content (%) of clay	100,00	154,55	88,00	142,86	85,19	147,06	91,30	153,85

Table A.44. Mass/Unit Area and Moisture Content Calculations for GCL-2-W-D1 under 30 m hydraulic head

Can no.	K37 (flat)	Y24 (crest)	212 (flat)	K14 (crest)	525 (flat)	M11 (crest)	107 (flat)	M8 (crest)
Can+cylinder (gr)	14,02	13,77	14,04	14,05	46,28	53,72	53,84	53,72
GCL+can+cylinder (gr)	14,52	14,22	14,59	14,34	46,82	53,96	54,33	54,12
Dry GCL+can (gr)	14,29	13,95	14,32	14,16	46,55	53,82	54,1	53,88
Dry GCL (gr)	0,27	0,18	0,28	0,11	0,27	0,10	0,26	0,16
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,61	0,41	0,64	0,25	0,61	0,23	0,59	0,36
initial mass of GCL (gr)	0,50	0,45	0,55	0,29	0,54	0,24	0,49	0,40
initial water content (%) of clay	85,19	150,00	96,43	163,64	100,00	140,00	88,46	150,00

Table A.45. Mass/Unit Area and Moisture Content Calculations for GCL-2-NW-D1 under 50 m hydraulic head

Can no.	K14 (flat)	Y20 (crest)	K17 (flat)	K5 (crest)	G4 (flat)	Y15 (crest)	H5 (flat)	K12 (crest)
Can+cylinder (gr)	13,95	11,92	11,15	13,86	14,13	14,06	14,02	11,32
GCL+can+cylinder (gr)	14,47	12,30	11,65	14,32	14,6	14,49	14,51	11,7
Dry GCL+can (gr)	14,22	12,09	11,43	14,05	14,38	14,25	14,29	11,48
Dry GCL (gr)	0,27	0,17	0,28	0,19	0,25	0,19	0,27	0,16
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,61	0,39	0,64	0,43	0,57	0,43	0,61	0,36
initial mass of GCL (gr)	0,52	0,38	0,50	0,46	0,47	0,43	0,49	0,38
initial water content (%) of clay	92,59	123,53	78,57	142,11	88,00	126,32	81,48	137,50

Table A.46. Mass/Unit Area and Moisture Content Calculations for GCL-2-W-D0.5 under 50 m hydraulic head

Can no.	Y15 (flat)	K12 (crest)	G4 (flat)	H5 (crest)	K5 (flat)	Y20 (crest)	K14 (flat)	K17 (crest)
Can+cylinder (gr)	14,04	11,28	14,14	13,89	13,88	11,22	13,91	12
GCL+can+cylinder (gr)	14,55	11,79	14,66	14,41	14,38	11,74	14,41	12,49
Dry GCL+can (gr)	14,32	11,55	14,42	14,17	14,16	11,49	14,18	12,26
Dry GCL (gr)	0,28	0,27	0,28	0,28	0,28	0,27	0,27	0,26
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,64	0,61	0,64	0,64	0,64	0,61	0,61	0,59
initial mass of GCL (gr)	0,51	0,51	0,52	0,52	0,50	0,52	0,50	0,49
initial water content (%) of clay	82,14	88,89	85,71	85,71	78,57	92,59	85,19	88,46

Table A.47. Mass/Unit Area and Moisture Content Calculations for GCL-2-NW-0.5 under 50 m hydraulic head

Can no.	Y15 (flat)	K12 (crest)	G4 (flat)	H5 (crest)	K5 (flat)	Y20 (crest)	K14 (flat)	K17 (crest)
Can+cylinder (gr)	14,04	11,28	14,14	13,88	13,88	11,22	13,89	12
GCL+can+cylinder (gr)	14,52	11,77	14,65	14,42	14,38	11,73	14,41	12,49
Dry GCL+can (gr)	14,31	11,55	14,42	14,16	14,16	11,49	14,17	12,26
Dry GCL (gr)	0,27	0,27	0,28	0,28	0,28	0,27	0,28	0,26
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,61	0,61	0,64	0,64	0,64	0,61	0,64	0,59
initial mass of GCL (gr)	0,48	0,49	0,51	0,54	0,50	0,51	0,52	0,49
initial water content (%) of clay	77,78	81,48	82,14	92,86	78,57	88,89	85,71	88,46

Table A.48. Mass/Unit Area and Moisture Content Calculations for GCL-2-W under 50 m hydraulic head

Can no.	Y15	K12	G4	H5	K5	Y20	K14	K17
Can+cylinder (gr)	14,02	11,28	14,16	13,82	13,88	11,23	13,9	12
GCL+can+cylinder (gr)	14,55	11,80	14,66	14,36	14,41	11,74	14,43	12,54
Dry GCL+can (gr)	14,30	11,56	14,43	14,1	14,16	11,5	14,19	12,29
Dry GCL (gr)	0,28	0,28	0,27	0,28	0,28	0,27	0,29	0,29
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,64	0,64	0,61	0,64	0,64	0,61	0,66	0,66
initial mass of GCL (gr)	0,53	0,52	0,50	0,54	0,53	0,51	0,53	0,54
initial water content (%) of clay	89,29	85,71	85,19	92,86	89,29	88,89	82,76	86,21

Table A.49. Mass/Unit Area and Moisture Content Calculations for GCL-2-NW under 50 m hydraulic head

Can no.	Y15	K12	G4	H5	K5	Y20	K14	K17
Can+cylinder (gr)	14,05	11,25	14,16	13,83	13,89	11,21	13,9	12,03
GCL+can+cylinder (gr)	14,57	11,76	14,69	14,38	14,41	11,72	14,43	12,52
Dry GCL+can (gr)	14,33	11,53	14,45	14,12	14,17	11,48	14,18	12,3
Dry GCL (gr)	0,28	0,28	0,29	0,29	0,28	0,27	0,28	0,27
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,64	0,64	0,66	0,66	0,64	0,61	0,64	0,61
initial mass of GCL (gr)	0,52	0,51	0,53	0,55	0,52	0,51	0,53	0,49
initial water content (%) of clay	85,71	82,14	82,76	89,66	85,71	88,89	89,29	81,48

Table A.50. Mass/Unit Area and Moisture Content Calculations for GCL-3-W-D2 under 5 m hydraulic head

Can no.	K13 (flat)	Y23 (crest)	Y25 (flat)	K7 (crest)	G4 (flat)	K5 (crest)	K17 (flat)	H5 (crest)
Can+cylinder (gr)	13,96	13,91	12,04	13,88	13,99	14,08	11,47	14,05
GCL+can+cylinder (gr)	14,45	14,40	12,57	14,25	14,39	14,55	11,97	14,32
Dry GCL+can (gr)	14,20	14,07	12,31	14,01	14,19	14,24	11,71	14,14
Dry GCL (gr)	0,24	0,16	0,27	0,13	0,20	0,16	0,24	0,09
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,55	0,36	0,61	0,30	0,45	0,36	0,55	0,20
initial mass of GCL (gr)	0,49	0,49	0,53	0,37	0,40	0,47	0,50	0,27
initial water content (%) of clay	104,17	206,25	96,30	184,62	100,00	193,75	108,33	200,00

Table A.51. Mass/Unit Area and Moisture Content Calculations for GCL-3-NW-D2 under 20 m hydraulic head

Can no.	Y15 (flat)	H15 (crest)	K5 (flat)	H3 (crest)	K17 (flat)	S14 (crest)	Y20 (flat)	T13 (crest)
Can+cylinder (gr)	14,70	13,97	14,17	14,23	11,13	14,01	11,35	11,34
GCL+can+cylinder (gr)	15,21	14,41	14,56	14,52	11,57	14,39	11,82	11,66
Dry GCL+can (gr)	14,96	14,13	14,39	14,34	11,37	14,15	11,59	11,46
Dry GCL (gr)	0,26	0,16	0,22	0,11	0,24	0,14	0,24	0,12
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,59	0,36	0,50	0,25	0,55	0,32	0,55	0,27
initial mass of GCL (gr)	0,51	0,44	0,39	0,29	0,44	0,38	0,47	0,32
initial water content (%) of clay	96,15	175,00	77,27	163,64	83,33	171,43	95,83	166,67

Table A.52. Mass/Unit Area and Moisture Content Calculations for GCL-3-W-D1.5 under 15 m hydraulic head

Can no.	E8 (flat)	E1 (crest)	E4 (flat)	E2 (crest)	A1 (flat)	E6 (crest)	K17 (flat)	E5 (crest)
Can+cylinder (gr)	33,31	37,25	38,59	37,91	37,06	37,76	11,45	37,15
GCL+can+cylinder (gr)	33,80	37,72	39,11	38,2	37,51	38,27	11,96	37,5
Dry GCL+can (gr)	33,55	37,42	38,86	38,02	37,29	37,94	11,72	37,28
Dry GCL (gr)	0,24	0,17	0,27	0,11	0,23	0,18	0,27	0,13
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,55	0,39	0,61	0,25	0,52	0,41	0,61	0,30
initial mass of GCL (gr)	0,49	0,47	0,52	0,29	0,45	0,51	0,51	0,35
initial water content (%) of clay	104,17	176,47	92,59	163,64	95,65	183,33	88,89	169,23

Table A.53. Mass/Unit Area and Moisture Content Calculations for GCL-3-NW-D1.5 under 35 m hydraulic head

Can no.	K16 (flat)	Y22 (crest)	K18 (flat)	K7 (crest)	G6 (flat)	Y11 (crest)	H8 (flat)	K17 (crest)
Can+cylinder (gr)	11,18	13,76	37,46	13,85	13,9	14,71	11,37	14,21
GCL+can+cylinder (gr)	11,65	14,18	37,86	14,33	14,37	15,02	11,89	14,63
Dry GCL+can (gr)	11,44	13,93	37,67	14,04	14,15	14,83	11,64	14,37
Dry GCL (gr)	0,26	0,17	0,21	0,19	0,25	0,12	0,27	0,16
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,59	0,39	0,48	0,43	0,57	0,27	0,61	0,36
initial mass of GCL (gr)	0,47	0,42	0,40	0,48	0,47	0,31	0,52	0,42
initial water content (%) of clay	80,77	147,06	90,48	152,63	88,00	158,33	92,59	162,50

Table A.54. Mass/Unit Area and Moisture Content Calculations for GCL-3-W-D1 under 25 m hydraulic head

Can no.	A2 (flat)	Y25 (crest)	Y23 (flat)	H5 (crest)	Z1 (flat)	S14 (crest)	C11 (flat)	S12 (crest)
Can+cylinder (gr)	11,41	12,03	14,15	11,04	11,15	14,14	27,72	11,02
GCL+can+cylinder (gr)	11,87	12,32	14,65	11,47	11,68	14,67	28,17	11,33
Dry GCL+can (gr)	11,66	12,15	14,41	11,2	11,42	14,35	27,96	11,14
Dry GCL (gr)	0,25	0,12	0,26	0,16	0,27	0,21	0,24	0,12
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,57	0,27	0,59	0,36	0,61	0,48	0,55	0,27
initial mass of GCL (gr)	0,46	0,29	0,50	0,43	0,53	0,53	0,45	0,31
initial water content (%) of clay	84,00	141,67	92,31	168,75	96,30	152,38	87,50	158,33

Table A.55. Mass/Unit Area and Moisture Content Calculations for GCL-3-NW-D1 under 50 m hydraulic head

Can no.	K14 (flat)	Y20 (crest)	K17 (flat)	K5 (crest)	G4 (flat)	Y15 (crest)	H5 (flat)	K12 (crest)
Can+cylinder (gr)	13,95	11,92	11,15	13,86	14,13	14,06	14,02	11,32
GCL+can+cylinder (gr)	14,39	12,29	11,66	14,16	14,63	14,57	14,45	11,63
Dry GCL+can (gr)	14,19	12,08	11,43	13,98	14,39	14,27	14,26	11,45
Dry GCL (gr)	0,24	0,16	0,28	0,12	0,26	0,21	0,24	0,13
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,55	0,36	0,64	0,27	0,59	0,48	0,55	0,30
initial mass of GCL (gr)	0,44	0,37	0,51	0,30	0,50	0,51	0,43	0,31
initial water content (%) of clay	83,33	131,25	82,14	150,00	92,31	142,86	79,17	138,46

Table A.56. Mass/Unit Area and Moisture Content Calculations for GCL-3-W-D0.5 under 50 m hydraulic head

Can no.	Y15 (flat)	K12 (crest)	G4 (flat)	H5 (crest)	K5 (flat)	Y20 (crest)	K14 (flat)	K17 (crest)
Can+cylinder (gr)	14,06	11,27	14,14	13,88	13,85	11,23	13,9	12,03
GCL+can+cylinder (gr)	14,56	11,76	14,64	14,39	14,34	11,72	14,41	12,49
Dry GCL+can (gr)	14,33	11,53	14,42	14,15	14,12	11,5	14,18	12,28
Dry GCL (gr)	0,27	0,26	0,28	0,27	0,27	0,27	0,28	0,25
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,61	0,59	0,64	0,61	0,61	0,61	0,64	0,57
initial mass of GCL (gr)	0,50	0,49	0,50	0,51	0,49	0,49	0,51	0,46
initial water content (%) of clay	85,19	88,46	78,57	88,89	81,48	81,48	82,14	84,00

Table A.57. Mass/Unit Area and Moisture Content Calculations for GCL-3-W under 50 m hydraulic head

Can no.	Y15	K12	G4	H5	K5	Y20	K14	K17
Can+cylinder (gr)	14,04	11,26	14,14	13,88	13,88	11,22	13,89	12,02
GCL+can+cylinder (gr)	14,54	11,82	14,68	14,43	14,45	11,78	14,42	12,54
Dry GCL+can (gr)	14,31	11,55	14,42	14,17	14,17	11,51	14,17	12,3
Dry GCL (gr)	0,27	0,29	0,28	0,29	0,29	0,29	0,28	0,28
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,61	0,66	0,64	0,66	0,66	0,66	0,64	0,64
initial mass of GCL (gr)	0,50	0,56	0,54	0,55	0,57	0,56	0,53	0,52
initial water content (%) of clay	85,19	93,10	92,86	89,66	96,55	93,10	89,29	85,71

Table A.58. Mass/Unit Area and Moisture Content Calculations for GCL-3-NW under 50 m hydraulic head

Can no.	Y15	K12	G4	H5	K5	Y20	K14	K17
Can+cylinder (gr)	14,04	11,28	14,14	13,88	13,88	11,22	13,89	12
GCL+can+cylinder (gr)	14,61	11,83	14,69	14,42	14,41	11,77	14,43	12,57
Dry GCL+can (gr)	14,33	11,57	14,42	14,16	14,16	11,51	14,17	12,29
Dry GCL (gr)	0,29	0,29	0,28	0,28	0,28	0,29	0,28	0,29
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,66	0,66	0,64	0,64	0,64	0,66	0,64	0,66
initial mass of GCL (gr)	0,57	0,55	0,55	0,54	0,53	0,55	0,54	0,57
initial water content (%) of clay	96,55	89,66	96,43	92,86	89,29	89,66	92,86	96,55

Table A.59. Mass/Unit Area and Moisture Content Calculations for GCL-4-W-D2 under 50 m hydraulic head

Can no.	Y23 (flat)	H5 (crest)	L10 (flat)	S12 (crest)	Y16 (flat)	E3 (crest)	O13 (flat)	E5 (crest)
Can+cylinder (gr)	13,99	11,26	33,64	11,12	11,33	36,97	33,51	37,12
GCL+can+cylinder (gr)	14,53	11,78	34,15	11,63	11,87	37,48	34,06	37,64
Dry GCL+can (gr)	14,28	11,53	33,92	11,38	11,62	37,24	33,81	37,39
Dry GCL (gr)	0,29	0,27	0,28	0,26	0,29	0,27	0,30	0,27
Area of the cylinder (cm ²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm ²)	0,66	0,61	0,64	0,59	0,66	0,61	0,68	0,61
initial mass of GCL (gr)	0,54	0,52	0,51	0,51	0,54	0,51	0,55	0,52
initial water content (%) of clay	86,21	92,59	82,14	96,15	86,21	88,89	83,33	92,59

Table A.60. Mass/Unit Area and Moisture Content Calculations for GCL-4-W-D1.5 under 50 m hydraulic head

Can no.	Y23 (flat)	S21 (crest)	K17 (flat)	K12 (crest)	Z1 (flat)	Y20 (crest)	H5 (flat)	Y25 (crest)
Can+cylinder (gr)	13,99	14,86	11,22	11,05	11,38	11,07	13,98	11,49
GCL+can+cylinder (gr)	14,52	15,39	11,74	11,56	11,9	11,59	14,53	11,99
Dry GCL+can (gr)	14,28	15,14	11,5	11,32	11,67	11,35	14,28	11,76
Dry GCL (gr)	0,29	0,28	0,28	0,27	0,29	0,28	0,30	0,27
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,66	0,64	0,64	0,61	0,66	0,64	0,68	0,61
initial mass of GCL (gr)	0,53	0,53	0,52	0,51	0,52	0,52	0,55	0,50
initial water content (%) of clay	82,76	89,29	85,71	88,89	79,31	85,71	83,33	85,19

Table A.61. Mass/Unit Area and Moisture Content Calculations for GCL-4-W-D1 under 50 m hydraulic head

Can no.	Y25 (flat)	S21 (crest)	K17 (flat)	Y23 (crest)	Z1 (flat)	Y20 (crest)	H5 (flat)	K12 (crest)
Can+cylinder (gr)	11,26	14,26	11,44	11,17	11,46	11,97	13,88	10,95
GCL+can+cylinder (gr)	11,78	14,81	11,97	11,7	11,97	12,48	14,42	11,48
Dry GCL+can (gr)	11,55	14,56	11,73	11,46	11,74	12,25	14,18	11,24
Dry GCL (gr)	0,29	0,30	0,29	0,29	0,28	0,28	0,30	0,29
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,66	0,68	0,66	0,66	0,64	0,64	0,68	0,66
initial mass of GCL (gr)	0,52	0,55	0,53	0,53	0,51	0,51	0,54	0,53
initial water content (%) of clay	79,31	83,33	82,76	82,76	82,14	82,14	80,00	82,76

Table A.62. Mass/Unit Area and Moisture Content Calculations for GCL-4-W under 50 m hydraulic head

Can no.	Y15	K12	G4	H5	K5	Y20	K14	K17
Can+cylinder (gr)	14,02	11,28	14,16	13,82	13,88	11,23	13,9	12
GCL+can+cylinder (gr)	14,56	11,83	14,69	14,38	14,42	11,77	14,47	12,55
Dry GCL+can (gr)	14,31	11,58	14,45	14,11	14,18	11,52	14,2	12,3
Dry GCL (gr)	0,29	0,30	0,29	0,29	0,30	0,29	0,30	0,30
Area of the cylinder (cm²)	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
mass/ area of dry GCL (gr/cm²)	0,66	0,68	0,66	0,66	0,68	0,66	0,68	0,68
initial mass of GCL (gr)	0,54	0,55	0,53	0,56	0,54	0,54	0,57	0,55
initial water content (%) of clay	86,21	83,33	82,76	93,10	80,00	86,21	90,00	83,33

Table A.63. Mass/Unit Area and Moisture Content Calculations for GCL-1 before testing (manufacturing values)

Can no.	Y15	Y25	K7	Y23	K10
Can+cylinder (gr)	9,42	6,76	9,37	6,48	9,43
GCL+can+cylinder (gr)	12,27	9,86	13,6	10,86	15,25
Dry GCL+can (gr)	11,98	9,45	13,05	10,49	14,71
Dry GCL (gr)	2,56	2,69	3,68	4,01	5,28
Area of the cylinder (cm²)	4,00	4,00	6,00	6,25	8,00
mass/ area of dry GCL (gr/cm²)	0,64	0,67	0,61	0,64	0,66
initial mass of GCL (gr)	2,85	3,10	4,23	4,38	5,82
initial water content (%) of clay	11,33	15,24	14,95	9,23	10,23
mass/ area of bentonite GCL (gr/cm²)	0,61	0,64	0,58	0,61	0,63

APPENDIX B: SPECIFIC GRAVITY AND ATTERBERG LIMIT TEST RESULTS

Specific Gravity Tests

Table B.1. Specific Gravity (G_s) determination for the sodium bentonite (SB)

Test no	1	2
Volume of flask	500 ml	500 ml
Mass of flask+water+soil = M_{bws}	728,77	689,51
Temperature ($^{\circ}\text{C}$)	22 $^{\circ}$	22 $^{\circ}$
Mass of flask+water = M_{bw}	698,44	658,69
Dish no	1	2
Mass of dish+dry soil	394,08	372,65
Mass of dish	345,56	323,62
Mass of dry soil = M_s	48,52	49,03
Mass of water = $M_w = M_s + M_{bw} - M_{bws}$	18,19	18,21
Temperature correction = $\alpha = \rho_T / \rho_{20^{\circ}}$	0,9996	0,9996
$G_s = \alpha M_s / M_w$	2,67	2,69
Average G_s	2,68	2,68

Table B.2. Specific Gravity (G_s) determination for the calcium bentonite (CB)

Test no	1	2
Volume of flask	500 ml	500 ml
Mass of flask+water+soil = M_{bws}	687,09	684,87
Temperature ($^{\circ}\text{C}$)	20 $^{\circ}$	20 $^{\circ}$
Mass of flask+water = M_{bw}	656,50	655,02
Dish no	1	2
Mass of dish+dry soil	315,57	353,60
Mass of dish	266,59	305,78
Mass of dry soil = M_s	48,98	47,82
Mass of water = $M_w = M_s + M_{bw} - M_{bws}$	18,39	17,97
Temperature correction = $\alpha = \rho_T / \rho_{20^{\circ}}$	1,00	1,00
$G_s = \alpha M_s / M_w$	2,66	2,66
Average G_s	2,66	2,66

Atterberg Limit Tests

Table B.3. Liquid limit test results for the sodium bentonite (SB)

Can no.	2B	H5	K3
Can weight(g)	9,86	9,29	9,70
Soil+can weight (g)	26,23	26,91	23,02
Dry soil+can weight (g)	13,15	13,17	12,98
Dry soil weight (g)	3,29	3,88	3,28
Water weight (g)	13,08	13,74	10,04
No. of blows	13	26	34
Water content (%)	397,57	354,12	306,10

Table B.4. Liquid limit test results for the calcium bentonite (CB)

Can no.	S13	K12	Y10
Can weight(g)	6,49	6,53	9,64
Soil+can weight (g)	12,81	11,75	13,17
Dry soil+can weight (g)	8,74	8,87	11,40
Dry soil weight (g)	2,25	2,34	1,76
Water weight (g)	4,07	2,88	1,77
No. of blows	19	28	33
Water content (%)	180,89	123,08	100,57

Table B.5. Plastic limit test results for the sodium bentonite (SB)

Can no.	G4	Y27
Can weight(g)	9,63	9,38
Soil+can weight (g)	10,78	9,91
Dry soil+can weight (g)	10,46	9,78
Dry soil weight (g)	0,83	0,40
Water weight (g)	0,32	0,13
Water content (%)	38,55	32,50

Table B.6. Plastic limit test results for the calcium bentonite (CB)

Can no.	Y16	Y25
Can weight(g)	6,52	6,72
Soil+can weight (g)	9,22	9,51
Dry soil+can weight (g)	8,48	8,67
Dry soil weight (g)	1,96	1,95
Water weight (g)	0,74	0,84
Water content (%)	37,76	43,08

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