DEVELOPMENT AND USE OF MOISTURE-SUCTION RELATIONSHIPS
FOR GEOSYNTHETIC CLAY LINERS

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ABSTRACT

Development and Use of Moisture-Suction Relationships for

Geosynthetic Clay Liners

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A laboratory test program was conducted to determine the moisture-suction relationships of geosynthetic clay liners (GCLs). Moisture-suction relationships were determined by combining suction data from pressure plate tests, contact filter paper tests, and relative humidity tests, then fitting water retention curves (WRCs) to the data. WRCs were determined for wetting processes and drying processes in terms of gravimetric moisture content and volumetric moisture content.

The effects of GCL type, hydration solution, wet-dry cycles, and temperature on the moisture-suction relationships were analyzed. The three GCLs of the test program consisted of configurations of woven and nonwoven geotextiles reinforced with needlepunched fibers. A geofilm was adhesively bonded to the nonwoven side of one of the GCL products. The hydration solution tests involved hydrating GCLs with deionized water, tap water, 0.1 M CaCl_2 , or soil water from a landfill cover test plot for a 30-day conditioning period prior to testing. Cyclic wet-dry tests were conducted on the GCL specimens subjected to 20 wet-dry cycles from 50% to 0% gravimetric moisture content prior to testing. Temperature tests were conducted at 2°C, 20°C, and 40°C.

GCL type affected moisture-suction relationships. The GCLs with an adhesively-bonded geofilm exhibited lower air-entry suction and higher residual

suction than GCLs without a geofilm. The degree of needlepunched fiber pullout during hydration contributed to hysteresis between wetting WRCs and drying WRCs. Hysteresis was high for suction values below air-entry suction and was low for suction values greater than air-entry suction.

Cation exchange reduced the water retention capacity for all three GCL types. The saturated gravimetric moisture contents were reduced from approximately 140% to 70% for wetting WRCs and 210% to 90% for drying WRCs for GCLs hydrated in deionized water compared to CaCl_2 solution. Hysteresis of the nonwoven product decreased from 71%, to 62%, to 28% with respect to deionized water, tap water, and CaCl_2 solution. Hysteresis of the woven product exposed to soil water was 24% and 0%, in terms of saturated gravimetric moisture content and saturated volumetric moisture content, respectively. The swell index, Atterberg Limits, mole fraction of bound sodium, and scanning electron microscopy images that were determined of bentonite from the conditioned GCLs indicated that changes in water retention capacity corresponded with cation exchange.

Wet-dry cycles and temperature affected the moisture-suction behavior for GCLs. Wet-dry cycles reduced hysteresis and increased the swelling capacity of GCL specimens. Microscopy images indicated that wet-dry cycles caused weak orientation of the clay particles. Increasing temperature resulted in a small decrease in water retention capacity.

Results of the test program provided a means for predicting unsaturated behavior for GCLs.

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Chapter 1: Introduction

Geosynthetic clay liners (GCLs) are manufactured hydraulic barriers used in applications such as solid and liquid waste containment facilities, waste piles, liquid containment structures such as ponds, impoundments, or reservoirs, and water conveyance canals as well as in agricultural applications. GCLs are composed of clay bonded to one or more geosynthetic materials. GCLs are designed to be a thin (5 to 10 mm thick) alternative to compacted clay liners (CCLs), which typically are 600 mm to 900 mm thick. The use of a GCL instead of a CCL makes additional airspace available for containment systems. When GCLs perform as designed, they have equivalent or superior hydraulic performance compared to CCLs.

GCLs will hydrate or dehydrate after installation and during service life, but limited data has been reported to explain or quantify the unsaturated behavior of GCLs during this process. The relationship between moisture content and suction, known as a water retention curve (WRC), may be used to determine the moisture content of a GCL during hydration or dehydration processes.

Consistently high moisture content and minimal exposure to concentrated salts and aggressive chemicals are necessary to retain adequate hydraulic performance of GCLs. A variety of environmental factors encountered in field applications tend to desiccate or induce chemical changes to the GCL which adversely affect the long-term performance of GCLs in barrier applications. Limited data is available to assess the effects of environmental factors on the WRCs of GCLs. The engineering properties of GCLs are affected by moisture

conditions. Relationships have been established between WRCs and engineering properties of soils, but such relationships have generally not been reported for GCLs.

A laboratory test program was conducted to determine the effects of GCL type, hydration solution type, wet-dry cycles, and temperature on moisture-suction relationships for GCLs. Moisture-suction relationships were determined by fitting WRCs to the combined data from three suction tests (to cover a wide range of suction values): the pressure plate test, filter paper test, and relative humidity test. WRCs were determined for each of the GCLs subjected to the simulated environmental factors. The effects of GCL type were analyzed by testing three reinforced GCL products. The effects of hydration solution were determined by conducting suction tests with deionized water, tap water, 0.1 M CaCl_2 solution, and by testing a GCL that had been exposed to soil water at a landfill cover test plot for 9 years. The effects of wet-dry cycles were assessed by subjecting GCL specimens 20 wet-dry cycles, consisting of 24-hour fluctuations between 50% and 0% moisture content, prior to suction testing. The effects of temperature were assessed by conducting suction tests at 2°C, 20°C, and 40°C. Supplemental tests, (index tests, scanning electron microscopy, and cation composition tests of the bentonite), were conducted to provide further explanation of trends observed from the determination of the GCL WRCs.

In this thesis, a review of the current literature related to GCL moisture-suction behavior, as well as relevant background information regarding clay mineralogy and structure, cation exchange, and suction measurement is

presented in Chapter 2. A description of the experimental test program is presented in Chapter 3. The results from the experimental test program are presented and discussed in Chapter 4. The WRC results were used to predict trends in the engineering properties (hydraulic conductivity and shear strength) of GCLs as well as moisture transfer between GCLs and adjacent soils in Chapter 5. Finally, conclusions for improvements to GCL installation practices are presented in Chapter 6. Additional test data are provided in an appendix.

Chapter 2: Literature Review

A current review of literature related to the moisture-suction relationships for geosynthetic clay liners (GCLs) is presented in this chapter. Background information related to landfill construction, GCLs, clay mineralogy, and soil suction is provided.

2.1 Introduction to Landfill Design and Construction

More than 225 million metric tons of municipal solid waste (MSW) was generated in the United States in 2012, of which nearly 125 million metric tons was disposed in landfills (EPA 2014). Landfilling is expected to remain the primary means of waste disposal in the United States due to the availability of inexpensive land and the need to dispose of material not suitable for recycling or incineration. Concern for the environmental impact of waste disposal has led to the development of increasingly effective and economical methods of waste containment using landfills.

Engineered landfills are waste disposal systems designed to minimize the environmental and health impacts of waste. The primary function of engineered landfills is to contain solid waste and to collect and remove waste byproducts, such as liquid and gaseous pollutants. Municipal solid waste (MSW) landfills are typically designed with the following systems (Qian et al. 2002):

1. Bottom and lateral side liner systems
2. Leachate collection and removal system
3. Gas collection and control system
4. Final cover system

Landfill designs vary based on the sequence of waste placement and the restrictions of the landfill site. An area fill is a landfill that involves very little excavation which is usually used in areas with high groundwater tables or where excavation is not practical. A trench fill is a landfill composed of a series of deep and narrow trenches which is used for containing small quantities of waste or hazardous waste in some states. Above and below ground fills involves extensive excavation of existing soil, and filling of waste and cover material above the existing grade. A valley fill involves waste placement between hills, in a manner that mimics the surrounding topography (Qian et al. 2002). Some common landfill configurations and waste placement sequences are presented in Figure 2.1.

Figure 2.1. Common Landfill Configurations and Waste Placement Sequences (Qian et al. 2002)

The landfill envelope is an important component of landfill design that isolates the waste mass and landfill byproducts from the surrounding

environment. The landfill envelope consists of a liner system, leachate collection and removal system, gas collection and removal system, and final cover system (Qian et al. 2002). Leachate is a liquid byproduct contaminant generated by the decomposition of wastes and by the downward flow of precipitation through the waste mass (Yesiller and Shackelford 2010). Gaseous byproducts include carbon dioxide and methane from the decomposition of organic waste that flow upward through the waste mass (Qian et al. 2002). The landfill envelope is designed to contain and collect both leachate and gas.

Liner systems and final cover systems both consist of multiple layers of high-permeability and low-permeability layers to collect and contain waste byproducts. The liner system is placed along the bottom and side slopes of the landfill in order to direct leachate to a sump, where it is pumped to a water treatment facility outside of the landfill envelope. In addition, low permeability layers are used to prevent leakage of the leachate to the surrounding soils. The components of a typical liner system are presented in Figure 2.2. The final cover system is placed along the top and side slopes of the landfill in order to direct gases to gas wells, where the gases are pumped to a power generation facility or gas flaring station. The final cover system also minimizes percolation of precipitation and surface runoff into the waste mass, thereby reducing leachate production. The components of a typical final cover system are presented in Figure 2.3.

Figure 2.2. Typical Components of MSW Landfill Liner Systems,
Adapted from Yesiller and Shackelford (2010)

Figure 2.3. Typical Components of MSW Landfill Cover Systems,
Adapted from Yesiller and Shackelford (2010)

The barrier layer is the low-permeability component of the landfill envelope (Qian et al. 2002). The barrier layer may consist of compacted clay liners (CCLs), geomembrane liners (GMLs), GCLs, or combinations thereof, depending on the application. Single liner systems rely on a single barrier layer to provide containment. For this reason, single liners are restricted to low-risk applications such as MSW landfill final cover systems. Redundancy in containment may be provided by placing a GML on top of the single liner. These two-component liner systems are referred to as single composite liners, which are the minimum level of protection required for higher-risk applications such as MSW landfill liner systems (Electronic Code of Federal Regulations 2014). A leak detection system, consisting of a high-permeability layer, may be placed between two single liners or two single, composite liners. The configurations of separate and single liners are referred to as double liners, or double composite liners, respectively. Double composite liner systems are required for high-risk applications, such as hazardous waste landfill liner systems. Conventional configurations of landfill liner barriers are presented in Figures 2.4, 2.5, and 2.6.

Figure 2.4. Single Barrier System

Figure 2.5. Single Composite Barrier System

Figure 2.6. Double Composite Barrier System

The federal Environmental Protection Agency (EPA) developed the Resource Conservation and Recovery Act (RCRA) in 1976, which governs waste disposal practices and waste facility design requirements. Minimum barrier layer requirements are mandated by RCRA Subtitles C, D, and F, as presented in Table 2.1. CCLs must be at least 0.6 m thick and have hydraulic conductivity less than 1×10^{-7} cm/sec for MSW liner barriers, whereas CCLs must be at least 0.45 m thick for MSW final cover barriers. CCLs must be at least 0.9 m thick for hazardous waste landfill liner barriers or at least 0.6 m thick for hazardous waste final cover barriers. GMLs must have thicknesses greater than 1.5 mm (60 mil) if constructed of high-density polyethylene (HDPE), or greater than 0.75 mm (30 mil) if constructed of other polymer resins. State and local regulations must meet

these minimum requirements, but are occasionally more demanding (Electronic Code of Federal Regulations 2014).

Table 2.1. Typical Landfill Barrier Layer Configurations

Barrier Type	Governing RCRA regulation	Typical barrier configuration
MSW final cover barrier	Subtitle D 40 CRF 258.60(a)	Single CCL
		Single GCL
MSW liner barrier	Subtitle D 40 CFR 258.40(b)	GML/CCL Single composite liner
		GML/GCL Single composite liner
Hazardous waste final cover barrier	Subtitle C 40 CRF 264.310	GML/CCL Single Composite liner ^a
		GML/GCL Single composite liner ^a
Hazardous waste liner barrier	Subtitle C 40 CRF 264.301	GML/CCL (x2) Double composite liner
		GML/GCL (x2) Double composite liner
		GML/GCL and GML/CCL Double composite liner

^a Recommended by EPA (1989)

There is an economic incentive to use landfill space efficiently. Landfill owners receive higher revenue if air volume is made available for waste placement by decreasing the solid volume of earthen barrier systems. Due to the low thickness and other advantages of GCLs, GCLs are increasingly used in lieu of CCLs as components of barrier systems. GCLs are approximately 1 cm thick, while CCLs are on the order of 0.6 m to 0.9 m thick. When CCLs are replaced with GCLs, 0.6 m to 2.4 m of landfill space is made available for waste placement, depending on the landfill barrier configuration, resulting in significant increases in revenue.

2.2 Geosynthetic Clay Liners

Geosynthetic Clay Liners (GCLs) are planar, manufactured hydraulic barriers consisting of a thin layer of powdered or granular sodium bentonite supported by geotextiles or geomembranes and held together by needle-punched fibers, stitch bonding, or adhesives (Koerner 2012). The bentonite mass per unit area of a GCL is typically in the range of 3.2 kg/m^2 to 6.0 kg/m^2 , depending on the manufacturer and product type. GCLs are manufactured in widths of 4.0 to 5.2 m and lengths of 30 m to 60 m, rolled around hollow tubes, and sealed to prevent moisture loss during delivery. The bentonite of the GCL is typically prepared to moisture contents of 20% to 40% prior to delivery, then hydrated while in service (CETCO 2009). Thicknesses of dry GCLs vary from 5 to 7 mm, whereas hydrated thicknesses can exceed 10 mm, depending on the overburden stress conditions (Koerner 2012).

GCLs are used in a variety of hydraulic barrier applications, including: pond liners, canal liners, waterproof liners for tunnels, liners for hazardous or radioactive liquid, and landfill liner and cover systems (Koerner 2012). GCLs are increasingly used as hydraulic barriers in landfill applications due to economic savings, time savings, and potentially better hydraulic performance in comparison to conventional liners. A distinct advantage of GCLs is the speed of deployment compared to conventional, compacted earthen barrier systems. GCLs are rapidly unrolled using guided equipment, as presented in Figure 2.7. Continuity of the barrier system is provided by overlapping the edges of GCL rolls.

Figure 2.7. Deployment of GCL on a Landfill Slope (CETCO 2014)

GCLs are considered equivalent components of conventional landfill barriers, however a number of technical advantages make GCLs preferable in contrast to CCLs and GMLs (Bouazza 2002). Sodium bentonite swells considerably when hydrated in water, which allows GCLs to have low hydraulic conductivity in the range of $(1 \text{ to } 5) \times 10^{-11} \text{ m/s}$ (Koerner 2012). GCLs also self-heal, i.e., punctures in the GCL of up to 75 mm in diameter, or large dessication cracks are filled by the tendency of the bentonite to swell in the presence of water (EPA 2001). A summary of advantages and disadvantages of GCLs are presented in Table 2.2.

Table 2.2. Advantages and Disadvantages of GCLs in Landfill Liner Systems (Yesiller and Shackelford 2010)

Geosynthetic clay liners in landfill applications	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Greater disposal capacity (thin) 	<ul style="list-style-type: none"> • Greater potential for puncture (thin)
<ul style="list-style-type: none"> • More rapid and simpler construction than CCLs 	<ul style="list-style-type: none"> • Potential problems with integrity of panel seams
<ul style="list-style-type: none"> • More reproducible material properties (manufactured) 	<ul style="list-style-type: none"> • Greater potential incompatibility (increase in k) when subjected to chemical solutions
<ul style="list-style-type: none"> • Greater resistance to environmental distress (e.g., wet/dry and freeze/thaw cycles) 	<ul style="list-style-type: none"> • Greater potential for reduced swelling capacity and increases in hydraulic conductivity resulting from multivalent-for-monovalent cation exchange
<ul style="list-style-type: none"> • Higher unit attenuation capacity than CCLs 	<ul style="list-style-type: none"> • Lower overall attenuation capacity than CCLs
<ul style="list-style-type: none"> • Easy to repair 	<ul style="list-style-type: none"> • Uncertain long-term integrity and performance
<ul style="list-style-type: none"> • More straightforward QA/QC procedures 	<ul style="list-style-type: none"> • Greater transport of contaminants via diffusion

GCLs are available in a variety of configurations. Geomembrane-backed GCLs are composed of bentonite adhered to a geomembrane. Geotextile-encased GCLs are composed of bentonite that is contained between a carrier (bottom) geotextile, and a cover (top) geotextile. Geomembrane-backed, geotextile-encased GCLs consist of a geofilm adhered to one of the geotextiles of a conventional geotextile-encased GCL. The geotextile components of GCLs are composed of either non-woven polypropylene fibers or thin, woven polypropylene strips.

GCLs are either unreinforced or manufactured with reinforcing elements. Unreinforced GCLs rely solely on the bentonite to provide shear strength. The

shear strength of saturated bentonite is extremely low, so the application of unreinforced GCLs is restricted to flat areas such as the bases of landfills (e.g., Fox and Stark 2004). Reinforced GCLs are manufactured with stitch-bonding or needlepunching that join the cover and carrier geotextiles together. The stitches or needlepunched fibers extend through the bentonite mass, which provides higher shear strength and allows reinforced GCLs to perform adequately on inclined surfaces, such as landfill slopes, up to 3H : 1V or 1.5H : 1V, depending on the level of reinforcement (CETCO 2014). Stitch-bonding is performed in rows, while needle-punching is performed in a distributed fashion across the GCL. Common GCL configurations are presented in Figure 2.8.

Figure 2.8. Common GCL Configurations (Yesiller and Shackelford 2010)

Uncertainty remains as to the long-term hydraulic performance of GCLs in line with the service life of landfills (NRC 2007). Landfills may operate for several decades and must be monitored for at least 30 years after closure (Electronic Code of Federal Regulations 2014). During this time period, GCLs are exposed to environmental stresses, detrimental interaction with adjacent soils, and exposure to byproducts of waste decomposition, which can dramatically influence the hydraulic performance of GCLs (e.g., Meer and Benson 2007, Barclay and Rayhani 2013). Research is necessary in order to adequately

understand and prepare for the long-term effects of GCLs deployed as hydraulic barriers in landfill applications.

2.3 Bentonite Clay Mineralogy

Bentonite clay mineralogy has a significant role in the water retention behavior of GCLs. Bentonite is a montmorillonite-based clay that is mined and processed for use from naturally-occurring bentonite deposits. The mineral composition of bentonite varies from 50% to 90% montmorillonite, depending on the source (Bostwick 2009, Lee et al. 2005). This section describes the hydro-physical-chemical behavior of montmorillonite, which provides framework for understanding the water retention behavior of GCLs.

Montmorillonite is a clay derived from the chemical weathering of soil, rock, or volcanic ash. Montmorillonite particles are small and platy, on the order of 1 nm thick and 100 – 1000 nm in effective diameter (Yong and Warkentin 1975). Montmorillonite particles have a large surface area to volume ratio (specific surface) and are highly active. Montmorillonite is susceptible to chemical interactions, which dictate its hydraulic, physical, and chemical behavior (Yong and Warkentin 1975, Mitchell and Soga 2005). Montmorillonite has a high affinity to water resulting in high swell index, high liquid limit, and low hydraulic conductivity.

2.3.1 Structure of Montmorillonite

The montmorillonite particle is composed of a planar organization of two structural units: silica tetrahedra (SiO_4) and alumina octahedra (AlOH_6) (Yesiller and Shackelford 2010). Silica tetrahedra share oxygens in a planar fashion to

form tetrahedral sheets; similarly, alumina octahedra share oxygens in a planar fashion to form octahedral sheets, illustrated by Figures 2.9 and 2.10.

Figure 2.9. Organization of Silicon Tetrahedral Sheet of Montmorillonite (Mitchell and Soga 2005)

Figure 2.10. Organization of Aluminum Octahedral Sheet of Montmorillonite (Mitchell and Soga 2005)

Montmorillonite is a 2:1 clay mineral, (i.e., two tetrahedral sheets are bonded to one octahedral sheet). The oxygens of the two tetrahedral sheets form strong hydrogen bonds to the hydroxyls of the single octahedral sheet. The

resulting thickness of the montmorillonite mineral is 0.96 nm (Mitchell and Soga 2005). Adjacent montmorillonite particles are attracted to each other by hydrated, exchangeable cations and by van der Waal's forces, and are simultaneously repelled by the mutually-negative charges of the montmorillonite particle surfaces (Yesiller and Shackelford 2010).

The surfaces of montmorillonite particles are negatively charged due to edge dissociation and isomorphous substitution (Yesiller and Shackelford 2010). Dissociation of hydroxyl groups, ($\text{OH}^- \rightarrow \text{O}^{2-} + \text{H}^+$) at broken montmorillonite edges, produces a positive charge deficiency at the clay surface by releasing protons (H^+) to the pore fluid. Edge dissociation contributes up to 20% of the charge deficiency of montmorillonite, whereas the remaining 80% of charge deficiency in montmorillonite is attributed to isomorphous substitution (Wypych and Satyanarayana 2004). Isomorphous substitution is the replacement of a similar-sized cation for that of an existing cation within the crystal lattice, e.g., Mg^{2+} in place of Al^{3+} . In montmorillonite, one Mg^{2+} cation replaces every sixth Al^{3+} ion, resulting in a significant charge deficiency (Mitchell and Soga 2005). In montmorillonite, isomorphous substitution occurs in the octahedral sheet which is relatively far away from the mineral surface and exchangeable cations responsible for interlayer bonding. Charge strength dissipates with increasing distance from the charge source, thus, interlayer bonding between adjacent montmorillonite particles is weak.

The weak bonds between adjacent montmorillonite particles allows cations and water to infiltrate the interlayer space resulting in extensive swelling

(Yesiller and Shackelford 2010). Cations such as Na^+ , K^+ , Ca^{2+} , and Mg^{2+} typically satisfy the charge deficiency, depending on the chemistry of the pore water. These cations are referred to as exchangeable cations because they are easily removed and replaced by different species of cations due to the weak attraction of the cations to the mineral surface (Yesiller and Shackelford 2010). A schematic is presented in Figure 2.11 that illustrates the association of two adjacent montmorillonite particles and the exchangeable cations and water associated with the interlayer space between the particles.

Figure 2.11. Particle Structure of Montmorillonite,
Modified from Yong and Warkentin (1975)

The charge deficiency of bentonite is balanced by hydrated cations and several layers of water molecules attached to the montmorillonite particle

surface. A measurement of the amount of the charge deficiency in a clay is termed the cation exchange capacity (CEC), expressed as milliequivalents (meq) per 100 grams of dry clay, where one equivalent is equal to one mol of electron charges. The CEC for montmorillonite is large in comparison to other clays and may vary from 80 to 150 meq/100 g (Mitchell and Soga 2005).

2.3.2 Cation Exchange in Bentonite

Exchangeable cations in the interlayer region of adjacent montmorillonite minerals may be replaced by different species of cations, in a process termed cation exchange. Cations in the pore fluid will replace existing exchangeable cations if the replacement is thermodynamically favorable. In general, cations of smaller diameter replace cations of larger diameter, and cations of larger valence replace cations of smaller valence. The replacement power increases in the order of $\text{Na}^+ < \text{K}^+ < \text{Mg}^{2+} < \text{Ca}^{2+} < \text{Al}^{3+} < \text{Fe}^{3+}$ (Mitchell and Soga 2005). Cation exchange and its effects on montmorillonite structure will occur even if concentrations of the cations of higher replacement power is small. For example, 0.005 M solutions of KCl, MgCl_2 , and CaCl_2 , caused decreased swelling of sodium bentonite (Jo et al. 2001).

Exchange of cations of lower replacement power in place of higher replacement power may also occur if the concentration of the cation of lower replacement power is high. This type of cation exchange occurs by mass action, (i.e., diffusion of bound cations of high replacement power away from the mineral surface along a concentration gradient, and subsequent replacement of those

mineral surface sites with cations of lower replacement power) (Mitchell and Soga 2005).

Sources of cation exchange include permeation of bentonite with solutions of dissimilar chemistry with the bentonite. Bentonite used in barrier systems may come into contact with adjacent soils that contain divalent cation concentrations of 0.005M to 0.015 M (e.g., Lin and Benson 2000, Egloffstein 2001, Thomson and Foose 2005). Cation exchange imposes changes in the engineering performance of bentonite in hydraulic barrier applications. Exchange for cations of higher replacement power causes a reduction in swell capacity, a reduction in liquid limit, changes in microfabric (refer to Section 2.3.3), and an increase in hydraulic conductivity. Selected studies that determined changes in bentonite behavior due to cation exchange are presented in Table 2.3.

Table 2.3. Response of Sodium Bentonite to Cation Exchange

Comparison	Response of bentonite	Reference
0.005 M CaCl ₂ to 1.0 M CaCl ₂ Hydration Solution	↓ Water retention capacity	El-Swaify and Henderson (1967)
0.005 M CaCl ₂ to 0.1 M CaCl ₂ Hydration Solution	↑ k (1 x 10 ⁻⁹ to 6 x 10 ⁻⁵ cm/sec)	Jo et al. (2001)
0.005 M CaCl ₂ to 0.1 M CaCl ₂ Hydration Solution	↓ Swell index (27 mL/2g to 9 mL/2g)	Jo et al. (2001)
0.005 M CaCl ₂ to 0.5 M CaCl ₂ Hydration Solution	↓ Swell index, ↓ Liquid Limit (reduction from 350-550% to 100%)	Lee et al. (2005)
Na-bentonite versus Ca-bentonite	Ca-bentonite exhibits larger voids	Dananaj et al. (2005)
Na-bentonite versus Ca-bentonite	Ca-bentonite exhibits larger bentonite particle sizes	Egloffstein (2001)

The effects of cation exchange on bentonite may be explained by the diffuse double-layer theory (Yesiller and Shackelford 2010). The concentration of exchangeable cations is highest at the montmorillonite surface, and decreases with distance from the surface due to a concentration gradient imposed by the influx of water to the interlayer region during hydration (Mitchell and Soga 2005). The combination of exchangeable, hydrated cations and bound water that are held in place by the charge deficiency of the montmorillonite mineral is referred to collectively as the diffuse double layer (DDL), as described by Yesiller and Shackelford (2010). The thickness of the DDL (t_{DDL}), is proportional to various parameters as presented in Eq. 2.1:

$$t_{DDL} \propto \sqrt{\frac{\varepsilon}{n_o v^2}} \quad (2.1)$$

where, ϵ is the dielectric constant of the pore fluid, n_o is the concentration of ions in the pore fluid, and v is the valence of the cations in the pore fluid, as described by Yesiller and Shackelford (2010). The boundary of the DDL is defined as the center of gravity of the electric potential versus distance relationship, as presented in the schematic in Figure 2.12. The t_{DDL} decreases when either cation concentration or cation valence increases.

The DDL extends in all directions from the surface of the montmorillonite mineral. Water that is within the DDL is considered immobilized, whereas water outside of the DDL is available for flow. Therefore, for a given volume, a low t_{DDL} results in a large area for flow and high hydraulic conductivity, whereas a high t_{DDL} results in flow restriction and low hydraulic conductivity, as presented in Figure 2.13.

Figure 2.12. Schematic Representations of the Diffuse Double Layer (DDL), Modified from Mitchell and Soga (2005)

Figure 2.13. Effect of t_{DDL} on Flow (Yesiller and Shackelford 2010)

The test method described by ASTM D7503 allows for the determination of the amount of bound cations (BC) and CEC present in fine-grained soils. BC and CEC results from ASTM D7503 are direct evidence of whether cation exchange has occurred and to what degree exchange has taken place. The BC is determined by displacing the existing cations of a soil specimen with a high concentration of index ions such as NH_4^+ . The displaced ions are collected in solution and the concentration is measured using inductively coupled plasma optical emission (ICP-OE) spectroscopy (EPA 2007, Scalia and Benson 2010). BC is calculated based on this concentration, minus the concentration of soluble cations (SC) determined by washing a soil specimen with deionized water. The CEC is determined by similarly displacing the NH_4^+ index ions of the BC specimen with a high concentration of K^+ ions and measuring the amount of index ions in solution. For sodium montmorillonite, sodium is the dominating BC, whereas calcium is the dominating BC for calcium montmorillonite. Values of BC are typically only determined for cations common in soils, e.g., Na^+ , K^+ , Ca^{2+} , and Mg^{2+} , but other cations such as Al^{3+} and Fe^{3+} may exist in small quantities (Scalia and Benson 2010).

2.3.3 Fabric of Bentonite

Fabric refers to the arrangement of particles, particle groups, and void spaces in a soil (Mitchell and Soga 2005). Bentonite fabric differs among macroscopic, microscopic, and ultra-microscopic viewing scales (Yong and Warkentin 1975). Macroscopic fabrics are visible with the naked eye and consist of the orientation of peds or granules (for GCLs) and macro-voids. Microfabrics

may be observed using optical microscopes or equipment with higher magnification abilities. Microfabrics consist of the orientation of bentonite clusters and inter-cluster voids. Ultra-microscopic fabrics can only be observed using electron microscopy. This smaller microfabric consists of the orientation of single montmorillonite platelets, or particles composed of multiple stacked platelets, intra-particle voids, and inter-particle voids (Yong and Warkentin 1975). The terminology of various structures observed in bentonite is presented in Figure 2.14.

Figure 2.14. Terminology for Montmorillonite Clay Assemblies, Modified from Yong (1999)

Bentonite exhibits a bimodal void system, or dual pore network (Yong and Warkentin 1975, Lloret et al. 2003). The fabric of bentonite is influenced by

external forces (e.g., compaction or wet-dry cycles) and internal forces (e.g., cation exchange or salt concentration).

Void size distributions were determined by mercury intrusion porosimetry (MIP) tests for heavily-compacted bentonite by Lloret et al. (2003). The authors determined that intra-particle voids were approximately 10 nm in diameter, whereas inter-particle voids were predominately 10,000 nm to 40,000 nm in diameter. Increased compaction effort reduced the size of inter-particle voids, but intra-particle void size remained unchanged (Lloret et al. 2003). In contrast to compacted bentonite, GCLs include granular bentonite and associated macrovoids from the manufacturing process and the inclusion of geotextile fibers. Bentonite within GCLs would likely exhibit a different pore size distribution than compacted bentonite.

Dissolved salts may cause changes to the bentonite fabric, as presented in Figures 2.15. High salt concentrations decrease interparticle repulsion and may induce flocculation, or random arrangement, of the bentonite particles (Yong and Warkentin 1975, Oster et al. 1980). The amount of salt that causes flocculation of a dispersed clay suspension is defined as the flocculation value. The flocculation value is 0.0012 to 0.0016 M NaCl for sodium-montmorillonite, whereas, the flocculation value is 0.00025 to 0.0012 M CaCl₂ for calcium-montmorillonite (Oster et al. 1980, Goldberg and Forster 1990). The degree of flocculation is directly related to the hydraulic conductivity and the size of microvoids, and is indirectly related to the swelling capacity (Mitchell and Soga, 2005).

a) Salt Flocculation

b) Non-salt Flocculation

c) Dispersion

Figure 2.15. Flocculated and Dispersed Clay Fabric (Lambe 1958)

2.4 Factors Affecting Hydraulic Performance of GCLs

The following section describes the factors that affect the long-term performance of GCLs, including: cation exchange, wet-dry cycles, temperature gradients, bulk GCL void ratio, and moisture transfer from adjacent soils. The following factors may directly affect hydraulic conductivity or may indirectly influence hydraulic conductivity by affecting the moisture content of the GCL.

2.4.1 Cation Exchange

Cation exchange of multivalent cations in place of native monovalent cations may potentially adversely impact the hydraulic performance of GCLs containing sodium bentonite. In landfill applications, cation exchange will occur in GCLs due to contact with landfill leachate, from percolation of precipitation through overlying soils, or from hydraulic contact with underlying soils (Melchior 2002, Benson et al. 2007, Meer and Benson 2007, Scalia and Benson 2011, Bradshaw et al. 2013). Cation exchange caused by subgrade hydration was inevitable when the soil contains abundant Ca^{2+} and Mg^{2+} ions (Meer and Benson 2007, Scalia and Benson 2011).

In GCLs containing sodium bentonite, exchangeable cations mainly consist of Na^+ . Initial BC values of GCLs are typically 50 – 90% for Na^+ and 5-25% for Ca^{2+} (Egloffstein 1997). Na^+ cations may be partially or completely replaced due to cation exchange. Scalia and Benson (2011) determined that cation exchange occurred more rapidly and completely when GCLs were installed adjacent to soils with high moisture content.

The impact of cation exchange on the hydraulic performance of nonprehydrated GCLs depends on the ionic strength and the relative abundance of monovalent to divalent cations (RMD), where ionic strength is the total molarity of the hydration solution, and the RMD is described by Eq. 2.2 (Kolstad et al. 2004).

$$RMD = \frac{M_m}{\sqrt{M_d}} \quad (2.2)$$

Where M_m is the total molarity of monovalent cations, and M_d is the total molarity of divalent cations. The degree of cation exchange is directly related to the ionic strength, whereas cation exchange is inversely related to the RMD. Jo et al. (2001) determined that GCLs that were hydrated in 0.1 M CaCl_2 exhibited values of hydraulic conductivity over 3 orders of magnitude higher than GCLs hydrated in deionized water (e.g., 6×10^{-5} cm/sec compared to 1×10^{-9} cm/sec). GCLs that were hydrated in solutions of multiple cation species with RMD less than 0.14 were subjected to cation exchange that increased hydraulic conductivity (Benson and Meer 2009).

The RMD and concentration of divalent cations affect the swelling behavior of GCLs. Norrish and Quirk (1954) and McBride (1994) determined that swell occurred in two stages for bentonite: crystalline swell and osmotic swell. Crystalline swell represented the small amount of swell that occurs when several layers of water became adsorbed to the montmorillonite particle surfaces (McBride 1994). Osmotic swell produced much greater swell, corresponding to the hydration of clay particles via concentration gradient. Osmotic swell of the interlayer region was due to the high cation concentration in the interlayer voids relative to the free water. Swell is directly related to RMD and indirectly related to ionic strength, whereas hydraulic conductivity is directly related to ionic strength and indirectly related to RMD (Kolstad et al. 2004).

If GCLs are hydrated rapidly by adjacent soils and achieve osmotic swell, GCLs retain low hydraulic conductivity, even in the presence of cation exchange (Lin and Benson 2000). When cation exchange occurs after GCLs are rapidly-

hydrated, only modest increases in hydraulic conductivity are incurred, typically by a factor of 3 to 6 (Egloffstein 2001). Scalia and Benson (2011) determined that osmotic swell to occurred only for GCLs greater than 35% moisture content. High moisture content and high osmotic swell correspond to low hydraulic conductivity. The hydraulic performance of a prehydrated GCL subjected to cation exchange is maintained unless the GCL is desiccated.

The effects of cation exchange on the hydraulic performance of GCLs are dependent on the moisture content of the GCL prior to cation exchange and changes to the GCL moisture content after cation exchange has occurred. There is a need to quantify the behavior of hydrating and dehydrating GCLs in order to assess the susceptibility of a GCL to cation exchange (e.g., Lin and Benson 2000, Meer and Benson 2007).

2.4.2 Wet-Dry Cycles

Wet-dry cycles may decrease hydraulic performance of GCLs by causing excessive shrinkage or by significantly decreasing swell capacity in conjunction with cation exchange. Wet-dry cycles may be imposed on GCLs by changes in moisture content of adjacent soils, or by daily solar heating of exposed geomembranes overlying the GCL (Olsen 2011).

Overlap distances of 150 mm and 600 mm typically specified for side-of-GCL roll and end-of-roll, respectively, may be insufficient to prevent panel separation of installed GCLs (Olsen 2011). Excessive shrinkage may develop with successive wet-dry cycles that eventually exceed the overlap distance of GCLs. Wet-dry cycles were suspected as the cause for formations of gaps

between GCL panels ranging from 300 mm to 450 mm, and up to 1200 mm (e.g., Thiel and Richardson 2005).

Wet-dry cycles may have adverse effects on hydraulic performance of GCLs, even if GCLs are dimensionally stable. When cation exchange occurs in the presence of wet-dry cycles, increases in hydraulic conductivity occur that render GCLs ineffective as hydraulic barriers (Lin and Benson 2000, Egloffstein 2001, Meer and Benson 2007). During desiccation of GCLs subjected to cation exchange, osmotic swell decreases permanently, desiccation cracks form, the self-healing capacity decreases, and hydraulic conductivity increases by 1.5 to 4 orders of magnitude, (e.g., from 1×10^{-9} and 1×10^{-7} cm/sec to 1×10^{-6} and 1×10^{-4} cm/sec) (Meer and Benson 2007). Permanent increases to hydraulic conductivity are realized when GCLs desiccate below 100% gravimetric moisture content (Meer and Benson 2007).

2.4.3 Temperature Gradients

GCLs may be subjected to temperature gradients from heat generated from waste decomposition or from heat supplied by solar radiation of exposed liner or cover systems. Heat generation due to waste decomposition causes elevated temperatures in the waste mass providing a temperature gradient toward the cover and liner systems. (Yesiller et al. 2005, Barclay and Rayhani 2013). Temperature gradients may produce coupled moisture flow and subsequent dessication of GCLs, which could adversely affect hydraulic performance of GCLs when coupled with cation exchange (e.g., Bradshaw et al. 2013).

Constant temperature gradients tend to desiccate previously-hydrated GCLs. Hoor and Rowe (2013) performed a series of closed-system tests on composite liners, consisting of geomembranes overlying GCLs placed on a silty sand subgrade, which were subjected to a constant temperature gradient of either $6.7^{\circ}\text{C}/\text{m}$ or $14.6^{\circ}\text{C}/\text{m}$ using a heat source placed on the geomembrane. The GCLs were hydrated to an 80% degree of saturation with 50 kPa overburden stress, prior to the application of temperature. Over a period of three years, the temperature gradients of $6.7^{\circ}\text{C}/\text{m}$ and $14.6^{\circ}\text{C}/\text{m}$ drove moisture from the relatively warmer liner to the relatively cooler subgrade, which desiccated the GCL from 80% to 65% and 80% to 21% saturation, respectively. Desiccation occurred because the rate of upward moisture flow (rate of hydration) was exceeded by the rate of downward vapor diffusion (rate of dehydration) (Hoor and Rowe 2013).

Temperature gradients applied by daily thermal cycles tend to inhibit GCL hydration. Rowe et al. (2011) performed a series of closed-system tests on composite liners, consisting of geomembranes overlying GCLs placed on silty sand subgrade, which were subjected to daily thermal cycles of 24°C to 60°C . The application of cyclic temperatures tended to decrease the equilibrium moisture content of the GCL. After seven weeks of thermal cycles, with 2 kPa applied overburden stress, the GCLs only reached a range of 17% to 30% gravimetric moisture content, compared to a range of 78% to 95% gravimetric moisture content for isothermal conditions (Rowe et al. 2011).

2.4.4 Bulk GCL Void Ratio

The bulk GCL void ratio, e_b , is a measure of void structure that normalizes the variable mass of bentonite in GCLs. The bulk GCL void ratio is determined by Eq. 2.3 and 2.4 (Petrov et al. 1997):

$$e_b = \frac{H_{GCL} - H_s}{H_s} \quad (2.3)$$

$$H_s = H_b + H_g = \frac{M_{bent}}{\rho_b(1 + w_o)} + \frac{M_{GEO}}{\rho_g} \quad (2.4)$$

Where, H_{GCL} is the GCL height, H_s is the equivalent height of solids, H_b is the height of bentonite solids, H_g is the height of geotextile solids, M_{bent} is the mass per unit area of the GCL, ρ_b is the density of bentonite solids (2.61 Mg/m³), w_o is the initial bentonite moisture content, M_{GEO} is the mass per unit area of the geotextiles of the GCL, and ρ_g is the density of polypropylene geotextile solids (0.91 Mg/m³), as described by Petrov et al. (1997). One limitation of Eq. 2.3 is that it assumes all soil solids are composed of pure bentonite, which is not typical.

Petrov et al. (1997) determined that the bulk GCL void ratio was directly related to hydraulic conductivity for GCLs. For a specific hydration solution, moisture condition, and mass of bentonite, low values of e_b corresponded to lower hydraulic conductivity, whereas high values of e_b corresponded to higher hydraulic conductivity. Low values of e_b are present in GCLs that are subjected to confining stress, whereas high values of e_b are present in GCLs that are hydrated in near-free-swell conditions, as presented in Figure 2.16.

Figure 2.16. Effect of Bulk GCL Void Ratio on Hydraulic Conductivity of GCLs (Petrov et al. 1997)

Increasing confinement stress induces consolidation in GCL specimens which decreases e_b and decreases the hydraulic conductivity for GCLs. Petrov et al. (1997) determined that confinement stress provided by needlepunched fibers decreased the bulk void ratio from 9 to 5 at 3 kPa overburden stress which reduced hydraulic conductivity by a factor of 2.5 to 3.5, compared to unreinforced GCLs. An increase in confining stress due to increased applied overburden stress from 3 kPa to 110 kPa caused the bulk void ratio to decrease from 5 to 2 and the hydraulic conductivity to decrease from 3.7×10^{-9} cm/sec to approximately 7.5×10^{-10} cm/sec.

2.4.5 Moisture Transfer from Adjacent Soils

GCLs may hydrate or dehydrate when placed adjacent to soils. The direction of moisture transfer depends on the water retention behavior of the soil, based on pore size distribution, plasticity, and other soil-specific parameters. The

moisture content of the soil influences the equilibrium moisture content of the GCL.

Hydration of GCLs from adjacent soils may be excessive for dry GCLs that are placed adjacent to wet soils, especially for low confining pressure (e.g., less than 100 kPa). Olsen (2011) determined that GCLs hydrated to a maximum of 165% moisture content when placed on wet sand. Rayhani et al. (2011) determined that GCLs hydrated to nearly 150% moisture content on soils at moisture contents near field capacity. Lake and Rowe (2000) determined that for conventional GCLs reinforced with needlepunched fibers, fiber pullout occurred, which caused permanent damage to the GCL.

Alternatively, desiccation of GCLs from adjacent soils may be excessive for hydrated GCLs that are placed adjacent to dry soils. Olsen (2011) determined in laboratory testing that GCLs lost moisture when placed on dry-of-optimum lean clay, to a minimum of approximately 20%. Rayhani et al. (2011) determined in laboratory testing that a GCL equilibrated to low moisture contents of 30 to 35% when placed on soils at residual moisture content. Desiccation due to moisture transfer of GCLs to adjacent soils could adversely affect hydraulic performance of GCLs when coupled with cation exchange (e.g., Bradshaw et al. 2013).

2.5 Soil Suction

Soil suction is the energy state, or potential, of the pore water in a soil. The determination of soil suction is the basis of determining stress states, hydraulic conductivity, and moisture transfer for unsaturated soils. Suction is either expressed as a sum of negative potentials as described by Lu and Likos

(2004) or as the positive sum of components of free energy (Fredlund et al. 2012). For convenience, soil suction is referred to as *suction* throughout this document with the understanding that it refers to a positive expression of the free energy of soil pore water. The following section describes suction theory, components of suction, and common methods of measuring suction.

2.5.1 Components of Total Soil Suction

Total suction is the thermodynamic potential of soil pore water compared to a reference potential of free water. Free water is pure water (containing no dissolved solutes) that has no interaction with surfaces that would impart curvature on the air-water interface, where gravity is the only external force (Lu and Likos 2004). Total suction is expressed as a function of relative humidity (RH), as presented in Eq. 2.5,

$$\psi = -\frac{RT}{v_{wo}\omega_v} \ln \left(\frac{\bar{u}_v}{\bar{u}_{vo}} \right) \quad (2.5)$$

where ψ is soil suction or total suction (kPa), R is the universal gas constant (8.314 J/mol K), T is the temperature (K), v_{wo} is the specific volume of water (i.e., the inverse of the density of water, m³/mol), ω_v is the molecular mass of water vapor (18.016 kg/kmol), $\bar{u}_v$ is the partial pressure of pore water vapor (kPa), $\bar{u}_{vo}$ is the saturation pressure of a flat surface of water at the same temperature (kPa), and the ratio $(\bar{u}_v/\bar{u}_{vo})$ is commonly referred to as the relative humidity, (RH). Although RH is a fraction when used in Eq. 2.5, RH is typically expressed as a range from 0 to 100%. A RH of 0% represents air devoid of water vapor, whereas

a RH of 100% represents air completely saturated with water vapor. Low relative humidity corresponds to high suction, whereas high relative humidity corresponds to low suction (Fredlund et al. 2012).

Alternatively, total suction can be expressed in terms of the sum of matric suction and osmotic suction, as presented in Eq. 2.6. This definition of total suction includes suction resulting from capillarity (matric suction) and suction resulting from chemical gradients (osmotic suction).

$$\psi = (u_a - u_w) + \pi \quad (2.6)$$

where $(u_a - u_w)$ is matric suction (kPa), u_a is the pore air pressure (kPa), u_w is the pore water pressure, and π is osmotic suction (kPa), as described by Fredlund et al. (2012).

Matric Suction

Matric suction, $(u_a - u_w)$, is the capillary component of free energy, i.e., the suction determined from the measurement of the partial pressure of water vapor in equilibrium with the soil water, relative to the partial pressure of water vapor over a flat surface of water of identical composition to the soil water (Fredlund et al. 2012). The suction behavior of soil voids may be simplified by treating the soil voids as a bundle of small tubes (capillary tubes) placed in contact with water. Water rises up the capillary tube to a certain height that depends on the surface tension of the water, the contact angle of the air-water interface, and the radius of the tube. This capillary rise, h_c (cm), or matric suction, $(u_a - u_w)$ (kPa), may be

determined by an adaptation of Kelvin's equation, as presented by Eq. 2.7 and Eq. 2.8,

$$h_c = \frac{2T_s \cos(\alpha)}{\rho_w g r} \quad (2.7)$$

or

$$u_a - u_w = \frac{2T_s \cos(\alpha)}{r} \quad (2.8)$$

where T_s is surface tension (mN/m), α is the contact angle of the air-water interface, ρ_w is the density of water (g/cm³), g is the acceleration due to gravity (980 cm/s²), and r is the radius of the capillary tube (cm).

T_s is the equilibrating force resulting from the pressure drop between the air-water interface, as presented in Figure 2.17. T_s is dependent on temperature, as presented in Table 2.4 (Lu and Likos 2004).

Figure 2.17. Schematic Representation of Surface Tension and Capillary Rise, Modified from Lu and Likos (2004) and Fredlund et al. (2012)

Table 2.4. Effect of Temperature on Surface Tension, (Lu and Likos 2004)

Temperature (°C)	T_s (mN/m)
0	75.6
10	74.22
20	72.75
30	71.18
40	69.56

The value of $2T_s \cos(\alpha)/r$ is the air-entry suction, ψ_{ae} , at a specific void size of a soil, i.e., a measure of the strength of the air-water interface. At $(u_a - u_w) < 2T_s \cos(\alpha)/r$, the surface tension of the air-water interface holds the water volume in the void intact. At $(u_a - u_w) > 2T_s \cos(\alpha)/r$, e.g., as a soil dehydrates, the air-water interface collapses and air volume replaces the water volume.

The magnitude of capillary rise is dependent on the surface tension of the air-water interface and the size of the soil void. When the void size is small, the air-entry suction is high and the air-water interface can withstand large applied pressures, i.e., the void has a high water retention capacity. In contrast, when the void size is large, the air-entry suction decreases and the water is easily replaced with air volume upon small applied pressures, i.e., the void has a small water retention capacity. The water retention capacity of various sizes of voids is presented in Figure 2.18. Soils contain a variety of void sizes and shapes with varying water retention capacities. Consequently, the void size distribution greatly affects the moisture content retained at a certain matric suction imposed on the soil (Lu and Likos 2004).

Figure 2.18. Effect of Void Size on Height of Capillary Rise and Matric Suction, Based on Lu and Likos (2004)

Osmotic Suction

Osmotic suction, π , is the solute component of free energy, or suction determined from the measurement of the partial pressure of a solution identical to the soil water relative to the partial pressure of free water (Fredlund et al. 2012). In other words, osmotic suction is suction that a soil exerts on water in response to a gradient of dissolved salts in the pore water with respect to the free water.

Osmotic suction is relatively constant over the entire range of suction as long as the concentration of the pore water is constant (Lu and Likos 2004). Osmotic suction is directly related to the concentration of dissolved salts in the

pore water, (e.g., Rao and Shivananda 2005). Values of osmotic suction of a Regina clay and a glacial till were 200 kPa and 300 kPa, respectively (Fredlund et al. 2012). Osmotic suction for bentonite is higher, e.g., approximately 1000 kPa for compacted sodium bentonite (Tang et al. 2002).

2.5.2 Methods of Suction Measurement

Multiple methods of suction measurement are available. The methods measure either total suction, matric suction, or osmotic suction and are generally restricted to a range of suction based on measurement accuracy. Moisture-suction relationships for GCLs occur over the entire range of suction so it is often necessary to employ multiple suction measurement methods to characterize the entire relationship. A variety of common suction measurement methods are presented in Figure 2.19. The following section describes some of the suction measurement methods applicable to determining moisture-suction relationships for GCLs.

Figure 2.19. Range of Suction Control for Various Techniques
(adapted from Beddoe et al. 2010)

Tensiometers

Tensiometers measure the matric suction of soils by applying a vacuum to a porous probe that is in intimate contact with the soil water. The probe is made of a high air-entry porous ceramic that allows for suction measurements up to 90 kPa. Vacuum is applied to the tensiometer until suction equilibrium with the soil is reached. At suctions above 90 kPa, cavitation occurs and the small air-water interfaces of the porous ceramic collapse which stops the moisture transfer from the soil through the probe (Fredlund et al. 2012).

Beddoe et al. (2010) developed a high-capacity tensiometer (HCT) that avoided the limitations imposed by cavitation. and was capable of measuring

suction up to 500 kPa for GCLs. Intimate contact of the tensiometer tip and the GCL was achieved by cutting a hole in the geotextile of the GCL, smearing bentonite paste on the tip, placing the tip to the exposed bentonite, and applying 2 kPa overburen with a small weight. The high-capacity tensiometer apparatus used for measuring matric suction of GCLs by Beddoe et al. (2011) is presented in Figure 2.20.

Figure 2.20. High-Capacity Tensiometer for Measuring GCL Suction in the Range of 1 kPa to 500 kPa (Beddoe et al. 2011)

Axis Translation Technique

The axis translation technique involves the application of positive air pressure to a soil specimen placed on a high air-entry ceramic pressure plate or a high air-entry pressure membrane until moisture equilibrium is reached. The pressure plates are typically rated to 50 kPa, 100 kPa, 500 kPa, to a maximum of 1500 kPa, whereas pressure membranes may be rated from 1500 kPa to 10,000

kPa (SoilMoisture Equipment Corp. 2014). The test method for conducting the axis translation technique is described by ASTM D6836. Multiple saturated specimens may be placed on a single saturated pressure plate or pressure membrane within the pressure vessel (a.k.a., pressure extractor). Upon application of air pressure, water is expelled from the voids of the soil which have a lower air-entry value than the applied pressure. The ceramic plate or membrane is connected to an outflow system which directs the outflow to a beaker. Air pressure is applied until outflow is observed to cease for a period of at least 24 hours, 48 hours, or 96 hours, depending on the applied air pressure. The samples are removed and moisture content is measured. Samples may be reused by repeating the test at a higher air pressure (i.e., higher suction), but this risks losing intimate contact of the sample to the pressure plate or pressure membrane.

Figure 2.21. Pressure Plate Apparatus for Determining Matric Suction

Filter Paper Technique

The filter paper technique is an indirect measurement of either matric suction or total suction, described by ASTM D5298. The range of measurable suction extends from 10 kPa to 100,000 kPa for the filter paper method. Matric suction is measured by placing filter papers in direct hydraulic contact with the soil (i.e., the contact filter paper method). In contrast, total suction is measured by suspending filter papers above a soil sample until vapor equilibrium is reached (i.e., the non-contact filter paper method). Both methods involve measuring the moisture content of one or two filter papers at the end of a 7-day equilibrium period with the soil specimen, then determining the suction corresponding to the filter paper moisture content from a calibration curve.

Leong et al. (2002) determined that the ASTM D5298 calibration curve does not yield accurate values of total suction, but it predicts matric suction reasonably well for test conditions without overburden and at 20°C. The ASTM D5298 calibration curve for both matric suction and total suction, as presented in Figure 2.22. Power et al. (2008) determined that if overburden is applied to the specimens during equilibrium, an adjustment is recommended for the calibration curve. If temperatures significantly less than or greater than 20°C are used during the equilibrium period, a temperature correction is also necessary, according to Haghighi et al. (2012).

Figure 2.22. Suction Calibration for Filter Paper Technique (ASTM D5298)

Relative Humidity Technique

The relative humidity technique measures total suction, via Kelvin's equation (Eq. 2.5), by measuring the partial pressure of air in equilibrium with a soil specimen. The typical suction range is 5000 kPa to 700,000 kPa depending on the capability of the sensor (Beddoe et al. 2010). Relative humidity values near 0% or 100% are difficult to determine accurately with a relative humidity sensor due to limitations of the sensors.

2.6 Water Retention Curves

The water retention curve (WRC), also known as the soil-water characteristic curve (SWCC), is the relationship of moisture content to suction of

a soil (e.g., Fredlund and Xing 1994). WRCs may be used to compare a variety of moisture parameters, including: the degree of saturation (S), volumetric moisture content (θ), or gravimetric moisture content (w), to soil suction (ψ). Gravimetric moisture content is commonly used in WRCs for geotechnical engineering, but volumetric moisture content and the degree of saturation also are used in WRCs when volumetric parameters are necessary (Fredlund et al. 2012).

Although the shape of water retention curves vary among soils and environmental conditions, typical WRCs exhibit a sigmoid shape and several points of interest, as illustrated by Figure 2.23. The intercept of the WRC with the water content axis (assumed to be either 0.1 or 1 kPa) represents the saturated soil condition, w_s , θ_s , or $S=100\%$. The intercept of the WRC with the suction axis (assumed to be 1,000,000 kPa) represents the oven-dried soil condition, $w=\theta=S=0$. Two changes in slope are typically present between the saturated and oven-dried states (Fredlund et al. 2011). The change in slope at low suction is the air-entry value of suction, ψ_{ae} corresponding with the air-entry moisture content, w_{ae} or θ_{ae} , at which air begins to replace pore water. At suctions greater than the air entry value, water is rapidly removed from the pore complex. Residual values of suction, ψ_r , and moisture content, w_r or θ_r , represent conditions at which most of the soil water has been removed and the remaining water consists of thin films around soil particles (Lu and Likos 2004). WRCs may be developed to represent moisture-suction relationships for either sorption (wetting WRCs) or desorption (drying WRCs) situations as illustrated by Figure

2.23. For clarity, the air-entry and residual moisture conditions are only presented for the drying curve.

Volumetric moisture content or the degree of saturation may be used as the measure of moisture for WRCs. The use of volumetric moisture content may normalize the variable swelling behavior among GCL products and may yield more representative values of air-entry suction than their gravimetric counterparts (Beddoe et al. 2011, Pham and Fredlund 2011). The volumetric format also allows for prediction of the unsaturated hydraulic conductivity function, as described in Chapter 5.

Figure 2.23. Determination of Moisture Content and Suction Values from WRCs

Wetting WRCs and drying WRCs are of similar form for a given soil, but differ due to hysteresis. Hysteresis is path-dependent behavior between the wetting WRC and drying WRC. Hysteresis is prevalent in the low suction range near air-entry conditions, where water retention behavior is primarily governed by capillary mechanisms. In contrast, hysteresis is less pronounced near residual conditions where the water retention behavior is primarily governed by adsorptive mechanisms (Lu and Likos 2004).

Mechanisms of hysteresis for soil WRCs include: a) trapped air due to the ink-bottle effect and b) contact angle hysteresis. The ink-bottle effect occurs as a result of filling of soil voids of dissimilar radii during hydration. Larger voids bounded by smaller voids may not hydrate due to the tendency for the capillary rise of water during hydration to stop at capillary breaks at the interface of the small void and the large void. In contrast, the same large void may be saturated when the soil is submerged in water, then dried from fully-saturated conditions, as presented in Figure 2.24. At a given applied suction, the tendency for water to occupy a greater portion of voids during dehydration, rather than hydration, is a mechanism that explains why drying WRCs often result in higher moisture contents for a given suction.

Figure 2.24. Capillary Tube Model Representation of the Ink-Bottle Effect (Lu and Likos (2004))

Hysteresis due to the air-water interface contact angle, α , is demonstrated by the schematic of Figure 2.25. Larger contact angles are present on the wetting front of a hydrating soil. In contrast, the contact angle of a drying front is much less for a dehydrating soil of similar composition. A comparison of the matric suction between the wetting front and the drying front may be made using Eq. 2.8. For a given capillary size, the lower contact angle of the drying front results in a larger matric suction than the matric suction of the wetting front. Therefore, contact angle hysteresis contributes to the tendency for the drying WRC to attain higher moisture content at a given suction (Lu and Likos 2004).

Figure 2.25. Water Droplet on Inclined Surface Illustrating Source of Contact Angle Hysteresis (Lu and Likos 2004)

2.6.1 Numerical Models for Water Retention Curves

Water retention curves are continuous, non-linear mathematical expressions for the moisture-suction relationships for porous materials. Many nonlinear models have been proposed to fit WRCs to experimental moisture-suction data, (e.g., Brooks and Corey 1964, Mualem 1976, van Genuchten 1980). Later models were proposed to describe soils of varying shapes of moisture-suction relationships (e.g., Fredlund and Xing 1994, Fredlund and Pham 2006), or to incorporate temperature effects (Jacinto et al. 2008). The models most commonly adopted in geotechnical engineering literature are the van Genuchten (1980) and the Fredlund and Xing (1994) WRC models.

The original van Genuchten (1980) equation for water retention curves is expressed by Eq. 2.9,

$$\theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (a_v \psi)^{n_v}} \right]^{m_v} \quad (2.9)$$

where Θ is the normalized volumetric moisture content, θ is the volumetric moisture content (%) at suction ψ (kPa), θ_r is the residual moisture content (%), θ_s is the saturated moisture content (%), and $\{a_v, m_v, n_v\}$ are fitting parameters specific to the van Genuchten WRC. The relationship between n_v and m_v , as described by Eq. 2.10, is commonly assumed, which reduces the flexibility of Eq. 2.9 but greatly simplifies the expression (Lu and Likos 2004). The assumption described by Eq. 2.10 is typically used for further analyses involving the WRC of Eq. 2.9.

$$m_v = 1 - \frac{1}{n_v} \quad (2.10)$$

A modified version of Eq. 2.9 results by assuming θ_r is equal to zero, and by replacing the volumetric moisture content terms with equivalent gravimetric terms, as presented in Eq. 2.11,

$$w(\psi) = \frac{w_s}{[1 + (a_v \psi)^{n_v}]^{m_v}} \quad (2.11)$$

Where: ψ is soil suction (kPa), $w(\psi)$ is the gravimetric moisture content (%), w_s is the saturated gravimetric moisture content (%) (Fredlund et al. 2011).

The Fredlund and Xing (1994) WRC is presented in Eq. 2.12. Experimental suction data of dry soils indicated that the maximum suction exhibited by soils was approximately 1,000,000 kPa (Fredlund and Xing 1994). A correction factor, $C(\psi)$, described by Eq. 2.13, enables Eq. 2.12 to express moisture-suction relationships over the entire range of suction. The correction

factor helps fit data in the high suction range, while minimally affecting the shape of the curve in the low suction range, as expressed by the boundary values of $C(1,000,000)$ which is equal to zero, and $C(0)$ which is equal to 1.

$$w(\psi) = C(\psi) \frac{w_s}{\{\ln[e + (a_f \psi)^{n_f}]\}^{m_f}} \quad (2.12)$$

$$C(\psi) = 1 - \frac{\ln(1 + \frac{\psi}{\psi_r})}{\ln[1 + (\frac{1000000}{\psi_r})]} \quad (2.13)$$

Where: $w(\psi)$ is the gravimetric moisture content (%), $C(\psi)$ is a correction factor, ψ_r is the residual suction (kPa), w_s is the saturated gravimetric moisture content (%), ψ is suction (kPa), $\{a_f, m_f, n_f\}$ are fitting parameters specific to the Fredlund and Xing (1994) WRC, and e is the base of the natural logarithm = 2.71828.

The fitting parameters influence the shape of the water retention curves in separate manners. An increase in the residual suction parameter, ψ_r , results in a shift of the WRC, mainly in the zone of residual suction. The value of the saturated moisture content, w_s or θ_s , determines the vertical axis intercept of the water retention curve. The a parameter defines the approximate location of the air-entry suction value. Small values of the symmetry parameter, m , results in a gentle slope in the high-suction range, and large values of the pore size distribution parameter, n , results in a sharp transition at the air-entry value.

Conventional analyses of moisture-suction relationships do not measure the wetting WRC (e.g., ASTM D6836). If the wetting WRC is necessary, the wetting WRC may be estimated from a translated version of the drying WRC

(Fredlund et al. 2011). Fredlund et al. (2011) indicated that appropriate shifts toward lower suction consist of 0.25 (log cycle), 0.50 (log cycle), and up to 1.0 (log cycle) for sandy, silty, and clayey soils, respectively. An example of predicting the wetting WRC, using this method, is presented in Figure 2.26. Fredlund et al. (2011) indicated the difficulty of determining the in-situ suction of a soil of given moisture content due to the range of moisture contents exhibited by hysteretic soils. The most-likely representation of in-situ moisture-suction relationships was determined to be represented by the median suction curve, as presented in Figure 2.25 (Fredlund et al. 2011).

Figure 2.26. Representation of WRC Most-Likely to Represent In-Situ Moisture-Suction Relationships (i.e., Median Suction) for Estimated WRCs (Fredlund et al. 2011)

Similarly, Fredlund et al. (2011) determined the path of wetting or drying of a hysteretic soil is difficult to determine due to the presence of wet-to-dry or dry-to-wet transition curves, called scanning curves, as presented in Figure 2.27.

Figure 2.27. Transitional WRCs (Scanning Curves) (Fredlund et al. 2011)

2.6.2 Factors Affecting Water Retention Curves for Bentonite

Previous studies determined the effects of compaction, cation exchange, and temperature on water retention behavior of bentonite. Meerdink et al. (1996) determined WRCs and the unsaturated coefficient of permeability at several suction values for compacted bentonite. Tinjum et al. (1997) and Miller et al. (2002) determined that increasing the compactive effort of a soil containing bentonite caused suction to increase at a given moisture content. Lloret et al. (2003) determined that the level of compaction had no effect related to changing the size of intra-aggregate voids. Similarly, the level of compaction did not influence intra-particle water retention behavior in the high suction range, as presented in Figure 2.28 (Lloret et al. 2003). Lloret et al. (2003) determined that

compaction affected inter-particle voids of bentonite, associated with the low range of suction. Hysteresis of moisture-suction relationships of compacted bentonite was observed by Villar and Lloret (2004). El-Swaify and Henderson (1967) determined a reduction of water retention capacity in the low range of suction for sodium montmorillonite that was exchanged for calcium. Villar and Lloret (2004) determined that the water retention capacity decreased for heavily compacted bentonite for increasing temperature in the range of 20°C and 80°C.

Figure 2.28. WRC for Heavily-Compacted Bentonite (Lloret et al. 2003)

2.6.3 Water Retention Curves for GCLs

Moisture-suction relationships for GCLs are not necessarily directly comparable to moisture-suction relationships for bentonite due to the presence of geotextile components and macrostructure differences due to the processing of

bentonite granules. Limited data exist on the determination of moisture-suction relationships for GCLs, and even less data exist on the effects of environmental factors on moisture-suction relationships for GCLs. A summary of experimental determinations of moisture-suction relationships for GCLs is presented in Table 2.6 at the end of this section.

Daniel et al. (1993) determined moisture-suction behavior for an unreinforced, adhesively-bonded GCL using a thermocouple psychrometer as well as the vapor equilibrium technique with salt solutions. Wetting WRC behavior was determined as the GCL was hydrated from initially dry conditions. The psychrometer test involved spraying a small GCL specimen with water, placing the GCL in an insulated test tube in direct contact with the psychrometer probe, and recording suction measurements for a period of two weeks. The vapor equilibrium technique was performed over a period of one to three weeks with salt solutions of known suction. Daniel et al. (1993) determined the equilibrium moisture contents and general conclusions regarding the moisture-suction relationships of the adhesively-bonded GCL, as presented in Table 2.5. The results indicated that the GCL retained a significant amount of moisture at suctions greater than 1500 kPa (the permanent wilting point for most plants). The GCL hydrated to a maximum gravimetric moisture content of 145% when submerged in water under 14 kPa overburden stress (Daniel et al. 1993).

Table 2.5. Moisture-Suction Relationship for Bentonite in a GCL
(Daniel et al. 1993)

Soil on which the GCL is Placed	Approximate Water Content (%) of Bentonite in GCL
Extremely dry soil that will not support plant growth (Soil suction > 1500 kPa)	< 50
Damp soil that will support sparse growth of plants (100 kPa ≤ Suction ≤ 1500 kPa)	50 – 100
Moist soil that will support growth of lush vegetation (0 kPa ≤ Suction ≤ 100 kPa)	100 – 140
Wet (Practically Saturated) Soil (Soil Suction = 0)	> 140

Barroso et al. (2006) validated the use of the contact filter paper method to measure moisture-suction relationships for unreinforced (adhesively-bonded) and reinforced (needle-punched) GCLs. Barroso et al. (2006) used the filter paper calibration of ASTM D5298, but employed a modified apparatus. Wetting WRC behavior was determined because the GCLs were hydrated from initially dry conditions. Two GCLs were hydrated and allowed to reach moisture equilibrium by sealing them together for one week. After one week, the moisture contents of the two GCL specimens were assumed to be equal (Barroso et al. 2006). For moisture contents less than 45%, GCLs were hydrated by spraying a known mass of water on the specimens. For moisture contents greater than 45%, GCLs were hydrated by submerging the specimens in water for a period necessary to achieve the specified moisture content. Three filter papers were placed between the two specimens, sealed, and allowed to equilibrate for an additional period of one week.

The results from Barroso et al. (2006) indicated that there was close agreement of moisture-suction data of GCL-4 with the moisture-suction data of the GCL from Daniel et al. (1993). Barroso et al. (2006) also determined that moisture-suction relationships did not vary based on the type of geotextile, (i.e., woven or nonwoven) that was in contact with the filter paper during the equilibrium period. A portion of the moisture-suction data was plotted in terms of volumetric moisture content and fitted using the van Genuchten (1980) equation (Eq. 2.9).

Southen and Rowe (2007) obtained moisture-suction data for GCLs using the axis translation technique. Drying WRC behavior was examined as GCLs were dehydrated from an initially saturated state. Specimens were submerged in DI water for 10 days then consolidated at 0.5 kPa, 3 kPa, or 100 kPa overburden stress, or tested without consolidation. Pressure plate tests were conducted on the unconsolidated specimens to suctions as high as 1500 kPa. Pressure membrane tests were conducted on the consolidated specimens to suctions as high as 9000 kPa. Southen and Rowe (2007) determined WRCs of moisture-suction data for GCLs using the van Genuchten (1980) and Fredlund and Xing (1994) equations (Eq. 2.9 and Eq. 2.12). The results indicated that the bulk GCL void ratio was reduced by two mechanisms: a) by increasing overburden stress and, b) by reducing the moisture content of the GCL. The results also indicated the need to ensure intimate contact of GCL specimens to the pressure plate in order to avoid scatter in the moisture-suction data. The authors indicated that the geotextiles that encapsulated the bentonite may have acted as a capillary barrier

and inhibited moisture transfer from the bentonite to the suction measurement apparatus (Southen and Rowe 2007).

Beddoe et al. (2010) established a multi-component test method to determine both wetting and drying WRCs for GCLs. The moisture-suction data was determined using a high-capacity tensiometer and a relative humidity sensor for the suction ranges of 1 to 500 kPa and greater than 5000 kPa, respectively. Wetting WRC specimens were hydrated by placing GCL panels on wet silty sand for 30 days with 2 kPa overburden stress, and periodically removing samples for suction testing. Drying WRC specimens were hydrated by submerging GCL panels in DI water for 30 days with 2 kPa overburden stress. Drying WRC specimens were air dried to target moisture contents prior to suction testing. Beddoe et al. (2010) determined that moisture content across a GCL specimen was rendered more consistent during dehydration if the perimeter was sealed with tape.

Beddoe et al. (2011) used the test method from Beddoe et al. (2010) to determine wetting and drying WRCs for four types of reinforced GCLs. Gravimetric and volumetric moisture-suction data were plotted and fitted using the Fredlund and Xing (1994) model. The gravimetric WRCs exhibited significant hysteresis between wetting WRCs and drying WRCs in the low suction range, yet hysteresis was small in the high suction range, as presented in Figure 2.29. Volumetric WRCs exhibited less hysteresis between wetting and drying curves than the gravimetric equivalents.

Figure 2.29. Typical Sigmoid Shape and Hysteresis of GCL WRC
(Beddoe et al. 2011)

The shape of GCL WRCs was determined to be product-specific. Heavily-reinforced GCLs, such as the thermally-treated, needle-punched, scrim-reinforced, GCL2 reached lower moisture contents than lightly-reinforced GCLs at a given suction, as presented by the comparison of Figure 2.29 and Figure 2.30. GCL2 also exhibited less hysteresis and lower bulk void ratio than the other GCLs from the test program. It was suggested that hysteresis and the shape of the GCL WRCs was more dependent on the macrostructure of the GCL, and less dependent on the unsaturated behavior of the bentonite. Fiber pullout was thought to have contributed to higher swell in the less-reinforced GCL1, GCL3, and GCL4 (Beddoe et al. 2011).

Figure 2.30. Moisture-Suction Relationships Exhibited Among Other GCL Products (Beddoe et al. 2011)

The measured wetting WRCs for GCLs did not correspond to those determined through analytical predictions, (e.g., from Fredlund et al. 2011). An approximate shift of 1.0 log cycles was recommended for estimating the wetting WRC if the drying WRC is known of a clayey soil (Fredlund et al. 2011). However, Figure 2.29 and 2.30 only exhibited a 1.0 log cycle shift at suctions below 100 kPa, whereas above 100 kPa, the shift was less than 1.0 log cycles, and much less than 1.0 log cycles at residual moisture conditions. Wetting WRCs should be measured directly, when possible, in order to maintain acceptable accuracy of moisture-suction relationships for suctions greater than 100 kPa.

Several GCL specimens from Beddoe et al. (2011) were subjected to one wet-dry cycle, consisting of hydration along the wetting WRC until approximately 10 kPa suction, followed by drying to specified moisture contents. Beddoe et al.

(2011) performed suction tests on the single-cycled specimens and determined that the specimens corresponded more closely with the wetting WRC than the drying WRC. The cycled specimens did not follow the expected transitional, scanning curves toward the drying WRC, as suggested by Fredlund et al. (2011). The effect of wet-dry cycles on GCL water retention curves may be enhanced by multiple wet-dry cycles.

Table 2.6. Summary of Experimental Determinations of GCL Water Retention Behavior

Product	Cover / Carrier Geotextile Type [Mass/Area] (g/m ²)	Bentonite Type [Mass/Area] (kg/m ²)	Reinforcement	Suction Tests Performed	Wetting or Drying WRC	Reference
Gundseal	0.5 mm HDPE GM ^a	Not provided [0.042]	None ^c	Psychrometer Vapor Equilibrium	Wetting	Daniel et al. (1993)
GCL-1	NW[220] / W[110]	Granular [4.67]	NP	Contact Filter Paper	Wetting	Barroso et al. (2006)
GCL-2	NW[220] / W[110]	Powdered [4.67]	NP	Contact Filter Paper	Wetting	Barroso et al. (2006)
GCL-3	NW[200] / W[125]	Granular [5.00]	NP	Contact Filter Paper	Wetting	Barroso et al. (2006)
GCL-4	0.5 mm HDPE GM ^a	Not provided [4.90]	None ^c	Contact Filter Paper	Wetting	Barroso et al. (2006)
G1	NW[200] / W[105]	Granular [4.34]	NP	Pressure Plate Pressure Membrane	Drying	Southen and Rowe (2007)
G2	NW[300] / W[200]	Powdered [5.00] ^b	NP	Pressure Plate Pressure Membrane	Drying	Southen and Rowe (2007)
GCL1	NW[242] / W[123]	Fine Granular	NP/Heat	HCT Relative Humidity	Wetting Drying	Beddoe et al. (2011)
GCL2	NW[232] / NWS[260]	Fine Granular	NP/Heat	HCT Relative Humidity	Wetting Drying	Beddoe et al. (2011)
GCL3	NW[283] / W[125]	Coarse Granular	NP	HCT Relative Humidity	Wetting Drying	Beddoe et al. (2010) Beddoe et al. (2011)
GCL4	NW[264] / NW[233]	Coarse Granular	NP	HCT Relative Humidity	Wetting Drying	Beddoe et al. (2011)

NW=Nonwoven

NP=Needle-punched

^a Mass/area not provided

^b 0.8 kg/m² of 5.00 kg/m² bentonite impregnated in NW geotextile

^c Bentonite was adhesively-bonded to GM

NWS=Nonwoven, scrim-reinforced

Heat=Thermally-treated

W=Woven

HCT=High-capacity tensiometer

2.7 Summary

Previous studies of moisture-suction relationships for GCLs provided a baseline for further research involving GCL WRCs. Methods of suction measurement and specimen preparation were established for use with GCLs (Barroso et al. 2006, Southen and Rowe (2007), Beddoe et al. (2010). Wetting WRCs and drying WRCs were developed for some reinforced GCLs and overburden stress and GCL type were determined to influence the shapes of the WRCs (Beddoe et al. 2011). Temperature gradients and temperature cycles that inhibited hydration were identified as mechanisms, which caused desiccation of GCLs (e.g., Rowe and Rayhani 2011, Sarabian and Rayhani 2013).

However, previous determinations of GCL WRCs were conducted to represent GCLs that existed in ideal conditions, (i.e., hydrated in dilute solutions, were not exposed to multiple wet-dry cycles, were not subjected to high or low temperature, and were not subjected to transfer from adjacent soils or from chemical interactions). Overall, limited moisture-suction data is available for GCLs. Furthermore, GCL WRCs have not been determined for needle-punched GCLs with adhesively-bonded geofilms. Effects of microstructure have not been reported for explaining GCL water retention behavior. The tendency of temperature gradients and temperature cycles to restrict GCL hydration have been examined, but the effects of constant, elevated and reduced temperatures on WRCs of previously hydrated GCLs have not been examined. WRCs have not been determined for GCLs that incorporate the effects of chemical, structural, and hydraulic changes that occur in field environments.

Previous studies identified the importance of considering hydraulic interactions among components of landfill barrier systems (e.g., Rowe 2005). GCLs may desiccate due to moisture transfer to adjacent soils (e.g., Olsen 2011). Meer and Benson (2007) determined that desiccation of GCLs coupled with cation exchange may increase hydraulic conductivity by several orders of magnitude. Quantifying the potential of moisture transfer of GCLs to adjacent soils has not been adequately assessed with potential use of WRCs.

This test program was conducted to determine the effects of cation exchange, wet-dry cycles, and exposure to high or low temperatures on the shape of GCL WRCs. WRCs were developed for GCLs subjected to cation exchange, wet-dry cycles, or high or low temperatures and were compared to WRCs of GCLs determined from baseline tests. Index behavior, microstructure, and chemical composition also were determined for the GCLs subjected to the various test conditions. Soil WRCs were determined and compared to GCL WRCs in order to investigate the feasibility of using WRCs to estimate suction and equilibrium moisture contents of GCLs that are placed in hydraulic contact with soils. Finally, the GCL WRCs were used to estimate the coefficient of permeability and the shear strength as functions of suction.

Chapter 3: Experimental Test Program

3.1 Introduction

This laboratory test program was undertaken to evaluate the effects of GCL type, hydration solution chemistry, wet/dry cycles, and temperature on the water retention behavior of GCLs. In addition, the water retention behavior of several soils was determined in order to study the moisture transfer between GCLs placed on soils typical in landfill barrier systems. The objectives of the test program were: (a) to develop a procedure to obtain water retention curves of GCLs for the entire range of suction, and (b) to explore the use of water retention curves for predicting the long-term effectiveness of GCLs deployed as hydraulic barriers when exposed to various environmental conditions. The test program is described in three parts: description of materials, specimen preparation procedures, and explanation of testing methods.

3.2 Materials Tested

Three types of needlepunched GCL products were used in the testing program. Four soils of varying sand and clay content were tested in order to simulate a range of soils typically placed in contact with GCLs. Three types of hydration solutions of varying chemistry and ion valence were used to simulate a range of chemical conditions that GCLs may encounter in the field.

3.2.1 GCLs Tested

Three types of GCLs were selected for the test program. All GCLs were manufactured by CETCO, of the Bentomat product line that uses a common

bentonite source, and similar manufacturing techniques. The GCL products varied among their geotextile configurations and mass per unit area of bentonite. All three GCLs contained a layer of granular bentonite encapsulated between two geotextiles. The bentonite granules consist of a minimum of 90% montmorillonite and were manufactured so that less than 1% passed the 75 μm (No. 200) sieve (CETCO 2007). A grain size distribution of the granulated bentonite is presented in Figure 3.1.

Figure 3.1. Grain Size Distribution for Granular Bentonite

The minimum swell index (ASTM D5890) and the maximum fluid loss (ASTM 5891) of the bentonite contained in the GCLs were reported to be 24 mL/2g and 18 mL, respectively (CETCO 2009). The bound cations (BC) were 37.3 meq/100g, 1.5 meq/100g, 20.2 meq/100g, and 5.0 meq/100g for Na⁺, K⁺, Ca²⁺, and Mg²⁺ ions, respectively, and the CEC was 74.6 meq/100g. The GCLs were bonded together by needlepunched fibers and did not include reinforcement from other methods (e.g., heat-tacking or scrim reinforcement). One of the GCLs also contained an adhesive-bonded geofilm, described below in further detail. The GCLs selected for the test program included ST, DN, and CLT from the Bentomat series. For consistency of terminology with Olsen (2011), Hanson et al. (2013), and Yesiller et al. (2014), Bentomat ST, Bentomat DN, and Bentomat CLT are referred to as WN2, NN1, and WNT, respectively, in reference to their geotextile configurations. Relevant GCL properties are presented in Figure 3.2, Table 3.1, and Table 3.2.

WN2 is a GCL composed of a layer of granular bentonite encapsulated by a light-weight, slit-film woven carrier geotextile and a medium-weight, nonwoven top geotextile. Fibers from the nonwoven geotextile are needlepunched through the GCL to the back of the woven geotextile. The internal reinforcement provided by these needlepunched fibers allow for applications requiring moderate shear strength on slopes up to 3H:1V. WN2 is highly specified for a variety of hydraulic barrier applications (CETCO 2009).

NN1 is a commonly-specified GCL composed of a layer of granular bentonite encapsulated between two heavy-weight nonwoven geotextiles. Similar

to WN2, the NN1 GCL is bonded by needlepunched fibers. NN1 can be used in applications where high internal and interface shear strengths are necessary, up to slopes of 1.5H:1 V (CETCO 2009).

WNT is a specialty GCL similar to WN2 in that it is composed of a layer of granular bentonite encapsulated between a light-weight slit-film woven geotextile and a medium-weight nonwoven geotextile. A 20-mil (0.5 mm) textured HDPE geofilm is adhesively bonded to the nonwoven geotextile. For calculations involving GCL thickness, 0.75 mm was used in place of 0.51 mm to account for variable thickness caused by the textured surface of the geofilm. Various properties of the geofilm are presented in Table 3.3. The geofilm increases hydraulic performance of the multi-component GCL and the texturing provides increased interface shear strength with adjacent geotextile products or soil materials. Therefore, WNT is commonly specified for steeply sloped applications (CETCO 2009).

WN2:

- Nonwoven cover geotextile
- Granular bentonite
- Woven carrier geotextile
- Needle-punched fibers

NN1:

- Nonwoven cover geotextile
- Granular bentonite
- Nonwoven carrier geotextile
- Needle-punched fibers

WNT:

- 0.5 mm textured geofilm
- Nonwoven cover geotextile
- Granular bentonite
- Woven carrier geotextile
- Needle-punched fibers

Figure 3.2. Components of the Tested GCLs (CETCO 2014)

Table 3.1. Summary of Properties of GCL Products Used in Test Program

Product Name	Panel Width/Length ^a (m/m)	Average Roll Weight ^a (kg)	Minimum GCL Peel Strength ^a (ASTM D 6496) (N/m)	MARV GCL Tensile Strength ^a (ASTM D 6768) (N/m)	GCL Hydrated Internal Shear Strength at 10 kPa confining ^a (ASTM D 5321) (ASTM D 6243) (kPa)	Index Flux ^a (ASTM D 5887) (m ³ /m ² -s)	Maximum Hydraulic Conductivity ^a ASTM D 5887 (cm/s)	Minimum Bentonite Dry Mass per Unit Area ^a ASTM D 5993 (g/m ²)	As Received Moisture Content ^b (%)
WN2 (Bentomat ST)	4.6 / 45.7	1200	610	5300	24	1 x 10 ⁻⁸	5 x 10 ⁻⁹	3600	36 40 ^c
NN1 (Bentomat DN)	4.4 / 45.7	1220	610	8800	24	1 x 10 ⁻⁸	5 x 10 ⁻⁹	3600	24
WNT (Bentomat CLT)	4.6 / 45.7	1340	440	7000	24	1 x 10 ⁻⁹	5 x 10 ⁻¹⁰	3600	30

^aValues provided by CETCO

^bValues determined in laboratory

^cValues determined in laboratory from GCL exhumed from landfill cover test plot

Table 3.2. Summary of Configuration of GCL Products Used in Test Program

Product Name	Cover Geotextile Type	Cover Geosynthetic Weight (g/m ²)	Bottom Geotextile Type	Bottom Geotextile Weight (g/m ²)
WN2 (Bentomat ST)	Nonwoven	200	Woven	105
NN1 (Bentomat DN)	Nonwoven	200	Nonwoven	200
WNT (Bentomat CLT)	Textured geofilm/ Woven	Geofilm: 605 GT: 200	Woven	105

Table 3.3. Properties of Geofilm Component of WNT (Olsen 2011)

Property	Test Method	Typical Value	Minimum Allowable Roll Value (MARV)
Thickness (mm)	ASTM D 1593	0.51	0.51
Yield Strength (kN/m)	ASTM D 1593	7.36	6.66
Break Strength (kN/m)	ASTM D 638	7.36	4.90
Yield Elongation (%)	ASTM D 638	13	10
Break Elongation (%)	ASTM D 638	200	100

3.2.2 Soils Tested

Four types of soils were used in this test program: a poorly graded sand (SP) and a sandy lean clay (CL) used in GCL hydration simulations from Olsen (2011), and two clayey sands (SC1 and SC2) that were exhumed from a landfill cover test plot in Florida. The orientations of SC1, SC2, and exhumed GCL prior to removal from the test plot are presented in Figure 3.3. The soils were selected to provide a representative range of water retention behavior among soils commonly placed in contact with GCLs in the field.

Figure 3.3. Stratigraphy of Landfill Cover Test Plot

Index tests were performed on each soil to allow both for USCS classification and analyses of results. Parameters and relationships obtained by these index tests included: specific gravity, particle size distribution, liquid and plastic limits, and laboratory compaction analysis.

Specific Gravity

The specific gravity of each test soil was determined according to ASTM D854. For each test, a 500 mL pycnometer was calibrated and weighed as specified, filled with de-aired de-ionized water, weighed again, then emptied. A motorized vacuum and an oscillating agitator were used in the de-airing processes. Bulk, moist soil was processed through a 4.75 mm (No. 4) sieve. A soil slurry composed of approximately 75 g to 100 g (dry mass) of moist, processed soil was mixed with de-ionized water, then poured into the empty pycnometer, according to Method A of ASTM D422. During de-airing, the pycnometer was agitated to release captured air within the slurry and to confirm the completion of de-airing at the end of 2 hours. Although soil types SC1 and SC2 had particles larger than 4.75 mm, specific gravities obtained for the test soils containing only particles less than 4.75 mm were assumed to be representative of the bulk soil. Specific gravity results are presented in Table 3.4.

Particle Size Distribution

Both sieve analysis and hydrometer test were conducted for each test soil based on ASTM D422. Bulk soil samples were wet-sieved with de-ionized water through a 0.075 mm (No. 200) sieve to separate the coarse soil fraction from the fine soil fraction. The coarse soil fraction was oven-dried at 110°C then sieved through 76.2 mm, 38.1 mm, 25.4 mm, 19.0 mm, 12.7 mm, 9.50 mm, 4.75 mm, 2.00 mm, 0.800 mm, 0.425 mm, 0.250 mm, 0.150 mm, and 0.075 mm sieves. The fine soil fraction was oven-dried at 110°C, then 50 g of soil was mixed with 125 mL of dispersant, and soaked for 16 hours. After the soaking period, the soil

slurry was blended in a dispersion cup, transferred to a sedimentation cylinder, filled to 1000 mL with de-ionized water, then inverted by hand. A 152H type hydrometer was used for the tests. The particle size distribution plots are presented in Figure 3.4. Cc and Cu are presented in Table 3.4.

Liquid Limit and Plastic Limit

The liquid limit and the plastic limit, also known as the Atterberg Limits, were determined for each soil according to test procedures included in ASTM D4318. Bulk, moist soil was wet-sieved through a 0.425 mm (No. 40) sieve, and the soil passing the sieve was dehydrated to approximately the liquid limit in a 60°C oven, thoroughly mixed, and sealed in a plastic bag for 16 hours. The liquid limit was determined using the multipoint method and the plastic limit was determined from soil prepared for the liquid limit test. The liquid limit, plastic limit, and plasticity index for each soil are included in Table 3.4.

Laboratory Compaction

Laboratory compaction tests were performed for each soil according to ASTM D698 using standard effort in order to obtain moisture-density relationships. Compaction Method B was adopted because all soils used in this test program conformed to the gradation requirements, i.e. less than 25% retained on a 9.52 mm (3/8 in) sieve. Soil type SC1 would have required an oversize correction for dry unit weight and moisture content, per ASTM D698 and ASTM C127. However, since oversize particles were not included in the samples prepared for this test program, and the amount of oversized particles were not sufficient to perform ASTM C127, the oversize correction was not applied.

The compaction process adhered to Method B of ASTM D698, as follows. Bulk moist soil was processed through a 9.52 mm sieve to exclude retained material from the compaction test. The processed soil was split into 5 samples, adjusted to target moisture contents by air-drying or spraying with water, then allowed to saturate in sealed plastic bags for 16 hours. Upon completion of the saturation period, the soils were compacted in 3 lifts in a standardized mold of 102 mm (4 in.) diameter and 944 cm³ (1/30 ft³) volume with a 24.5 N (5.5 lb) manual rammer, dropped from a height of 305 mm (12 in.), at a frequency of 25 drops per lift. Compacted samples were then trimmed and weighed, and a moisture content specimen was collected for each compacted sample. Dry unit weights were computed and compaction curves were constructed for comparison with soil specimens prepared according to Section 3.4.

Table 3.4. Summary of Index Tests for Test Soils

Soil	G _s	LL (%)	PL (%)	PI (%)	C _u	C _c	As-Received Moisture Content (%)
SP	2.67	NP	NP	NP	4.5	0.95	2.0
CL	2.73	33	15	18	--	--	3.7
SC1	2.64	34	15	19	2.1	0.99	23.7
SC2	2.66	28	11	17	--	--	17.2

C_u = Coefficient of Uniformity = D₆₀/D₁₀

C_c = Coefficient of Gradation = (D₃₀)²/[(D₁₀)(D₆₀)]

G_s = Specific Gravity

LL = Liquid Limit

NP = Non-Plastic

-- = Not determined

PL = Plastic Limit

PI = Plasticity Index

Figure 3.4. Grain Size Distributions for Test Soils

3.2.3 Hydration Solutions

Three hydration solutions of varying salinity were prepared in order to examine the effect of hydration solution chemistry on the water retention behavior of GCLs. De-ionized water (DI), local tap water (Tap), and 0.1 M CaCl_2 (CaCl_2) were selected to simulate dilute, moderately saline, and heavily saline hydration solutions, respectively. De-ionized water was procured from a reverse osmosis apparatus. Local tap water, ranging in hardness from 120 to 370 mg/L, was obtained periodically from the laboratory. Ion content in tap water was expected to fluctuate, but average concentrations of typical ions in the tap water are provided in Table 3.5. Batches of 0.1 M CaCl_2 were prepared by mixing 11.10 g of 96.0% ACS reagent-grade CaCl_2 crystals with 1 L of de-ionized water.

Table 3.5. Common Ions Present in Tap Water in San Luis Obispo

Ion	Average Concentration (mg/L)	Concentration Range (mg/L)
Sodium	30	25-35
Potassium	2.0	2.0
Calcium	35	25-40
Magnesium	30	25-45
Iron	0.0*	0.0*
Aluminum	0.15	0.02-0.4
Chlorine	0.7	0.2-1.5
Fluoride	0.5	0.2-1.0

(Furukawa, 2014)

*Small amounts of iron may be carried by the distribution system during pipe repairs or during high flow conditions (Furukawa 2014)

3.3 GCL Specimen Preparation

Extensive preparation of GCLs specimens was required in order to minimize disturbance, simulate field conditions, and maintain consistency with other studies (e.g., Beddoe et al 2010, Beddoe et al. 2011, Olsen 2011). GCLs were delivered by the manufacturer as 1 m (machine direction) x 4.5 m (cross-machine direction) end-of-roll bulk samples. Smaller 279 mm x 356 mm panel samples were cut from the bulk samples, then cut into six 102 mm (4 in.) diameter and two 51 mm (2 in.) diameter test samples, per panel. The 102 mm diameter samples were used for the filter paper tests and the relative humidity tests. The sample size was intended to correspond with common sizes used in GCL hydraulic conductivity tests. In addition, it is the author's belief that this sample size allowed for having adequate moisture to conduct the filter paper and relative humidity suction measurement tests. The 51-mm-diameter samples used for the pressure plate tests were of the typical size used in pressure plate tests. Samples were either hydrated or dehydrated to target moisture contents prior to suction measurements. A 2 kPa overburden was applied during sample hydration and suction testing in order to provide promote even hydrating and provide intimate contact with suction apparatuses, respectively. The following section explains the process of preparing the variety of GCL samples used in this test program.

3.3.1 GCL Specimen Preparation - Wetting WRC

The GCL water sorption retention curve (i.e., wetting curve) represents the suction behavior of a GCL hydrated from an initially dry state. Specimens

intended to produce data along the wetting curve were prepared in a relatively dry state, then hydrated, to simulate suction behavior during hydration. Undesired dehydration of the GCL was minimized by limiting exposure to the atmosphere as well as by sealing each sample in two, nested 1 L plastic freezer bags.

GCL specimens were cut from the 279 mm x 356 mm panel samples with a sharp utility knife and a 1020-mm-diameter cutting die. The cutting die was held firmly on the panel while the utility knife was used to make an initial cut around the perimeter of the die to expose the bentonite. To minimize the loss of bentonite during specimen removal, the perimeter of the specimen was first wetted with a small stream of the hydration solution intended for the test (i.e., DI, Tap, or CaCl_2). This moisture was accounted for by measuring the mass of water used, and by assuming that half of that water mass used during cutting remained in the specimen, while the other half of the water mass was absorbed by the remainder of the GCL panel (i.e., outside of the perimeter of the test specimen). After approximately 5 minutes, the perimeter of the specimen was cut again with the utility knife. The specimen was carefully removed from the panel, trimmed of excess geotextile, and sealed in the two nested plastic bags.

The initial gravimetric moisture content of the bentonite of the GCL (hereafter referred to as GCL moisture content) was determined in order to predict the dry mass of bentonite within each GCL specimen and to predict how much water was necessary to hydrate the GCL specimens to their target moisture contents. Bentonite was removed from excess GCL panel scraps that

were not exposed to hydration solution during cutting. Approximately 30 g of bentonite was weighed, and placed in a 110°C oven until constant mass was attained, and moisture content was calculated per ASTM D2216.

The perimeter of each GCL specimen was covered in a layer of electrical tape. Beddoe et al. (2010) identified that moisture content variations existed across GCL specimens during uncontrolled dehydration of a saturated GCL. The author believes that similar moisture variations existed during uncontrolled hydration (i.e., without taped edges) of a dry GCL, so all GCL specimens were taped in this test program. The tape was cut multiple times and folded down onto the top side of the GCL to avoid interactions with the contact of the filter papers to the GCL during the filter paper tests. The mass of each strip of tape was recorded before it was applied to the GCL. Specimens were labeled in gold ink on the electrical tape according to method used to prepare the specimen. Hydration solution, GCL type, target moisture content, and wetting or drying curve were specified, (e.g., Tap ST 160W).

Each wetting curve GCL specimen was sprayed with one of three hydration solutions (described in Section 3.2.3) to a target moisture content. The mass per unit area of geosynthetics, the mass of tape, the mass of water applied to the specimen during cutting, the initial GCL moisture content, and the target GCL moisture content affected the required mass of water necessary to hydrate the specimen to its target moisture content. Eq. 3.2 was used to calculate the target mass of the hydrated GCL specimen.

$$M_s = \frac{(M_{tot} - M_{gt} - M_{ring})}{(1 + \omega_{init})} \quad (3.1)$$

$$M_{target} = (M_s)(1 + \omega_{target}) + M_{gt} + M_{ring} \quad (3.2)$$

where: M_{tot} is the total mass of the specimen (i.e., $M_{tot} = M_s + M_w + M_{gt} + M_{ring}$), M_s is the mass of dry bentonite solids, M_w is the mass of water, M_{gt} is the mass of geosynthetics, M_{ring} is the mass of tape (for GCLs only) or specimen ring (for soils only), ω_{init} is the initial moisture content of the bentonite, ω_{target} is the target moisture content of the GCL specimen, and M_{target} is the target mass of the specimen at the target GCL moisture content. A plastic bag was zeroed on an electronic mass balance and the GCL specimen was placed in the bag. Half of the water required to hydrate the specimen was sprayed on one side of the GCL inside the plastic bag. The GCL specimen was then flipped over and the remaining water was sprayed on the other side of the GCL. The total mass of the GCL was monitored to avoid excessive hydration and to ensure an equal distribution of water mass on the GCL. For high moisture contents, multiple applications of water were necessary to allow time for the specimen to absorb the water. Upon reaching the target mass and corresponding target moisture content, the GCL was placed with the carrier geotextile oriented down in the plastic bag. The specimen and plastic bag were sealed in an additional plastic bag to decrease moisture loss due to diffusion, observed by Beddoe et al. (2010). This configuration was improved by spraying water between the two layers of sealed plastic bags to further reduce moisture losses from the specimen due to diffusion.

Upon hydration to the target mass, a 2 kPa overburden was applied by the weight of a brick distributed over a rigid wooden plate, centered over the GCL above the plastic bags. Beddoe et al. (2010) recommended 2 kPa as the overburden stress that allowed near-free-swell conditions, yet promoted adequate contact between GCL specimens and suction equipment. Application of this overburden during hydration likely limited differential swelling and induced pre-consolidation.

GCL specimens were hydrated for a period of 30 days in a temperature-controlled laboratory ($20^{\circ}\text{C} \pm 2^{\circ}\text{C}$). Several days were required to hydrate the bentonite within GCLs uniformly, and bentonite submerged in water continued to absorb water in small amounts beyond 30 days. However, 30 days was used for a common hydration period due to time constraints, consistent with Beddoe et al. (2010) and Beddoe et al. (2011). Fredlund et al. (2011) noted that soil specimens may transition from wetting curve to drying curve upon dehydration along a 'scanning curve'. Since small amounts of moisture likely escaped the double-bagged configuration over 30 days, it is possible that this would cause a right-ward shift in the wetting curve occurred. To reduce this effect over time and maintain hydration along the wetting curve, the overburden was removed from the GCL at 23 days, and one gram of hydration solution was sprayed on the bottom side of the GCLs. At the end of the 30 days, suction tests (described in Section 3.5) were performed on the GCL specimens.

3.3.2 GCL Specimen Preparation - Drying WRC

The GCL water desorption retention curve (drying curve) represents the suction behavior of a GCL specimen dehydrated from a completely saturated state. Specimens intended to produce data along the drying curve were saturated for a period of 30 days under 2 kPa overburden stress, then dehydrated, to simulate suction behavior during dehydration. Undesired dehydration of the GCL was prevented by limiting exposure to the atmosphere and by sealing each specimen in two plastic 1-liter bags. However, undesired dehydration of samples intended for the drying curve is essentially inconsequential because additional dehydration affects neither the position nor shape of the drying branch of the water retention curve.

A saturation setup was constructed for each GCL panel intended to be used for producing data along the drying curve. The perimeter of a 279 mm x 356 mm GCL panel was sealed with duct tape and placed carrier geotextile-side down in a clear plastic tub. Taped edges prevented bentonite leakage from the GCL panels and promoted even hydration throughout the panel. A 279 mm x 356 mm acrylic plate was drilled with holes spaced 25 mm apart and placed on top of the GCL. A layer of 0.1 mm (4 mil) plastic sheeting was placed on top of the acrylic plate, and evenly-distributed bags of sand producing 2 kPa of vertical stress were enclosed in the plastic sheeting. The acrylic plate allowed for evenly-distributed overburden while the drilled holes allowed the drainage of fluids (i.e., air and water) from the GCL panel during hydration and stress application conditioning. The plastic sheeting isolated water from the overburden material.

Porous material (multiple layers of grout stop netting) was placed above and the GCL, as well as between the acrylic sheet and plastic sheeting in order to allow equal access of moisture to the surface area of the GCL and to facilitate the escape of air bubbles through the acrylic plate. A lid was placed on each saturation setup and was sealed with a layer of shrink-wrap. The assembled saturation apparatus is presented in Figure 3.5.

Figure 3.5. Saturation Setup for Hydrating GCL Specimens for the Drying WRC (View from Cross-Section)

One of three hydration solutions (described in Section 3.2.3) was added to the saturation setup until the depth of solution was level with the top of the GCL panel. Additional solution was periodically added to the saturation setup until moisture uptake by the GCL ceased. To ensure maximum GCL saturation, the GCL panel remained in the saturation apparatus for at least 30 days, similar to the procedure from Beddoe et al. (2010).

After the hydration period, each GCL panel was removed from the saturation apparatus and samples were cut and prepared similar to specimens

described in Section 3.3.1. A sharp utility knife and cutting dies were used to obtain six 102 mm and two 51 mm circular specimens from each GCL panel, as illustrated in Figure 3.6.

Figure 3.6. Cutting GCL Specimens from Hydrated GCL Panels

Surface water was removed from each saturated GCL specimen with a paper towel. The saturated moisture content of the bentonite was determined from bentonite removed from the excess trimmings of each GCL panel. The perimeter of each GCL specimen was sealed with electrical tape to promote the equal distribution of moisture content upon dehydration. Volumetric readings consisting of six diameters and six thicknesses were measured with digital calipers for each GCL specimen upon completion of suction testing and prior to dehydration, as presented in Figure 3.7. Volumetric measurements allowed for the calculation of volumetric moisture parameters, such as: volumetric moisture content, degree of saturation, and bulk GCL void ratio (Petrov et al. 1997) and

the construction of water retention curves in terms of these volumetric parameters.

Figure 3.7. Volumetric Measurements Recorded with Digital Calipers

The estimated dry bentonite mass of each GCL specimen was determined from Eq. 3.1, where ω_{init} was the saturated bentonite moisture content collected from the GCL panel corresponding to the specimen.

Each GCL specimen was air-dried to a target moisture content based on the estimated dry bentonite mass and Eq. 3.2. The GCL specimens were placed on drying racks and a motorized fan was used to expedite dehydration. The specimens were periodically rotated and flipped to equalize dehydration across the specimens. The masses of the GCL specimens were measured to monitor the progress of dehydration. Once the specimens reached their target masses, the specimens were returned to their plastic bags to avoid excessive dehydration. Upon reaching the target dehydration moisture content, suction tests (Described in Section 3.5) were conducted on the GCL specimens.

3.3.3 GCL Specimen Preparation- Wet/Dry Cycles

Several GCL panels of the Bentomat DN (NN1) type were subjected to 20 wet-dry cycles prior to preparation described in Sections 3.3.1 and 3.3.2 in order to examine the effects of wet-dry conditioning on GCL water retention curves. The procedure for wet-dry cycling followed Olsen (2011) in order to compare strain behavior of this test program with that presented in Olsen (2011). GCL panels measuring 279 mm x 356 mm were cut from bulk samples of NN1 with a sharp utility knife, in the same manner as described in Section 3.3.1. The GCL panels were placed, unrestrained, on metal trays with the carrier geotextile oriented downward. Two reference marks in both the machine and cross-machine directions were made on the panels with spacings of 305 mm distances. Along the machine and cross-machine directions between the inner edges of the reference markers were recorded with digital calipers. These measurements were recorded initially and after each hydration and dehydration period in order to track strain after subsequent wet-dry cycles.

For drying cycles, the trays and GCLs were first transferred to a 60°C oven and dehydrated until less than 0.1% change in mass was achieved over a 1 hour period. Then for wetting cycles, the GCL panels were hydrated with a fine spray of de-ionized water applied to the top sides of the GCLs to approximately 50% gravimetric moisture content based on predictions from Eq. 3.1 and Eq. 3.2. GCL panels were hydrated for 8 hours on trays enclosed in large plastic bags. GCL panels dried adequately within 16 hours, resulting in a total of 24 hours to accomplish one hydration and one drying cycle. Multiple wet-dry cycles induced

curling at GCL edges, but the zone of strain measurements at central locations on the panels was subject to minimal distortion from curling. When curling was present at the location of the reference markers, the caliper points were gently pushed down at the location of the markers to flatten the measurement surface. The GCL panels were each exposed to 20 complete wet-dry cycles, then further suction test preparation was performed according to procedures detailed in Section 3.3.1 and 3.3.2.

3.3.4 GCL Specimen Preparation - Temperature Tests

Approximately 60 GCL specimens were hydrated in DI water at 20°C for 30 days, according to procedures outlined in Sections 3.3.1 and 3.3.2, and were then subjected to further conditioning at either a low temperature (2°C) or at a high temperature (40°C). GCL specimens were sealed in two plastic bags under 2 kPa overburden and were exposed to temperature conditioning in an insulated chamber for a period of 24 hours plus the duration of each suction test (described in Section 3.5). The objective of conditioning previously-hydrated GCL specimens at high and low temperatures was to determine the effect of temperature on the shape of GCL water retention curves when compared to water retention curves at 20°C.

The insulated chamber was designed to minimize temperature fluctuations for temperature conditioning and suction testing at 2°C and 40°C. The chamber was constructed from a modified 305 mm x 914 mm x 356 mm cooler with 38 mm thick insulated walls. Perforated aluminum sheets were placed on top of bricks at the bottom of the chamber. A small fan circulated air throughout the

chamber. The fan and the holes in the sheets allowed airflow within the chamber, while the relatively thick sheet provided a rigid surface on which to place the GCL specimens. The bricks beneath the sheets served two purposes: a) provide stable heat storage, and b) elevate the sheets to allow loops of flexible copper pipe to pass above and below the sheets. A dual refrigeration and cooling apparatus was used to circulate a 50% mixture (by weight) of propylene glycol and water through the copper pipes. Propylene glycol, an antifreeze, was necessary to maintain flow of the refrigerant solution during the 2°C tests. An auxiliary submersible pump increased flow through the copper pipes. The apparatus was carefully designed to achieve temperature equilibrium within the chamber and resist daily temperature fluctuations of more than $\pm 0.5^\circ\text{C}$.

Figure 3.8. Temperature Control Box Consisting of an Insulated Box, Copper Pipe, and a Dual Heater and Cooler

GCL specimens were strategically placed in the insulated chamber to avoid temperature gradients across the specimens. For pressure plate tests

(described in Section 3.5.1), the pressure plate extractor was wrapped evenly in the copper pipe in order to achieve constant temperature within the extractor. For filter paper tests and relative humidity tests, it was observed that GCL bags placed in direct contact with the aluminum sheet exhibited higher temperatures at the contact surface and lower temperatures away from the contact surface, which often led to the formation of condensation on the GCL, itself. To avoid this, an additional wooden plate was placed below each GCL specimen to insulate the GCL from concentrated heat sources and thereby reduce temperature gradients across the GCL specimens. 2 kPa overburden stress was applied to the specimens with bricks in the same manner as described in Sections 3.3.1 and 3.3.2. Temperatures immediately above and below the GCL specimens were monitored with thermocouples attached to a data logger. Due to heat loss in the system, the control apparatus was set to -6.8°C or 47.2°C to achieve temperatures of 2°C or $40^{\circ}\text{C} \pm 1^{\circ}\text{C}$, respectively in the GCL specimens. At the completion of the 24-hour temperature conditioning, GCL specimens for the filter paper test and relative humidity test were quickly removed from their bags, were wiped free of any visible condensation, and returned to their bags. This process was completed within the confines of the chamber to avoid heat loss (or gain) that would otherwise induce problematic condensation on the rest of the GCL specimens. Specimens were accessed from the top of the chamber with an acrylic plate equipped with two gasketed holes. The acrylic plate reduced the escape of heat from the chamber, and the gasketed holes allowed manual access to the specimens. It was assumed that after 24 hours, the specimens had

equilibrated with the temperature environment intended for testing, and were ready for suction testing at 2°C and 40°C.

3.4 Soil Specimen Preparation

The soils described in Section 3.2.2 were prepared to moisture contents and unit weights listed in Table 3.6. Compaction criteria for SP and CL corresponded with previous research by Olsen (2011), while compaction criteria for SC1 and SC2 represented approximate field compaction conditions from the landfill cover system from which they were exhumed. Prior to compaction, the soils were allowed to hydrate in sealed plastic bags for at least 16 hours. The soils were compacted into brass sample rings, then suction tests were performed on the soils, according to Section 3.5.

Table 3.6. Compaction of Soil Specimens

Soil Name	Target Molding Water Content (%)	Target Dry Unit Weight (kN/m ³)	Measured Molding Water Content (%)	Measured Dry Unit Weight (kN/m ³)
SP	Multiple Values	16.3	Multiple Values	16.3
CL (dry of optimum)	6.8	14.6	6.7	14.9
CL (wet of optimum)	18.6	17.0	19.1	17.3
SC1	14.5	15.5	14.1	15.5
SC2	15.0	16.4	13.8	17.1

Custom compaction methods were pursued in order to achieve the relatively low densities listed in Table 3.6. The altered compaction scheme included a reduction in the number of applied blows per lift, as well as a reduction in the number of lifts compared to the standard compaction effort using ASTM D

698. The experimental compaction efforts were selected in order to correctly model the desired soil fabric and to ease sampling of the compacted soil.

Soil compaction and sampling methods varied among the soil types based on the ease of transferring compacted soils to the individual brass sample ring. The brass rings, measuring 63.4 mm (2.5 in.) outer diameter x 25.4 mm (1 in.) high with 1.0 mm (0.04 in.) ring wall thickness, were selected to contain specimens during testing. The size of the brass rings was selected to be wide enough to perform the filter paper suction test (described in Section 3.5.2), yet short enough to maintain relatively short equilibrium times during the pressure plate test (described in Section 3.5.1). The brass rings were also durable which allowed soil to be compacted directly in the rings or held firmly in place during sample trimming. The remainder of Section 3.4 describes how compaction technique and sampling of soils varied for each soil.

3.4.1 Preparation of Sand (SP)

Poorly graded sand (SP) was tamped into brass rings to achieve a unit weight of $16.3 \text{ kN/m}^3 \pm 0.3 \text{ kN/m}^3$. The dry density was selected for consistency with subgrade tests from Olsen (2011). SP samples were compacted in either dry or moist conditions because molding water content was assumed to not affect water retention for cohesionless sand. The target dry unit weight of SP was plotted alongside the compaction curve of SP using standard effort, as presented in Figure 3.9. The lack of cohesion required SP specimens to be prepared differently than CL, SC1, and SC2 specimens.

Figure 3.9. Compaction of SP

Specimen preparation for the wetting branch of the water retention curve involved mixing a known mass of dry sand with a known mass of tap water. The soil-water mix was tamped into the brass ring of known volume, until achieving the dry unit weight of 16.3 kN/m^3 , then sealed in two plastic bags, leveled with the straightedge, and allowed to hydrate for at least 24 hours.

Specimen preparation for the drying branch of the water retention curve involved tamping dry sand, of known mass into the brass rings of known volume, directly on the pressure plate apparatus as described in ASTM D6836. Tamping was performed with a small, flat weight and the top of the sample was leveled with a stiff, metal straightedge. Several layers of window screen were placed on top of each sand specimen, and a 2 kPa overburden was distributed over each sample with a small aluminum plate. Up to 6 specimens were placed within the pressure plate extractor using this configuration. SP specimens intended for producing drying curve data were hydrated by inundation on a pressure plate for 24 hours, further described in Section 3.5.1. Some SP specimens were partially-dehydrated during the pressure plate test, removed from the pressure plate extractor, air-dried to residual water content conditions, then subjected to the relative humidity test, per Section 3.5.3.

3.4.2 Preparation of Clay (CL) Compacted at Dry-of-Optimum Conditions

Low plasticity clay (CL) samples, compacted dry-of-optimum moisture content, were prepared for suction testing using two methods: a) compacted, then hydrated by spraying, or b) compacted, then hydrated by inundation on a pressure plate. Tap water was used in the hydration of CL for consistency with Olsen (2011).

The method for compacting dry-of-optimum CL was chosen to represent soil structure and density conditions from subgrade testing performed in Olsen (2011). Air-dry CL was hydrated with tap water and mixed until achieving the target moisture content of 6.8%. The moist soil was separated into 1800 g

samples then sealed in plastic bags for at least 16 hours. 500 g of soil was placed in the bottom of a 152.4 mm (6 in.) diameter compaction mold and loosely leveled. Three brass rings were placed, side-by side, on top of the base soil. The remaining 1300 g of soil was placed over the rings and loosely leveled. 16 blows with a 24.5 kN (5.5 lb) hammer were applied to the soil in a single lift, from a drop height of 304.8 mm (12 in.), in a pattern resembling that of ASTM D698. The soil column was extruded with a hydraulic jack, and trimmed to remove the three embedded specimen rings. Dry-of-optimum CL specimens tended to crumble when excess soil was removed from around the brass rings. The small voids exposed by crumbling were filled with excess CL that was processed through a 0.425 mm sieve and the specimens were leveled with a metal straight-edge. Moisture contents were determined from excess CL trimmings. Specimens were weighed to ensure that dry density was within $14.6 \text{ kN/m}^3 \pm 0.5 \text{ kN/m}^3$. The resulting unit weight and moisture content of the experimental compaction procedure are plotted alongside the laboratory compaction curve for CL, as presented in Figure 3.10. The compacted specimens do not lie on the compaction curve because the compaction scheme for preparing specimens was designed to be consistent with subgrade test specimens from Olsen (2011) which did not achieve target compaction values.

Figure 3.10. Compaction of CL

Hydration of CL specimens used for the wetting branch of the water retention curve involved spraying each side of the sample with tap water to a targeted moisture content. For samples for which the target moisture content was less than the molding water content, samples were dried in a 60°C oven until constant mass was observed over a 1 hour period (i.e., effectively dry). Then, the specimens were sprayed with tap water to their targeted moisture content. This

procedure ensured that all wetting branch samples followed a wetting path to their targeted moisture content.

Hydration of CL specimens used for the drying branch of the water retention curve involved inundation of specimens directly on a pressure plate, as described in Section 3.5.1. The specimens and pressure plate were placed within the pressure plate extractor, then several layers of window screen were placed on top of each CL specimen, and a 2 kPa overburden was distributed over each specimen with a small aluminum plate. Window screen was used to allow air to escape from the soil samples during saturation. The extractor was filled with tap water until level with the bottom of the CL samples. Tap water was added in 3 mm increments over a period of several hours until level with the top of the CL samples. Specimens were hydrated for 24 hours which allowed CL specimens to swell and expel pore air from the top of the sample and through the window screen. Previous experience and degree-of-saturation calculations validated that inundation was sufficient to fully saturate CL dry-of-optimum specimens. Vacuum saturation of CL specimens at dry-of-optimum conditions was not performed due to the risk of sloughing.

3.4.3 Preparation of Clay (CL) Compacted at Wet-of-Optimum Conditions

Sandy lean clay (CL) specimens, compacted wet-of-optimum moisture content, were prepared for suction testing using two methods: a) compacted into brass rings, dried in a 60°C oven, then hydrated by spraying, or b) compacted into brass rings, then hydrated by vacuum in a saturation chamber. Tap water was used in the hydration of CL for consistency with Olsen (2011).

The method for compacting wet-of-optimum CL was chosen in order to reproduce soil structure and density conditions from subgrade testing performed in Olsen (2011). Air-dry CL was hydrated with tap water and mixed until achieving the target moisture content of 18.6%. The moist soil was separated into 1600 g specimens then sealed in plastic bags for at least 16 hours. 500 g of soil was placed in the bottom of a 152 mm (6 in.) diameter compaction mold and loosely leveled. Three brass rings were placed, side-by side, on top of the base soil. The remaining 1100 g of soil was placed over the rings and loosely leveled. 40 blows with a 24.5 kN (5.5 lb) hammer were applied to the soil in a single lift, from a drop height of 305 mm (12 in.), in a pattern resembling that of ASTM D698. The soil column was extruded with a hydraulic jack, the excess soil was carefully removed from around the sample rings with a wire saw, and the samples were leveled. The prepared specimens were weighed to ensure that dry density was within $\pm 0.5 \text{ kN/m}^3$ of 17.0 kN/m^3 . The experimental compaction results for wet-of-optimum CL were plotted alongside the CL compaction curve are presented in Figure 3.10. Moisture content of the compacted CL was measured in order to determine the amount of water to apply to each CL sample during hydration.

Hydration of CL specimens used for the wetting branch of the water retention curve involved drying samples in a 60°C oven and spraying each side of the specimen with tap water to a targeted moisture content. Specimens were dried in a 60°C oven until constant mass was observed over a 1 hour period and the specimens were effectively dry. Then, the specimens were sprayed with tap

water to their targeted moisture content. This procedure ensured that all wetting branch specimens followed a wetting path to their targeted moisture content.

Hydration of CL specimens used for the drying branch of the water retention curve involved vacuum-aided saturation in a saturation chamber. Vacuum-aided saturation was necessary to saturate the CL specimens due to the low hydraulic conductivity of the CL compacted at wet-of-optimum conditions. The saturation chamber was constructed of a sealed, pressure-rated vessel connected to a motor-operated pump capable of applying 275 kPa (40 psi) of vacuum pressure. Two compacted CL specimens were placed in the saturation chamber, then several layers of window screen were placed on the top and bottom of each CL specimen, and a 2 kPa overburden was distributed over each specimen with a small aluminum plate. The assembled saturation chamber and specimens are illustrated in Figure 3.11.

Figure 3.11. Soil Specimens in Brass Rings Hydrating in a Saturation Chamber

Tap water was filled to a height of 10 mm above the CL specimens in order to observe escaping pore air. The saturation chamber was tilted and gently shaken to assist escaping pore air. Vacuum pressure of 275 kPa (40 psi) was applied until pore air no longer escaped from the specimen (typically after 20 minutes). The degree of saturation was calculated to ensure that the specimens were fully saturated. Saturated CL specimens were transferred to a pressure plate and suction testing was performed according to Section 3.5.1.

3.4.4 Preparation of Landfill Cover Sand (SC1)

Yellow clayey sand (SC1) was prepared for suction testing using two methods: a) compacted into brass rings, dried in a 60°C oven, then hydrated by spraying, or b) compacted into brass rings, then hydrated by vacuum in a saturation chamber. SC1 soil was hydrated with deionized water in order to retain the original pore fluid chemistry of the soil. SC1 soil was exhumed from the landfill test plot, delivered to the laboratory in a sealed plastic container, then processed prior to use in suction testing. The as-compacted moisture content and dry unit weight at the test plot were 14.5% and 15.5 kN/m³, respectively (Abichou 2013).

In order to simulate the relatively loose field placement conditions for SC1, specimens were compacted in the laboratory with reduced effort. Bulk, moist soil was processed through a 9.5 mm (3/8 in.) sieve in order to break up soil clods and remove oversized particles. As-received moisture content of SC1 was 23.7%, so the soil was spread out in large tray, dehydrated to the targeted 14.5% moisture content in a 60°C oven, and mixed frequently. The conditioned soil was

split into 2000 g samples and sealed in plastic bags for at least 16 hours. Each 2000 g sample was compacted in a 102 mm (4 in.) mold, in three equal lifts with a 24.5 kN (5.5 lb) hammer, from a drop height of 305 mm (12 in.). 8 blows were delivered per lift in a pattern resembling that of ASTM D698.

The compacted sample was removed from the compaction mold with a hydraulic jack and trimmed to approximately 76 mm (3 in.) diameter with a metal spatula. The end of the metal spatula was cut so that a small metal point protruded from the bottom side of the spatula, as presented in Figure 3.12. The length of this point was slightly less than the (1 mm) wall thickness of the brass ring so that when dragged along the bottom perimeter of the brass ring, the compacted specimen was trimmed to 64 mm (2.5 in.) diameter. The compacted sample was trimmed with this tool in a method suggested by ASTM D6836 for disturbed samples compacted in the laboratory. By applying light pressure to the brass ring during the trimming process, the brass ring was fit snugly to the compacted sample. After the brass ring was completely fitted to the compacted sample, a thin wire saw was used to remove the trimmed specimen from the rest of the compacted specimen. The ends of the specimen were leveled with a metal straightedge, weighed, then placed in a sealed plastic bag. Three SC1 specimens could be obtained from each compacted sample. Moisture contents were determined from extra cuttings from the compacted sample. The dry unit weights and moisture contents of the SC1 specimens obtained from the experimental compaction procedure are plotted alongside the compaction curve for SC1 using standard effort, as presented in Figure 3.13.

Figure 3.12. Trimming Compacted SC1 to Obtain Ring-Lined Specimens

Figure 3.13. Compaction of SC1

Hydration of SC1 specimens used for the wetting branch of the water retention curve involved drying samples in a 60°C oven and spraying each side of the specimen with deionized water to a targeted moisture content. Specimens were dried in a 60°C oven until effectively dry. Then, the specimens were sprayed with deionized water to their targeted moisture content. This procedure

ensured that all wetting branch specimens followed a wetting path to their targeted moisture content.

Hydration of SC1 specimens used for the drying branch of the water retention curve involved vacuum-aided saturation in a saturation chamber, as described in Section 3.4.3. However, deionized water, instead of tap water, was used to hydrate the SC1 samples in the saturation chamber. Degree-of-saturation calculations validated that the saturation chamber was sufficient to fully saturate the SC1 samples. Saturated SC1 samples were transferred to a pressure plate and suction testing was performed according to Section 3.5.1.

3.4.5 Preparation of Landfill Cover Sand (SC2)

Orange clayey sand (SC2) was prepared for suction testing using two methods: a) compacted into brass rings, dried in a 60°C oven, then hydrated by spraying, or b) compacted into brass rings, then hydrated by vacuum in a saturation chamber. SC2 soil was hydrated with deionized water in order to retain the original pore fluid chemistry of the soil. SC2 soil was exhumed from the landfill test plot, delivered to the laboratory in a sealed plastic container, then processed prior to use in suction testing. The as-compacted moisture content and dry unit weight at the test plot were 15.0% and 16.4 kN/m³, respectively (Abichou, 2013).

In order to simulate these relatively loose field placement conditions for SC2, samples were compacted in the laboratory with reduced effort, as described in Section 3.4.4, but with the following modifications. As-received moisture content of SC2 was 17.2%, so the soil was spread out in large tray,

dehydrated to the targeted 15.0% moisture content in a 60°C oven, and mixed frequently. The conditioned soil was split into 2200 g samples and sealed in plastic bags for at least 16 hours. Each 2200 g sample was compacted in a 102 mm mold, in three equal lifts with a 24.5 kN hammer, from a drop height of 305 mm. 11 blows were delivered per lift in a pattern resembling that of ASTM D698. Each compacted sample was removed from the compaction mold, trimmed with the modified spatula tool, and separated into brass rings, which yielded three 63.5 mm specimens. Moisture contents were determined from extra cuttings from the compacted sample. The dry unit weights and moisture contents of the SC2 specimens obtained from the experimental compaction procedure are plotted alongside the compaction curve for SC2 using standard effort, as presented in Figure 3.14.

Figure 3.14. Compaction of SC2

Hydration of SC2 specimens used for the wetting branch of the water retention curve involved drying specimens in a 60°C oven and spraying each side of the specimen with deionized water to a targeted moisture content. Specimens were dried in a 60°C oven until effectively dry. Then, the specimens were sprayed with deionized water to their targeted moisture content. This

procedure ensured that all wetting branch specimens followed a wetting path to their targeted moisture content.

Hydration of SC2 specimens used for the drying branch of the water retention curve involved vacuum-aided saturation in a saturation chamber, as described previously in Section 3.4.3. Deionized water, instead of tap water, was used to hydrate the SC2 specimens in the saturation chamber. Degree-of-saturation calculations validated that the saturation chamber was sufficient to fully saturate the SC2 specimens. Saturated SC2 specimens were transferred to a pressure plate and suction testing was performed according to Section 3.5.1.

3.5 Test Methods

The following test program describes four types of suction tests that were performed on both GCLs and soil samples. GCL samples and soil samples were conditioned according to Sections 3.3 and 3.4, respectively, then subjected to one of four tests: the pressure plate test (ASTM D6836), the filter paper test (ASTM D5298), the relative humidity test, or a series of measurements to determine the gravimetric moisture content, volumetric moisture content, and bulk GCL void ratio at the fully-saturated condition. The combined results of these tests defined the shapes of water retention curves. A best-fit process was used to fit water retention curves to the suction data.

Three types of tests were performed on bentonite from GCL specimens that were prepared according to Sections 3.3.2 and 3.3.3. Swell index tests (ASTM D 5890), liquid limit and plastic limit tests (ASTM D4318), and SEM imaging of bentonite microstructure were performed on bentonite extracted from

GCL panels that were submerged in hydration solutions described in Section 3.2.3, and prepared according to Section 3.3.2. Results from these bentonite-based tests were used in conjunction with results from suction testing in order to further explain water retention behavior for GCLs.

3.5.1 Pressure Plate Suction Test for GCLs and Soils

A 500 kPa (5 bar) pressure plate extractor equipped with either a 50 kPa (0.5 bar) plate or a 300 kPa (3 bar) plate was used to determine water retention behavior of GCLs and soils in the suction range of 5 kPa to 300 kPa. Suction tests using this apparatus followed guidelines specified in Method C of ASTM D6836 and operational instructions given by the manufacturer (SoilMoisture Equipment Corp 2008). Air pressure was supplied by an air compressor and large storage tank.

Controlling Pressure for the Pressure Plate Extractor

The apparatus to perform the pressure plate test includes a pressure manifold, ceramic pressure plate(s), and the pressure extractor. The pressure manifold contains valves and regulators to control the flow of pressurized air to the extractor. Saturated pressure plates were placed in the extractor, connected to the outflow ports, and sealed in the extractor by bolting the extractor lid to the extractor base. To deliver pressurized air to the extractor, the air valve at the extractor was closed, the regulators were set to the desired air pressure, and the supply valve was slowly opened. Conversely, to evacuate air from the extractor, the valve at the compressed air source was closed, the air valve to the extractor

remained open, the pressure regulators were set to zero until all of the pressure was released from the regulator and pressure plate extractor.

Saturation and Check of Ceramic Pressure Plates

The porous ceramics of the pressure plates were fully-saturated prior to suction testing. An initially air-dry pressure plate was soaked in a metal bowl in the same hydration solution as the suction test specimens for 30 minutes. The pressure plate was then placed upon the lowest set of rungs in the pressure extractor and flexible rubber tubing was connected from the pressure plate outflow port to the pressure extractor outflow port. Additional hydration solution was de-aired with a motorized vacuum pump and agitator until dissolved air dissipated. The de-aired hydration solution was poured into the pressure extractor until it covered the pressure plate by approximately 75 mm. The pressure plate and the samples were hydrated in the same solution in order to avoid inducing an osmotic gradient between the plate and specimens during testing. The lid of the pressure extractor was placed on the base and secured with bolts. The air pressure was set to 75 kPa on the pressure manifold, and the supply valve was slowly opened to supply air pressure to the extractor. After 30 minutes, this pressure was increased to at least the pressure intended for use in the suction test. Pressure was applied to the plate for at least 24 hours and solution expelled from the outflow port was drained into a large bowl. If more hydration solution was required during saturation, the pressure extractor was depressurized, opened, and additional de-aired solution was added to submerge the pressure plate. For quality control purposes, the hydraulic conductivity of the

pressure plate was calculated based on the dimensions of the porous ceramic and outflow volume measured over a few minutes.

In order to avoid damaging the ceramic, the applied air pressure never exceeded the pressure rating of the plate. Since ASTM D6836 requires at least 75 kPa air pressure to be applied during saturation, an alternative method was pursued for saturating the pressure plate rated to 50 kPa. The 50 kPa plate was submerged in de-aired hydration solution and the solution was drawn through the plate with a hand-held vacuum pump directed to an Erlenmeyer flask. De-aired solution was drawn through the pressure plate until air bubbles were no longer visible in the outflow tubing from the pressure plate.

Performing the Pressure Plate Test

Fully-saturated GCL specimens or fully-saturated soil specimens (prepared according to Section 3.3 or 3.4, respectively) were placed on top of the fully-saturated pressure plate. GCLs were placed with their carrier geotextiles in contact with the plate surface. Each sample was twisted slightly on the pressure plate in order to promote good hydraulic contact between the sample and the pressure plate. Up to six 64-mm-diameter soil specimens or six 51-mm-diameter GCL specimens were tested on a single pressure plate, but only specimens possessing similar soil properties were tested simultaneously. Window screen and weights producing 2 kPa overburden stress were placed over the samples. The pressure extractor was sealed, and excess water was removed from the plate using a small syringe. The specimens were allowed to equilibrate in the pressure extractor at atmospheric pressure for 48 hours.

At the end of 48 hours, the air pressure supply valve was closed, the pressure regulators were set to the initial desired pressure, then the air pressure supply valve was opened. (Note: at least two soil specimens were removed after the 48 hour equilibrium time to determine the saturated moisture content as described in Section 3.5.4). The pressure plate tests were generally performed at suctions of 6 kPa, 10 kPa, 30 kPa, 50 kPa, 100 kPa, and 300 kPa for soil specimens. The pressure plate tests were generally performed at suctions of 30 kPa and 100 kPa for GCL specimens.

Upon the application of pressure, moisture from the plate and from the samples was expelled from the extractor. For monitoring purposes, it was useful to collect this water in either a graduated cylinder or a system of horizontal tubing with an air release valve. The air pressure was applied until the outflow ceased for at least 24 hours. At the completion of 24 hours, the pressure extractor was de-pressurized, the outflow tube was clamped to prevent backflow, and a few specimens were removed and weighed. The pressure extractor was sealed with the remaining specimens, then the pressure plate test was repeated at a higher pressure. Specimens were not reused (i.e. removed and returned to position) within the extractor due to the risk of losing hydraulic contact between the sample and the pressure plate. Moisture-suction data were determined by measuring the equilibrium moisture content of the specimen at the applied air pressure, i.e. applied suction.

3.5.2 Filter Paper Suction Tests for GCLs and Soils

The contact filter paper test was performed to measure matric suction of either GCL specimens or soil specimens in the suction range of 10 kPa to 10,000 kPa. The procedure for performing the filter paper test on GCLs was based on ASTM D5298 and Barroso (2006), with modifications to the number of filter papers used, and the number of specimens used. The procedure for performing the filter paper test on soils adhered to ASTM D5298. The technique involved placing a filter paper in contact with a GCL specimen or two soil specimens (previously prepared according to Section 3.3 or Section 3.4) until suction equilibrium was attained between the filter paper and the specimen. A 7-day matric suction equilibrium period was selected based on ASTM D5298 and an investigation of matric suction accuracy by Leong et al. (2002). The filter papers used in this test program were Whatman grade 42 discs of 55 mm in diameter that were not exposed to biocides. Contamination of filter papers was avoided by using metal tweezers during handling. Moisture-suction data were constructed by determining the moisture content of the specimen and the suction of the specimen at the conclusion of the 7-day equilibrium period, where suction was calculated from the filter paper's moisture content using a pre-determined calibration curve.

Filter Paper Calibration

The contact filter paper method is an indirect measurement of matric suction; therefore a calibration curve is necessary to relate the moisture content of the filter paper to the suction of the filter paper (equivalent to the suction of the

specimen). The calibration curve proposed by Haghighi et al. (2012) was selected because it incorporates temperature effects necessary to conduct temperature-dependent suction tests. The calibration curve produced by Haghighi et al. (2012) is described by Eq. 3.3,

$$Ln\psi = \frac{(a + b * W_f + c * T + d * W_f * T)}{(1 + f * W_f + g * T + h * W_f * T)} \quad (3.3)$$

where: ψ_m is suction (kPa); a , b , c , d , f , g , and h are dimensionless fitting parameters; W_f is the filter paper gravimetric moisture content, and T is the temperature in Kelvin.

An adjustment was made to this calibration curve to account for the effect of the 2 kPa overburden stress used in this test program, as suggested by Power et al. (2008). During the calibration curve-fitting process, the calibration curve parameters and suction values were held constant, while the moisture content W_f was multiplied by 1.15 to account for the difference between filter papers with 2 kPa overburden compared to filter papers without overburden, based on Power et al. (2008). New fitting parameters were assigned to the corrected data points by fitting a curve based on Eq. 3.3 using the Solver function in Microsoft Excel and are presented in Table 3.7. The final calibration curves, corrected for both temperature and overburden effects, are presented in Figure 3.15. The ASTM D5298 calibration curve is included for reference.

Table 3.7. Filter Paper Calibration Parameters

Parameter	Baseline Parameters ^a	20°C, 2 kPa Overburden Correction	2°C, 2 kPa Overburden Correction	40°C, 2 kPa Overburden Correction
a	10.8616232	10.8616232	10.8616232	10.8616232
b	-0.0637635	-0.0637635	-0.0637635	-0.0637635
c	-0.0405607	-0.04056072	-0.04056071	-0.04056073
d	0.00021864	0.00021851	0.00021861	0.00021843
f	0.01908312	0.01908313	0.01908312	0.01908313
g	-0.0036483	-0.00364805	-0.00364817	-0.00364795
h	-0.0000765	-0.000075064	-0.000075698	-0.000074407

^aParameters obtained from Haghighi et al. (2012)

Figure 3.15. Filter Paper Calibration Curves Based on Temperature, Corrected for 2 kPa Overburden Stress

Filter Paper Test Apparatus

Two types of test apparatuses were constructed for the filter paper test: one for non-standard filter paper tests on GCL specimens, and one for standardized filter paper tests on soil specimens per ASTM D5298. There were two separate goals when constructing the apparatuses: a) increase accuracy for the filter paper test on GCL specimens, and b) maintain consistency with the ASTM D5298 standard for filter paper tests on soil specimens. The two apparatuses are presented in Figure 3.16.

Figure 3.16. Filter Paper Suction Test Apparatuses (View of Cross-Section)

The apparatus for the filter paper test on GCLs consisted of a single GCL specimen and four filter papers that were enclosed in two nested plastic bags. For each filter paper test on GCLs, a single 102-mm-diameter specimen was prepared according to Section 3.3. Single GCL specimens were used for the filter paper test in order to eliminate the possibility of moisture variation between dual GCL specimens, observed by Barroso (2006). The GCL specimen was placed

with the carrier geotextile facing down on a 127-mm- diameter acrylic plate. A stack of four oven-dried filter papers was placed between the carrier geotextile and the acrylic plate. The outer two filter papers were used to protect the two inner filter papers from bentonite and miscellaneous debris. The advantage of using two inner filter papers (versus one, specified in ASTM D5298) is the ability to measure suction twice for one specimen to identify a poor test (scatter in filter paper moisture content). Power et al. (2008) indicated that this may increase accuracy of the suction measurements. The GCL specimen, stack of filter papers, and acrylic plate were placed in two nested plastic bags, and a small amount of water was sprayed between the bags to reduce moisture loss from diffusion.

For each filter paper test on soil, two 64-mm diameter soil specimens of similar moisture content were prepared according to Section 3.4. The specimens were placed on top of each other and sealed in a plastic bag for 24 hours to reduce small variations of moisture content between the two specimens. For testing, the soil specimens were separated and a stack of 3 oven-dried filter papers were inserted between the soil specimens. The inner filter paper was cut slightly smaller than the cover filter papers in order to prevent direct contact with the soil. The stack of soil specimens and filter papers was sealed in two plastic bags. The suction of the soil specimen and of the filter papers was allowed to equilibrate over a period of 7 days for all tests.

Intimate contact between the specimens and the filter papers was achieved by the application of a 2 kPa overburden stress on the plastic bag

apparatus to accelerate suction equilibrium between the specimen and the filter papers. The overburden consisted of the weight of a brick distributed evenly over the specimen by a (102-mm-diameter wooden, or 64-mm-diameter aluminum) plate placed over the exterior of the plastic bags. Each weight and bag assembly was maintained at an ambient temperature of approximately 20°C, with less than 3°C variation, per ASTM D5298. For temperature-dependent tests, the ambient temperature was maintained at either 2°C or 40°C with less than 1°C variation in the temperature control box described in Section 3.3.4. The suction of the specimens and of the filter papers was allowed to equilibrate over a period of 7 days.

Figure 3.17. Filter Paper Suction Tests for Multiple GCL Specimens

Filter Paper Test Measurements

At the conclusion of the 7-day suction equilibrium period, the specimens were removed from the plastic bags. The mass of a metal moisture tin and lid, T_c , was measured with a scale accurate to 0.0001 g. Each inner filter paper was

quickly transferred to the moisture tin and the lid was closed to reduce error from evaporation. The combined moist mass of the filter paper and the tin, M_1 , was measured and the filter papers were dried in their tins, with lids slightly ajar, in a 110°C oven for at least 2 hours. At the completion of two hours, the tin lids were closed and were placed back in the oven for 15 minutes. Each tin was removed individually and cooled for exactly 1 minute. The combined dry mass of the hot tin and the filter paper, M_2 , was measured, as well as the mass of the hot tin with the filter paper removed, T_h . The moisture content of the filter paper, W_f , was calculated by Eq. 3.4,

$$W_f = 100 * \frac{m_w}{m_f} = 100 * \frac{M_2 - T_h}{M_1 - M_2 + T_h - T_c} \quad (3.4)$$

where m_w is the mass of water in the filter paper and m_f is the mass of the dry filter paper. Moist mass and dry mass measurements of the specimens were recorded in order to determine the gravimetric moisture content. The volume of each GCL specimen was determined using six diameter and six thickness measurements that were recorded with digital calipers. Volumetric moisture content, bulk GCL void ratio, and degree of saturation were calculated for each GCL specimen from the volumetric measurements.

3.5.3 Relative Humidity Test for GCLs and Soils

The relative humidity tests were conducted to determine total suction of GCL specimens and of soil specimens in the high suction range of 5,000 kPa to 400,000 kPa. Relative humidity was measured with a Lascar EL-USB-2-LCD+ device equipped with a Sensirion SHT15 relative humidity and temperature

sensor. The sensor is capable of measuring relative humidity from 10 to 90% at an accuracy of $\pm 2\%$ RH. The sensor measures relative humidity at an accuracy of $\pm 4\%$ at relative humidity below 10% or above 90%. The temperature sensor is accurate to $\pm 0.5^{\circ}\text{C}$ for temperatures between 0°C and 40°C . The device is presented in Figure 3.18.

Figure 3.18. Relative Humidity Device

Checking the Factory Calibration

The factory calibration of the relative humidity device was verified prior to testing. A two-point check was performed by suspending the relative humidity sensor above salt solutions in a small, sealed container. Magnesium chloride and sodium chloride solutions were prepared according to ASTM E104 to subject the sensor to low and high relative humidities, respectively. The sensor was suspended for at least 12 hours above the solution. The published relative humidities of saturated magnesium chloride and saturated sodium chloride salts are 33.1% and 75.5% at 20°C , respectively. The calibration was verified when the relative humidity recorded by the sensor matched the relative humidity of the two salt solutions.

Measuring Relative Humidity of GCLs and Soils

The relative humidity test was performed on GCL specimens or soil specimens that were prepared according to Sections 3.3 or 3.4, respectively. Specimens were placed in two nested plastic bags. Water was not sprayed between the bags because moisture loss due to diffusion was negligible. Plastic bags were selected as the test enclosure to minimize equilibrium time by reducing air space above the specimens. The relative humidity sensor was activated on a computer and sealed in the plastic bags with the specimen. The sensor end of the relative humidity device was centered over a specimen, as presented in Figure 3.19.

Figure 3.19. Relative Humidity Test Apparatus for GCL and Soil Specimens

GCL specimens were oriented so that the carrier geotextile was facing up, toward the relative humidity sensor. The sensor recorded relative humidity and temperature measurements every 5 minutes for a period of 12 hours which was typically enough time to attain humidity equilibrium in the plastic bag apparatus.

At the end of the equilibrium period, the relative humidity device was removed, the final relative humidity and temperature were recorded, and the total suction, ψ (kPa) was calculated using Eq. 3.5,

$$\psi = -\frac{RT}{\nu_{w0}\omega_v} \ln\left(\frac{rh}{100}\right) \quad (3.5)$$

where: R is the universal gas constant, T is the temperature (K), rh is the relative humidity (%), ν_{w0} is the specific volume of water (m³/kg), and ω_v is the molecular mass of water vapor (kg/kmol). Values for the constants used in Eq. 3.5 are listed in Table 3.8.

Table 3.8. Constants Used in Eq. 3.5

Term	Value	Unit
R	8.31432	J/(mol•K)
ν_{w0} at 20°C	998.2	m ³ /kg
ν_{w0} at 2°C	1000	m ³ /kg
ν_{w0} at 40°C	992.2	m ³ /kg
ω_v	18.016	kg/kmol

Similar to the filter paper test procedure, moist and dry mass measurements for both GCL and soil specimens were recorded in order to calculate the gravimetric moisture content associated with the total suction from the relative humidity test. Volumetric measurements were recorded for GCL specimens in order to calculate volumetric moisture content, bulk GCL void ratio, and the degree of saturation associated with the total suction from the relative humidity test. Moisture-suction data were constructed by pairing the moisture

content of the specimen with the total suction calculated from the relative humidity test.

3.5.4 Saturated Moisture Content

The moisture content axis intercept of each water retention curve was determined from fully-saturated GCL specimens. It was assumed that GCL panels were fully-saturated after a hydrating period of 30 days (i.e. prepared according to Section 3.3.2) and the corresponding suction of the saturated GCL had diminished nearly to zero. The moisture content of fully-saturated GCL specimens was assumed to correspond to a suction of 1 kPa, consistent with assumptions made by Beddoe et al. (2011). Gravimetric moisture content was determined from saturated and dry mass measurements. Volume of GCL specimens was determined using six diameter and six thickness measurements that were recorded with digital calipers. Volumetric moisture content, bulk GCL void ratio, and degree of saturation were calculated for each GCL specimen from the volumetric measurements.

The gravimetric moisture content at 1 kPa suction also was determined for the soils described in Section 3.4. Specimens were compacted and hydrated in the same manner used to prepare soil specimens for the drying branch of their water retention curves. The soil specimens were hydrated by submersion in water on a pressure plate or by vacuum saturation in a saturation chamber under 2 kPa overburden stress, as described in Section 3.4. The hydrated specimens were transferred to the pressure plate in their brass rings, excess water was removed from the plate, 2 kPa overburden was placed on the specimens, and

the specimens were sealed within the pressure extractor. After 24 hours, at least two specimens of each soil were removed from the extractor, weighed with their rings, then oven-dried to determine the oven-dry mass and the gravimetric moisture content corresponding to 1 kPa suction, according to ASTM D2216.

3.5.5 Fitting Water Retention Curves to Moisture-Suction Data

Water retention curves (WRCs) were fitted to suction data using a best-fit process. The curves were generated using the water retention curve equation developed by Fredlund and Xing (1994) and dimensionless parameters which were unique to the specimen type, specimen conditioning method, and hydration method. The Fredlund and Xing (1994) equation (Eq. 3.6) is presented below. Gravimetric moisture content data and parameters are interchangeable with equivalent data and parameters in terms of θ , or S (Fredlund and Xing 1994). WRCs in terms of θ are discussed in this chapter, whereas moisture-suction relationships in terms of S and e_b are included in the Appendix.

$$w(\psi_i) = C(\psi_i) \frac{w_s}{\{\ln[e + (a\psi_i)^n]\}^m} \quad (3.6)$$

Where: $w(\psi_i)$ = predicted gravimetric moisture content

$C(\psi_i)$ = the correction function,

$$C(\psi_i) = 1 - \frac{\ln(1 + \frac{\psi_i}{\psi_r})}{\ln[1 + (\frac{1000000}{\psi_r})]} \quad (3.7)$$

Where:

ψ_i = measured suction value (kPa)

ψ_r = residual suction fitting parameter

w_s = saturated gravimetric moisture content fitting parameter
 e = base of the natural logarithm = 2.7183
 a, m, n = fitting parameters

The least squares procedure was conducted to determine the best-fit WRC to the measured suction data, (ψ_i, w_i) . The Solver function in Microsoft Excel was used to iterate combinations of the w_s, a, m, n , and ψ_r parameters until the sum of squared residuals, as presented in Eq. 3.8, was minimized and the best-fit parameters were determined for the suction data set. The curve-fitting process was repeated for all suction data included in the test program. Sample results of the curve-fitting process are presented in Figure 3.20.

$$\sum r_i^2 = \sum [w(\psi_i) - w_i]^2 \quad (3.8)$$

Figure 3.20. Best-Fitting Process for WRCs.

One difficulty arose when fitting water retention curves to some data sets. Steeply-curved suction data sets and incomplete suction data sets did not result in convergence of the iterative fit of the fitting parameters. If a data set lacked data in the low suction range, (e.g., 10 kPa to 100 kPa), the average saturated moisture content was assigned to the w_s parameter. The saturated moisture content data were not necessary to produce curve fits for most of the data sets due to the presence of an adequate number of suction data points.

3.5.6 Index Tests on Conditioned GCLs

The swell index, plastic limit, and liquid limit were determined from bentonite removed from GCL panels exposed to the hydration solutions listed in Section 3.2.3. The GCL panels were submerged in the hydration solutions for 30 days, (i.e., prepared according to Section 3.3.2), then moist bentonite was removed from each of the panels. All GCLs in this test program contain bentonite from a common source, but, for consistency, bentonite for these index tests were collected from the WN2 type GCL. The moist bentonite was dried in a 110°C oven, and further sample preparation followed ASTM D5890 and ASTM D4318 for determining the swell index, and liquid and plastic limits, respectively.

Swell Index of Conditioned GCLs

The swell indices of solution-conditioned GCLs were determined according to ASTM D5890 in order to observe the change in swell of bentonite as it was exposed to increasingly saline solutions. Swell indices were determined for virgin bentonite, bentonite saturated in deionized water for 30 days, bentonite saturated in tap water for 30 days, bentonite saturated in 0.1 M CaCl_2 solution for 30 days, and from bentonite exposed to soil water from the landfill cover test plot in Florida. Each of the oven-dried bentonite samples were ground with a mortar and pestle until 100% passed the 0.15 mm (No. 100) sieve and 65% passed the 0.075 mm (No. 200) sieve in order to exclude lingering geotextile fibers and larger bentonite aggregates. 2 g of each processed bentonite was sprinkled in increments of 0.1 g over a period of 3 hours into graduated cylinders containing 90 mL of deionized water. The swell index is the resulting swell volume of the 2

g of bentonite at the end of 16 hours and is reported as mL swell per 2 g clay. The manufacturer's minimum reported swell index for the GCLs used in this test program is 25 mL/2g (CETCO 2014). The swell indices for the conditioned GCLs were determined in order to observe changes in swell behavior as a result of solution salinity.

Liquid and Plastic Limits of Conditioned GCLs

The liquid and plastic limits of solution-conditioned GCLs were determined according to ASTM D4318 in order to compare the plasticity indexes of bentonite exposed to hydration solutions of varying salinity. Liquid and plastic limits were determined from virgin bentonite, bentonite saturated in deionized water for 30 days, bentonite saturated in tap water for 30 days, bentonite saturated in 0.1 M CaCl_2 solution for 30 days, and from bentonite exposed to soil water from the landfill cover test plot in Florida. Oven-dried samples of each bentonite were ground with a mortar and pestle and processed through a 0.425 mm (No. 40) sieve in order to remove lingering geotextile fibers. At least 200 g of bentonite paste was prepared by thoroughly mixing deionized water with each of the bentonite samples to approximately the liquid limit. The bentonite pastes were sealed in plastic bags for 16 hours to hydrate. At the end of 16 hours, the bentonite was mixed again by repeatedly squeezing the plastic bags. The multipoint method (Method B) was used to determine the liquid limit, according to ASTM D4318. The remaining bentonite paste from each liquid limit test was dehydrated to the plastic limit using a fan and paper towels. The plastic limit was obtained by determining the moisture content of hand-rolled threads that

crumbled at 3.2 mm (1/8 in.). The plasticity index was calculated from the liquid and plastic limits for each of the bentonite samples.

3.5.7 Scanning Electron Microscopy on Conditioned GCLs

Scanning electron microscopy (SEM) images were obtained of bentonite from GCLs that were exposed to hydration solutions of varying concentrations. Images were obtained of virgin bentonite, bentonite hydrated in deionized water for 30 days, bentonite hydrated in tap water for 30 days, bentonite exposed to 20 wet-dry cycles using deionized water, bentonite exposed to 20 wet-dry cycles using tap water, and bentonite exposed to 20 wet-dry cycles using 0.1 M CaCl_2 . In addition, images were obtained for dry bentonite and for fully-saturated bentonite. SEM images were collected in order to observe changes in bentonite microstructure when exposed to hydration solutions of varying salinity, as well as multiple wet-dry cycles.

Bentonite specimen preparation was performed carefully to minimize disturbance that could affect the SEM image. Dry bentonite granules or wet bentonite paste were removed from solution-conditioned GCL panels using a thin blade. The material was carefully stored in cling film and enclosed within 25 mm diameter plastic bottles that were sealed with electrical tape. The bottles were transported to a laboratory at the University of California, Santa Barbara where the bentonite samples were subjected to further processing. Bentonite samples were adhered to imaging pedestals with double-sided copper tape. The pedestals were then transferred to a Sputter Coater which applied a thin layer of gold to the samples in the presence of argon gas. The copper tape and the gold

coating were applied in order to reduce charge accumulation and to improve image quality. Up to 12 samples prepared in this manner were loaded into the SEM apparatus in Figure 3.21.

Figure 3.21. Coated Bentonite Samples Loaded into SEM Apparatus

An Inspect S Electron Scanning Microscope was used to capture images of the bentonite microstructure. Imaging was performed at the extreme vacuum of 7 Pa absolute pressure at a voltage of 10 kV. Due to the vacuum inside the SEM apparatus, moisture was rapidly evacuated from the bentonite samples, so all images were captured in dry conditions. Magnifications up to 20,000 x were possible, with resolution on the order of 10 nm. Representative images were compared at 10,000 x magnification among the various bentonite samples.

3.5.8 Bound Cations and Cation Exchange Capacity Tests

The amount of bound cations (BC) and the cation exchange capacity (CEC) were determined for conditioned bentonite specimens that were removed

from the three types of GCLs. The intent of this testing was to determine direct evidence of cation exchange in the bentonite in order to support conclusions regarding water retention behavior of GCLs.

The BC and CEC were determined according to procedures described by ASTM D7503, using inductively coupled plasma optical emission spectroscopy (ICP-OE) which adhered to USEPA Method 6010B (EPA 2007). The BC determination involved washing a 10 g bentonite sample with 1 M NH_4OAc (ammonium acetate) solution to force the exchangeable cations into solution. The cations in solution were subsequently identified with ICP-OE, consistent with Scalia and Benson (2010). A separate 2 g bentonite specimen was washed with DI water in order to determine the amount of soluble cations (SC) which is necessary to calculate BC. The CEC was determined by washing the sample from the BC test with 1 M KCl solution to force nitrogen into solution which was analyzed for nitrogen content with the spectrometer.

3.6 Summary of Experimental Test Program

An extensive test program was conducted in order to determine the effects of GCL type, hydration method, hydration solution chemistry, wet/dry cycling, and temperature on the water retention behavior of GCLs. Four suction test methods, (pressure plate test, filter paper test, relative humidity test, and the determination of the saturated moisture content), were used to define moisture-suction relationships for GCLs exposed to variable environmental conditions. The four suction test methods also were conducted on soils that were commonly placed in contact with GCLs to define moisture-suction relationships for the soils.

Supplementary tests were performed on conditioned bentonite of the GCLs and the test soils for classification purposes and for further analysis of water retention behavior. A summary of the test experimental test program is presented in Table 3.9.

Table 3.9. Summary of Experimental Test Program

Test	Material	Hydration solution (at 20°C)				Wet-Dry Cycling	Temperature	
		DI	Tap	0.1 M CaCl ₂	Landfill Cover	20 cycles	2°C	40°C
GCL Suction	WN2	47	41	31	25	x	28	38
	NN1	48	37	27	x	29	x	x
	WNT	40	40	28	x	x	x	x
Soil Suction	SP	x	20	x	x	x	x	x
	CL (dry of opt)	x	13	x	x	x	x	x
	CL (wet of opt)	x	15	x	x	x	x	x
	SC1	12	x	x	x	x	x	x
	SC2	9	x	x	x	x	x	x
Swell Index	Bentonite ^a	2	2	1	1	x	x	x
Liquid and Plastic Limit	Bentonite ^a	1	1	1	1	x	x	x
Scanning Electron Microscopy	Bentonite ^a	Yes	Yes	Yes	x	Yes	x	x
BC & CEC ^b	Bentonite	Yes	Yes	Yes	Yes	x	x	x

^a Bentonite was exhumed from WN2 GCL^b Performed by the University of Wisconsin, Madison

x Not performed

Chapter 4: Results and Discussion

4.1 Introduction

Results of the experimental test program are presented in this chapter. Moisture-suction relationships were determined for both GCLs and test soils by fitting water retention curves to suction data obtained from the tests. Moisture-suction relationships for GCLs in terms of gravimetric moisture content, (w), and volumetric moisture content, (θ) are presented in this chapter. Moisture-suction relationships in terms of the degree of saturation, (S), and bulk GCL void ratio, (e_b), are included in the Appendix. Baseline water retention behavior is examined for three types of GCLs using DI water. Water retention behavior is examined for GCLs as a function of chemistry of hydration solution, wet-dry cycles, and temperature, compared to the baseline behavior. Water retention behavior of the test soils is presented to study the moisture transfer between GCLs and adjacent soils. Finally, the results of index tests conducted on conditioned GCLs are presented, followed by the results of scanning electron microscopy tests conducted on conditioned bentonite, and cation composition tests of the bentonite. The supplementary tests were determined to provide supporting data used to describe the observed of the water retention curves for GCLs.

4.2 Determination of Moisture-Suction Relationships for GCLs

Water retention curves were determined for GCLs that were exposed to a variety of environmental conditions commonly encountered in landfill applications. The intent of this testing was to: a) determine the moisture-suction

relationships of GCLs, and b) analyze the effects of various environmental conditions on the moisture-suction relationships of GCLs. Three types of GCL specimens were subjected to: i) one of three hydration solutions, ii) twenty wet-dry cycles, or iii) 2°C, 20°C, or 40°C ambient temperatures. Results from three suction tests, including the: pressure plate test, filter paper test, and relative humidity test, were combined to determine moisture-suction behavior of GCLs for the entire range of soil suction (1 kPa to 1,000,000 kPa). Water retention curves were plotted as a function of matric suction, with the exception of the total suction data measured with the relative humidity sensor. Following Beddoe et al. (2011), the osmotic component of total suction was estimated at 1000 kPa for sodium bentonite and was deemed inconsequential for influencing the shape of the water retention curves at suctions above 10000 kPa. The horizontal axis of the water retention curves is labeled 'suction' to clarify that the suction axis is not purely a measure of matric suction. Water retention curves were fitted to both wetting and drying data of the GCLs in order to determine the magnitude of hysteresis between the two moisture conditions. The Fredlund and Xing (1994) parameters used in (Eq. 4.1) to generate the water retention curves are included in the Appendix.

Functional parameters such as air-entry suction, (ψ_{ae}), and residual suction, (ψ_r), and their corresponding moisture contents were determined from the intersections of straight line segments fitted to the legs of the water retention curves, (i.e., knees of the curves). Functional parameters in terms of gravimetric

moisture content, volumetric moisture content, and the degree of saturation are presented in the following sections for interpreting moisture-suction behavior.

4.2.1 Baseline Tests

Water retention curves (WRCs) developed for the WN2, NN1, and WNT type GCLs using deionized (DI) water provided baseline data in the test program. The intent of these baseline tests was to: a) determine if moisture-suction behavior varied among the GCL types, and b) compare the moisture-suction response of a GCL during hydration (wetting WRC) to the moisture-suction response of a GCL during dehydration (drying WRC). Both gravimetric and volumetric versions of water retention curves are presented for each of the three GCL types in Figures 4.1, 4.2, and 4.3. Less volumetric suction data are depicted than gravimetric suction data because a larger portion of the test program was dedicated to gravimetric measurements. The model parameters used to generate the water retention curves are included in the Tables 4.1 and 4.2.

Table 4.1. Fredlund and Xing (1994) Parameters
(Baseline Tests, Gravimetric Basis)

GCL Type	Water Retention Curve	ψ_r (kPa)	w_s (%)	a (kPa)	m	n
WN2	Wetting	189	142	617	0.353	11.6
	Drying	2280	200	270	0.836	3.39
NN1	Wetting	10000	139	521	0.673	4.85
	Drying	1010	210	220	0.673	4.04
WNT	Wetting	574	145	100000	26.4	0.604
	Drying	33500	214	249	1.39	1.61

Table 4.2. Fredlund and Xing (1994) Parameters
(Baseline Tests, Volumetric Basis)

GCL Type	Water Retention Curve	ψ_r (kPa)	θ_s (%)	a (kPa)	m	n
WN2	Wetting	7580	69.4	586	0.496	4.11
	Drying	24600	84.6	430	0.343	20.0
NN1	Wetting	89900	63.3	507	0.898	2.03
	Drying	40100	84.1	355	0.449	9.28
WNT	Wetting	362	63.6	533	0.835	0.955
	Drying	45500	75.3	493	0.708	4.77

Figure 4.1. Moisture-Suction Relationships for WN2 GCL (Baseline Test)

Figure 4.2. Moisture-Suction Relationships for NN1 GCL (Baseline Test)

Figure 4.3. Moisture-Suction Relationships for WNT GCL (Baseline Test)

Several observations were made regarding the shape of the water retention curves. All water retention curves were sigmoid in shape, attributed to the form of Eq. 3.6. At relatively low suction, (suction lower than ψ_{ae}), the moisture content of the GCL was high because the GCL had absorbed a maximum amount of water. At intermediate suction, (suction between ψ_{ae} and ψ_r), the moisture content was highly variable upon small changes in suction. The variability in the moisture content at intermediate suction resulted in a steeper slope than that at low suction. At high suction (suction higher than ψ_r), the moisture content was low because the small amount water remaining in the GCL was tightly adsorbed to intra-aggregate voids and clay particle surfaces (Lu and Likos 2004).

The shapes of the water retention curves were similar among the GCL types. Along the wetting WRC, for GCLs hydrated from a dry state, suction decreased rapidly with small increases in moisture content. At a state of high suction ($\psi > 1000$ kPa), moisture content was low, associated with adsorbed water films, hydration of intra-aggregate voids, and crystalline swell (McBride 1994). Residual water contents corresponded to suction values of approximately 1000 kPa to 5000 kPa. Moisture content increased significantly as suction decreased from 1000 kPa to 100 kPa, associated with hydration of inter-aggregate voids and osmotic swell (McBride 1994). At suction values between 300 to 100 kPa, smaller increases in moisture content were observed. GCLs specimens along the wetting curve hydrated to a maximum of approximately 150% gravimetric moisture content (60% volumetric moisture content).

Along the drying curve, for GCLs dehydrated from a saturated state, and suction increased rapidly with small decreases in moisture content. In this stage, a small amount of free water was expelled from the GCL and the largest macro-voids, but nearly all of the remaining water was held by the menisci of the small voids in the swollen bentonite. Values of ψ_{ae} were approximately 100 to 300 kPa among the drying WRCs indicating that the water in the largest-diameter inter-particle voids began to be replaced by air at suction values of 100 to 300 kPa. As suction was increased from 300 kPa to 1000 kPa, the water in successively smaller voids was replaced with air until GCLs dehydrated to ψ_r . The rapid evacuation of water at suction values greater than ψ_{ae} is expressed as the steep portion of the GCL WRC. The steepness of the GCL WRC may be directly related to the void size distribution, i.e., steep WRCs correspond to narrow void size distributions and sudden evacuation of water with increasing suction. For comparison, soils that contain a wide range of void diameters would be expressed in the WRC with a gradual decline of moisture content for suctions greater than ψ_{ae} .

The most pronounced feature of the GCL moisture-suction relationships was the hysteresis between the wetting branch and the drying branch of the water retention curves. The drying curve typically exhibited higher moisture content than the wetting curve at a given suction. The largest amount of hysteresis occurred at or below air-entry suction. Hysteresis was present in approximately equal amounts among the GCLs. Hysteresis of w_s ranged from 58 to 71 percentage points, and hysteresis of θ_s , (i.e., residual air content), ranged

from 11 to 21 percentage points. In terms of both gravimetric and volumetric moisture contents, the NN1 type GCL exhibited the highest amount of hysteresis at saturated conditions. The water retention curves tended to cross each other at suctions between 500 kPa and 10,000 kPa. Crossover of the data occurred due to the convergence of moisture-suction data between the wetting WRC and the drying WRC. The magnitude of hysteresis decreased at residual moisture conditions. Hysteresis of w_r ranged from 4 to 9 percentage points, and θ_r ranged from 4 to 12 percentage points. Values of w_s , ψ_{ae} , w_{ae} , ψ_r , w_r , and hysteresis are presented in Tables 4.3 and 4.4.

The relationship of bulk GCL void ratio with suction, as presented in Figure 4.4, indicates hysteresis in shrink/swell behavior of GCLs, consistent with observations by Beddoe et al. (2011). GCLs that hydrated along the wetting curve swelled to e_b values up to 3.5, indicating moderate volume changes due to swelling. Whereas, GCL specimens that were used for the drying curve swelled to greater e_b values of up to 5.5. Hysteresis in the e_b – suction relationship due to shrink/swell corresponds with hysteresis observed in the GCL WRCs. Shrinkage of GCL specimens along the drying curve corresponded with reduced hysteresis of the e_b – suction relationship at suctions greater than 100 kPa. Shrinkage of GCL specimens due to increasing suction was likely due to increasing capillary tensile forces between clay particles, as observed by Yong and Warkentin (1975) for clayey soils. Bulk GCL void ratio figures for each GCL type and test are included in the Appendix.

Figure 4.4. Hysteretic Bulk GCL Void Ratio Relationship with Suction

Table 4.3. Gravimetric Hysteresis Determined from WRCs (Baseline Tests)

Hydration Solution	GCL Type	Water Retention Curve	Saturated Moisture Content w_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content w_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content w_r (%)
DI water	WN2	Wetting	142	457	134	1480	20
		Drying	200	166	198	1060	28
		Hysteresis ^a	58	-291	64	-420	8
	NN1	Wetting	139	384	139	1550	23
		Drying	210	148	207	932	27
		Hysteresis ^a	71	-236	68	-618	4
	WNT	Wetting	145	149	128	6860	11
		Drying	214	93	208	1700	20
		Hysteresis ^a	69	-56	80	-5160	9

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

Table 4.4. Volumetric Hysteresis Determined from WRCs (Baseline Tests)

Hydration Solution	GCL Type	Water Retention Curve	Saturated Moisture Content θ_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content θ_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content θ_r (%)
DI water	WN2	Wetting	69	390	69	2440	20
		Drying	85	330	85	808	29
		Hysteresis ^a	16 ^c	-60	16	-1632	9
	NN1	Wetting	63	263	63	2928	14
		Drying	84	287	84	758	26
		Hysteresis ^a	21 ^c	24	21	-2170	12
	WNT	Wetting	64	127	61	10900	10
		Drying	75	351	75	1440	14
		Hysteresis ^a	11 ^c	224	14	-9460	4

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

^c Defined as residual air content

Hysteresis between the wetting and drying branches of the GCL water retention curves was likely due to a combination of three mechanisms: a) capillary effects, b) varying bentonite macrostructures and microstructures, and c) different magnitudes of needle-punched fiber pullout (Lu and Likos 2004, Lake and Rowe 2000, Hoor and Rowe 2013). These mechanisms are further described below.

Capillary phenomena induced hysteresis between wetting and drying water retention curves of GCLs. Capillary effects contributing to hysteresis likely resulted from: a) the 'ink-bottle' effect and b) varying contact angle of the air-water interface (Lu and Likos 2004). The ink-bottle effect was likely present due to voids of varying diameters within the bentonite that may have trapped air bubbles in the larger portions of the voids, inhibited GCL swell, and contributed to residual air content. The contact angle, α , of a hydrating soil is larger than that of a drying soil. Matric suction is inversely related to contact angle, based on Eq. 2.8, which explains why matric suction for wetting WRCs was lower than the drying WRCs at equivalent moisture contents. In both instances, GCLs hydrated from a dry state reached lower moisture content than GCLs dehydrated from a fully-saturated state at the same level of suction, as previously presented in GCL water retention curves in Figures 4.1, 4.2, and 4.3.

Macrostructure differences between wetting WRC specimens and drying WRC specimens may have contributed to hysteresis. Remnant bentonite granules were present in wetting curve specimens, yet drying curve specimens did not exhibit remnant granules at equivalent values of suction. Drying curve

specimens had fully-developed gel structures corresponding to full osmotic swell. The difference in macrostructure between wetting curve and drying curve GCL specimens, as presented in Figure 4.5, is consistent with observations made by Shan and Daniel (1991), Olsen (2011), Scalia and Benson (2011), and others. GCLs exhibiting a gel structure would have higher air-entry moisture content and higher air-entry suction due to higher degrees of saturation and smaller void size.

Figure 4.5. Macrostructures of GCL Specimens (Wetting and Drying WRCs)

Pullout of needle-punched fibers GCLs contributed to hysteresis between the wetting and drying water retention curves. Needle-punched fiber pullout was apparent for GCLs that were saturated by inundation in DI water in preparation for suction tests along the drying curve. The overburden stress of 2 kPa applied to the GCL allowed for near-free-swell conditions, which resulted in straightening and disconnecting of the needle-punched fibers from the backs of the carrier geotextiles. Similar observations were made by Lake and Rowe (2000) and Hoor and Rowe (2013). Once the fibers were disconnected, the confining stress

provided by the needle-punched fibers was lost and further osmotic swell of the bentonite occurred. In contrast, GCLs hydrated from a dry state did not have adequate access to water in order to induce full osmotic swell and full fiber pullout. Specimens used for the wetting WRC were sprayed with a finite amount of moisture, whereas specimens used for the drying WRC were inundated with water. Higher overburden stresses during hydration would reduce hysteresis by reducing fiber pullout.

A comparison of the WRCs from this study with other published studies yielded generally similar responses with DI water. Hysteresis of the moisture-suction behavior was observed by Beddoe et al. (2011) for GCLs, but in lesser amounts and over a wider range of suction. The greater hysteresis observed in the current study is probably attributable to the difference in bentonite mass per unit area, and suction test methods. GCL 1 from Barroso (2006) and GCL3 from Beddoe et al. (2011) are presented as a comparison to the current study in Table 4.5 and Figure 4.6.

Table 4.5. Comparison to Published Moisture-Suction Relationships

Item	Barroso (2006)	Beddoe et al. (2011)	Current Study
GCL Name	GCL1	GCL3	WN2
Geotextiles	W/NW	W/NW	W/NW
Bentonite Mass/Area MARV (g/m^2)	4670	4008	3600
Montmorillonite Percentage, (%)	N/A	53-58 ^a	>53-58 ^a
Suction Test Method	Contact Filter Paper	High-capacity Tensiometer, RH Sensor	Pressure Plate, Filter Paper, RH Sensor
Air-Entry Moisture Content, θ_{ae} (%)	N/A	75	85
Residual Moisture Content, θ_r (%)	N/A	15-25	29
Maximum Hysteresis (percentage points)	N/A	15	16
Bulk GCL void ratio, e_b	N/A	2-6	1.5-5.5

^a Based on Bostwick (2009)

Figure 4.6. Comparison of WRCs to Published Moisture-Suction Relationships

4.2.2 Hydration Solution Tests

WRCs were developed for the WN2, NN1, and WNT type GCLs that were hydrated in DI water, tap water, or 0.1 M CaCl₂ solution. Water retention curves were also developed for WN2 GCL that was exposed to soil water from a landfill cover test plot, exhumed, and subsequently exhumed and rehydrated in DI water in the laboratory. The test names were designated as the tap water test, CaCl₂ solution test, and exhumed GCL test, collectively referred to as the hydration solution test, for quick reference to other tests (e.g., baseline test). The intent of the hydration solution test was to determine the effects of hydration solution and associated cation exchange on GCL moisture-suction behavior. These water

retention curves are presented in terms of gravimetric moisture content and volumetric moisture content. A graphical comparison of moisture-suction behavior among the three hydration solutions is presented for each GCL type in Figures 4.7 through 4.12. The model parameters used to generate the water retention curves are included in the Appendix.

Cation exchange imposed two main changes in the shape of water retention curves of GCLs: a) a reduction in moisture content at a given suction, and b) a reduction in hysteresis, in terms of moisture content at a given suction. The results of the baseline tests conducted with DI water were compared to the tap water test, CaCl_2 solution test, or exhumed GCL test. Results indicated that the reduction of moisture content and amount of hysteresis of water retention curves of GCLs was inversely related to the concentration of divalent cations in the hydration solution. Values of saturated moisture content, air-entry moisture content, residual moisture content, associated suction values, and hysteresis are presented in Tables 4.6 and 4.7.

Figure 4.7. Gravimetric Moisture-Suction Relationships for WN2 GCL (Hydration Solution Tests)

Figure 4.8. Volumetric Moisture-Suction Relationships for WN2 GCL (Hydration Solution Tests)

Figure 4.9. Gravimetric Moisture-Suction Relationships for NN1 GCL (Hydration Solution Tests)

Figure 4.10. Volumetric Moisture-Suction Relationships for NN1 GCL (Hydration Solution Tests)

Figure 4.11. Gravimetric Moisture-Suction Relationships for WNT GCL (Hydration Solution Tests)

Figure 4.12. Volumetric Moisture-Suction Relationships for WNT GCL (Hydration Solution Test)

Table 4.6. Gravimetric Hysteresis Determined from WRCs (Hydration Solution Tests)

Test Name	Hydration Solution	GCL Type	Water Retention Curve	Saturated Moisture Content w_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content w_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content w_r (%)
Baseline test	DI water	WN2	Wetting	142	457	134	1480	20
			Drying	200	166	198	1060	28
			Hysteresis ^a	58	-291	64	-420	8
		NN1	Wetting	139	384	139	1550	23
			Drying	210	148	207	932	27
			Hysteresis ^a	71	-236	68	-618	4
		WNT	Wetting	145	149	128	6860	11
			Drying	214	93	208	1700	20
			Hysteresis ^a	69	-56	80	-5160	9
Tap water test	Tap water	WN2	Wetting	167	92	157	5420	14
			Drying	205	219	204	1190	24
			Hysteresis ^a	38	127	47	-4230	10
		NN1	Wetting	135	661	134	1620	31
			Drying	197	212	200	886	31
			Hysteresis ^a	62	-449	66	-734	0
		WNT	Wetting	138	185	134	3320	11
			Drying	187	143	186	1060	31
			Hysteresis ^a	49	-42	52	-2260	20

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

Table 4.6. (continued). Gravimetric Hysteresis Determined from WRCs (Hydration Solution Tests)

Test Name	Hydration Solution	GCL Type	Water Retention Curve	Saturated Moisture Content w_s (%)	Air-Entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content w_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content w_r (%)
CaCl ₂ solution test	0.1 M CaCl ₂ solution	WN2	Wetting	82	515	81	3410	29
			Drying	94	333	89	6200	28
			Hysteresis ^a	12	-182	8	2790	-1
		NN1	Wetting	80	709	76	66400	3
			Drying	108	219	87	46000	7
			Hysteresis ^a	28	-490	11	-20400	4
		WNT	Wetting	79	505	78	1290	35
			Drying	103	329	68	79200	13
			Hysteresis ^a	24	-176	-10	77910	-22
Exhumed GCL test	Soil water ^c DI water	WN2	Wetting	59	32	57	1700	31
			Drying	83	20	72	1880	29
			Hysteresis ^a	24	-12	15	180	-2

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

^c 9 years of prior contact with moist soil in a landfill cover test plot, containing abundant multi-valent cations

Table 4.7. Volumetric Hysteresis Determined from WRCs (Hydration Solution Tests)

Test Name	Hydration Solution	GCL Type	Water Retention Curve	Saturated Moisture Content θ_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content θ_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content θ_r (%)
Baseline test	DI water	WN2	Wetting	69	390	69	2440	20
			Drying	85	330	85	808	29
			Hysteresis ^a	16 ^c	-60	16	-1632	9
		NN1	Wetting	63	263	63	2928	14
			Drying	84	287	84	758	26
			Hysteresis ^a	21 ^c	24	21	-2170	12
		WNT	Wetting	64	127	61	10900	10
			Drying	75	351	75	1440	14
			Hysteresis ^a	11 ^c	224	14	-9460	4
Tap water test	Tap water	WN2	Wetting	86	69	73	24400	7
			Drying	86	346	83	830	30
			Hysteresis ^a	0	277	10	-23570	23
		NN1	Wetting	63	611	62	1840	18
			Drying	77	282	77	852	22
			Hysteresis ^a	14 ^c	-329	15	-988	4
		WNT	Wetting	71	209	67	17300	4
			Drying	74	200	74	1720	14
			Hysteresis ^a	3 ^c	-9	7	-15580	10

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

^c Defined as residual air content

Table 4.7. (continued). Volumetric Hysteresis Determined from WRCs (Hydration Solution Tests)

Test Name	Hydration Solution	GCL Type	Water Retention Curve	Saturated Moisture Content θ_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content θ_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content θ_r (%)
CaCl ₂ Solution test	0.1 M CaCl ₂ solution	WN2	Wetting	60	19	54	8000	14
			Drying	69	482	67	6300	21
			Hysteresis ^a	9 ^c	463	13	-1700	7
		NN1	Wetting	46	689	44	47700	6
			Drying	70	212	60	50500	6
			Hysteresis ^a	24 ^c	-477	16	2800	0
		WNT	Wetting	50	397	50	6840	18
			Drying	62	299	50	68900	12
			Hysteresis ^a	12 ^c	-98	0	62060	-6
Exhumed GCL test	Soil water ^d DI water	WN2	Wetting	68	1	65	37900	12
			Drying	68	20	59	2870	23
			Hysteresis ^a	0 ^c	19	-6	-35030	11

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

^c Defined as residual air content

^d 9 years of contact with moist soil in a landfill cover test plot, containing abundant multi-valent cations

The shape of water retention curves of GCLs hydrated in tap water varied among the three GCL types. Values of w_s , θ_s , w_{ae} , θ_{ae} , w_r , θ_r , ψ_{ae} , and ψ_r from the tap water test were compared to equivalent values from the baseline tests. Tap water test values of w_s and θ_s were varied from w_s and θ_s from the baseline tests by -23% to +27% and -7% to +7%, respectively. Similar fluctuations in w_{ae} and θ_{ae} for the tap water test ranged from -22% to +23% and -7% to +6%, respectively, compared to values from the baseline tests. Values of w_r and θ_r fluctuated by -13% to +4% and -6% to +11%, respectively. Values of ψ_{ae} and ψ_r both fluctuated by ± 1 log cycle. Consistent trends of individual water retention curves between tap water and baseline tests were not apparent.

Results from the CaCl_2 solution test indicated a dramatic reduction in moisture content in the suction range of 1 kPa to 1000 kPa of both wetting and drying water retention curves, with respect to water retention curves determined from the baseline tests. The reduction in moisture content was observed in terms of both gravimetric and volumetric water contents. Values of w_s , θ_s , w_{ae} , θ_{ae} , w_r , and θ_r from the CaCl_2 test were less than those of the baseline tests, as presented in Table 4.8. Values of w_s of wetting curves and drying curves decreased by approximately 60% and 100%, respectively, for all three GCL types. Values of θ_s decreased by approximately 15% for both wetting and drying curves for all three GCL types. The reduction in moisture content resulted in a downward shift in the water retention curves in Figures 4.7 through 4.12.

Table 4.8. Effects of Hydration Solution on Individual WRCs

GCL Type	Water Retention Curve	Hydration Solution	Saturated Moisture Content, w_s (%)	Saturated Moisture Content, θ_s (%)	Air-Entry Moisture Content, w_{ae} (%)	Air-Entry Moisture Content, θ_{ae} (%)	Residual Moisture Content, w_r (%)	Residual Moisture Content, θ_r (%)
WN2	Wetting	DI water	142	69	134	69	20	20
		0.1 M CaCl_2	82	60	81	54	29	14
		Soil water	59	68	57	65	31	12
	Drying	DI water	200	85	198	85	28	29
		0.1 M CaCl_2	94	69	89	67	28	21
		Soil water	83	68	72	59	29	23
NN1	Wetting	DI water	139	63	139	63	23	14
		0.1 M CaCl_2	80	46	76	44	3	6
	Drying	DI water	210	84	207	84	27	26
		0.1 M CaCl_2	108	70	87	60	7	6
WNT	Wetting	DI water	145	64	128	61	11	10
		0.1 M CaCl_2	79	50	78	50	35	18
	Drying	DI water	214	75	208	75	20	14
		0.1 M CaCl_2	83	62	72	50	13	12

The reduction in moisture content of the water retention curves from the CaCl_2 solution test was a result of cation exchange. Aqueous Ca^{2+} from the CaCl_2 hydration solution replaced the bound Na^+ cations on the bentonite particle surfaces, effectively converting the sodium bentonite within the GCL to calcium bentonite. CEC and bound cation tests were conducted to verify this hypothesis and are discussed later in this chapter. The larger valence of the Ca^{2+} ions decreased the thickness of the DDL and reduced osmotic swell of the bentonite (Yesiller and Shackelford 2010, Scalia and Benson 2011). For suction values greater than residual suction, (approximately 1000 kPa), moisture contents from the baseline tests were similar to moisture contents of the CaCl_2 solution test. It is likely that the moisture-suction behavior at high suction values is not dependent on the effects of cation exchange due to the absence of otherwise cation-sensitive osmotic swell at high suction. Values of ψ_r determined from the CaCl_2 solution test increased with respect to ψ_r from the baseline tests which may be due to osmotic suction induced by the CaCl_2 solution increasing total suction measurements of the relative humidity sensor.

WRCs obtained from the exhumed GCL test were similar to water retention curves obtained from the CaCl_2 solution test. Cation exchange imposed by 9 years of exposure to soil water inhibited osmotic swell of the WN2 GCL. The species and concentrations of cations present in the soil water were not determined, but BC and CEC results indicate an abundance of calcium and magnesium ions. The absence of osmotic swell caused a reduction in moisture content of both the wetting WRC and the drying WRC, resulting in downward

shifts of the water retention curves of the exhumed WN2 GCL with respect to the water retention curves of WN2 determined from the baseline tests. The downward shifts of w_s of the wetting WRC and drying WRC of the exhumed GCL test were by 80 and 120 percentage points, respectively, compared to the WRCs determined from the baseline test. The downward shifts of the exhumed GCL water retention curves exceeded the downward shifts of the CaCl_2 solution test by 20 percentage points. Cation exchange and swell reduction were more severe for the exhumed WN2 GCL than the WN2 GCL hydrated in 0.1 M CaCl_2 , as presented by bulk GCL void ratio data in Figure 4.13. The larger influence of cation exchange observed from the results of the exhumed GCL test compared to the CaCl_2 test was likely attributed to the longer exposure time for cation exchange to occur in the exhumed GCL (i.e., 9 years, compared to 1 month).

Hydration of GCLs in the field may be initially exposed to dilute solutions that promote osmotic swell, then exposed to cation exchange over time. The moisture-suction behavior of a GCL in this hydration environment is unknown. The wetting WRC would likely resemble the wetting WRC of the GCL hydrated in DI water. Similarly, the drying WRC in the low suction range would likely resemble the drying WRC of the GCL hydrated in DI water. However, with increasing suction and corresponding desiccation, the shape of the drying WRC would likely transition to suction behavior similar to the WRCs for GCLs hydrated in CaCl_2 solution. The transition would likely be complete at moisture contents less than 100% gravimetric moisture content, corresponding to the moisture content that caused permanent changes to the GCL hydraulic conductivity of

desiccated GCL samples exposed to cation exchange (Meer and Benson 2007). Future testing should be conducted to determine the wetting WRC and drying WRC for GCLs initially hydrated in dilute conditions, then exposed to cation exchange over time.

Cation exchange resulted in a reduction of hysteresis between wetting WRCs and drying WRCs of GCLs hydrated in solutions containing divalent cations compared to those hydrated with DI water. Cation exchange reduced moisture content of the drying WRC more than the moisture content of the wetting WRC with respect to WRCs determined from the baseline test, resulting in a net reduction in hysteresis (Yesiller et al. 2014). The reduction of hysteresis of the GCL WRCs was a function of increasing cation valence and concentration of the hydration solution, as suggested in Table 4.9. Hydration of GCLs in tap water, a relatively dilute solution, reduced hysteresis of w_{ae} and θ_{ae} by 2 to 28 percentage points, and 6 percentage points, with respect to those determined from the baseline tests. Hydration of GCLs in 0.1 M CaCl_2 solution, a relatively concentrated solution, reduced hysteresis of w_{ae} and θ_{ae} by 56 to 90 percentage points, and 3 to 14 percentage points, with respect to those determined from the baseline tests. Long-term exposure to soil water caused an intermediate reduction in hysteresis of GCL water retention behavior, compared to tap water and CaCl_2 tests.

Figure 4.13. Bulk GCL Void Ratio of WN2 GCL from Hydration Solution Tests

An additional explanation for reduction in hysteresis of the GCL WRCs for the CaCl_2 solution test and exhumed GCL test is that sufficient osmotic swell was not achieved to induce pull-out of the needle-punched fibers. Osmotic swell did not occur in the sodium bentonite that underwent cation exchange with 0.1 M CaCl_2 solution or with soil water. Low amounts of osmotic swell allowed the needle-punched fibers to remain intact, so swelling of GCL specimens of the wetting and drying curves was similar, as suggested by bulk GCL void ratio of Figure 4.13.

Table 4.9. Effects of Hydration Solution on Hysteresis

GCL Type	Hydration Solution	Saturated Moisture Content, w_s (%)	Saturated Moisture Content, θ_s (%)	Air-Entry Moisture Content, w_{ae} (%)	Air-Entry Moisture Content, θ_{ae} (%)
WN2	DI	58	16	64	16
	Tap	38	0	47	10
	0.1 M CaCl_2	12	9	8	13
	Soil water	24	0	15	-6
NN1	DI	71	21	68	21
	Tap	62	14	66	15
	0.1 M CaCl_2	28	24	11	16
WNT	DI	69	11	80	14
	Tap	49	3	52	7
	0.1 M CaCl_2	24	12	-10	0

4.2.3 Cyclic Wet-Dry Test

Water retention curves were developed for the NN1 type GCL that were subjected to 20 wet-dry cycles using DI water. The intent of this testing was to determine the moisture-suction response of a GCL exposed to wet-dry cycles. These water retention curves were published in Hanson et al. (2013) in terms of gravimetric moisture content. Both gravimetric and volumetric versions of the

water retention curves are presented in Figure 4.14. The model parameters used to generate the water retention curves are included in the Appendix.

Wet-dry cycles had two notable effects on the shape of GCL water retention curves, compared to water retention curves determined from the baseline tests: a) a vertical shift upward due to increased swelling capacity, and b) decreased hysteresis between wetting and drying curves. Values of w_s , θ_s , w_{ae} , θ_{ae} , w_r , θ_r , ψ_{ae} , and ψ_r determined from the water retention curves of wet-dry cycled GCLs were compared to values determined from non-cycled GCLs (baseline tests), and presented in Table 4.10 and Table 4.11.

Wet-dry cycles that fully dehydrate clay specimens increased the swelling capacity of expansive clays (Basma et al. 1996). This phenomenon was assumed to apply to the bentonite clay in the GCLs to explain the increase in saturated moisture content of wet-dry cycled GCLs when compared to non-cycled GCLs. Wet-dry cycling was responsible for an increase of approximately 40 percentage points for the wetting WRC and an increase by approximately 30 percentage points in terms of w_s . Wet-dry cycles caused an increase in θ_s of the wetting curve by 7 percentage points, and a decrease in θ_s of the drying curve by 4 percentage points when compared to values of GCL water retention curves not exposed to wet-dry cycles (baseline test). Increased swelling of sodium bentonite subjected to wet-dry cycles may be due to rearrangement of bentonite particles and corresponding change in the bentonite microfabric to a more dispersed structure. Microfabric of wet-dry cycled bentonite is discussed in Section 4.6.

Figure 4.14. Moisture-Suction Relationships for NN1 (Cyclic Wet-Dry Test)

Table 4.10. Gravimetric Hysteresis Determined from WRCs (Cyclic Wet-Dry Test)

Hydration Solution	Conditioning	GCL Type	Water Retention Curve	Saturated Moisture Content w_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content w_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content w_r (%)
DI water	None	NN1	Wetting	139	384	139	1550	23
			Drying	210	148	207	932	27
			Hysteresis ^a	71	-236	68	-618	4
DI water	20 Wet-dry Cycles	NN1	Wetting	186	62	174	5200	12
			Drying	240	113	237	1510	21
			Hysteresis ^a	54	51	63	-3690	9

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

Table 4.11. Volumetric Hysteresis Determined from WRCs (Cyclic Wet-Dry Test)

Hydration Solution	Conditioning	GCL Type	Water Retention Curve	Saturated Moisture Content θ_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content θ_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content θ_r (%)
DI water	None	NN1	Wetting	63	263	63	2928	14
			Drying	84	287	84	758	26
			Hysteresis ^a	21 ^c	24	21	-2170	12
DI water	20 Wet-dry Cycles	NN1	Wetting	70	134	69	4980	15
			Drying	80	219	80	1500	22
			Hysteresis ^a	10 ^c	85	11	-3480	7

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

^c Defined as residual air content

Wet-dry cycles caused the bentonite macrostructure of GCL specimens of the wetting WRC to resemble specimens of the drying WRC. Wet-dry cycles caused the bentonite granules to merge during swelling and crack during dehydration. Destruction of these clay macro-features due to wet-dry cycles is consistent with observations by Basma et al. (1996) and Olsen (2011). Hydration to 50% gravimetric moisture content induced sufficient osmotic swell to merge bentonite granule boundaries. Subsequent oven-drying induced dessication cracks similar to dessication cracks observed in the bentonite of GCLs that were dried from a fully-saturated state. The granule size of specimens subjected to 20 wet-dry cycles between 0% and 50% gravimetric moisture content was observed to be larger than the granule size of virgin GCL specimens, and smaller than the macrostructure of drying curve specimens, as presented in Figure 4.15.

Figure 4.15. Macrostructure of Dried GCL Specimens

Wet-dry cycles caused decreased hysteresis between the wetting WRC and drying WRC, when compared to GCL water retention curves not exposed to wet-dry cycles. Hysteresis was reduced by 5 to 17 percentage points in terms of gravimetric moisture content and by 10 percentage points in terms of volumetric moisture content. This reduction in moisture-suction hysteresis may be attributed to a reduction in hysteresis of bentonite macrostructure between specimens of the wetting curve compared to specimens of the drying curve, as indicated by Figure 4.15. Hydration of wet-dry cycled specimens resulted in higher moisture content than non-cycled specimens, which may be attributed to a narrower pore-size distribution of cycled specimens. A pore-size analysis, e.g., by mercury intrusion, would need to be conducted on both cycled and non-cycled specimens to confirm this mechanism. A narrower pore-size distribution may decrease the hysteresis of WRCs attributed to ink-bottle effects, as suggested by Ng and Pang (2000), which would help explain the reduced hysteresis of water retention curves of wet-dry cycled GCLs.

4.2.4 Temperature Tests

WRCs were developed for the WN2 type GCL that was hydrated in DI water and conditioned at 2°C, 20°C, or 40°C. GCL specimens were not subjected to temperature gradients, (e.g., Barclay and Rayhani 2013), in order to isolate the effects of temperature on GCL moisture-suction behavior. Both gravimetric and volumetric versions of the water retention curves for variable temperatures are presented in Figure 4.16 and 4.17. The model parameters used to generate the water retention curves are included in the Appendix.

Temperature had a minimal influence on water retention behavior of GCLs. GCL water retention curves that were determined at 2°C, 20°C, and 40°C test temperatures were similar. Bulk GCL void ratio among the GCLs tested at 2°C, 20°C, and 40°C indicated similar degrees of swelling, as presented in Figure 4.16. Trends of moisture content or suction as a function of temperature indicated that increasing temperatures resulted in a small decrease in water retention capacity for previously-hydrated GCLs.

Figure 4.16. Gravimetric Moisture-Suction Relationships for WN2 (2°C, 20°C, 40°C)

Figure 4.17. Volumetric Moisture-Suction Relationships for WN2 (2°C, 20°C, 40°C)

Figure 4.18. Bulk GCL Void Ratio Relationships for WN2 (2°C, 20°C, 40°C)

A small decrease in ψ_{ae} for wetting curves was observed with increasing temperature in the low suction range. The inverse relationship of ψ_{ae} with temperature was consistent in terms of both gravimetric and volumetric water retention curves, but only for the wetting branch of the water retention curve, as presented in Tables 4.12 and 4.13. The drying branch of the water retention curve did not exhibit moisture or suction trends associated with temperature.

The small decrease in water retention capacity of GCLs soils due to temperature may be attributed to a reduction in surface tension with increasing temperature (Philip and de Vries 1957, Milly 1984, Bachmann and van der Ploeg 2002). Milly (1984) proposed a temperature correction for suction, $\psi(\theta)$, as presented in Eq. 4.1.

$$\psi(\theta) = \psi e^{[-C_{\psi}(T-T_o)]} \quad (4.1)$$

Where: ψ is any point along the reference water retention curve, T_o is a reference temperature, T is the predicted temperature, and C_{ψ} is a correction factor equivalent to $0.0068 \text{ }^{\circ}\text{C}^{-1}$. A comparison of measured suction values of the wetting curves to predicted changes in suction using Eq. 4.3 is presented in Table 4.14. Equation 4.3 underestimated the measured suctions from the 2°C test and reasonably predicted measured suctions determined from the 40°C test.

Table 4.12. Gravimetric Hysteresis Determined from WRCs (Temperature Tests)

Hydration Solution	GCL Conditioning ^c	GCL Type	Water Retention Curve	Saturated Moisture Content w_s (%)	Air-Entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content w_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content w_r (%)
DI water	2°C	WN2	Wetting	135	795	133	2550	30
			Drying	233	62	219	5070	23
			Hysteresis ^a	98	-733	86	2520	-7
DI water	20°C	WN2	Wetting	142	457	134	1480	20
			Drying	200	166	198	1060	28
			Hysteresis ^a	58	-291	64	-420	8
DI water	40°C	WN2	Wetting	140	271	139	2020	24
			Drying	234	110	228	4760	18
			Hysteresis ^a	94	-161	89	2740	-6

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

^c Hydration for all temperature tests occurred at 20°C with DI water

Table 4.13. Volumetric Hysteresis Determined from WRCs (Temperature Tests)

Hydration Solution	GCL Conditioning ^c	GCL Type	Water Retention Curve	Saturated Moisture Content θ_s (%)	Air-Entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content θ_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content θ_r (%)
DI water	2°C	WN2	Wetting	74	565	73	3030	30
			Drying	88	101	84	10400	10
			Hysteresis ^a	14 ^d	-464	11	7370	-20
DI water	20°C	WN2	Wetting	69	390	69	2440	20
			Drying	85	330	85	808	29
			Hysteresis ^a	16 ^d	-60	16	-1632	9
DI water	40°C	WN2	Wetting	69	340	68	5460	8
			Drying	83	247	82	5560	16
			Hysteresis ^a	14 ^d	-93	14	100	8

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

^c Hydration for all temperature tests occurred at 20°C with DI water

^d Defined as residual air content

Table 4.14. Measured Suction Compared to Eq. 4.3 Predictions

Temperature T	Measured volumetric moisture content, θ (%)	Measured suction at $T_o = 20^\circ\text{C}$, ψ (kPa)	Measured suction at temperature, T (kPa)	Predicted Corrected Suction ^a , $\psi(\theta)$ (kPa)
2°C	60	580	925	655
	40	1130	2100	1280
	20	6000	20800	6780
40°C	60	580	495	505
	40	1130	1180	985
	20	6000	3750	5235

^a Determined using Equation 4.3

It is likely that the small influence of temperature on the moisture-suction relationships was masked by the scatter in moisture-suction data at low suctions. Values of w_s varied among the temperature tests from 185% to 264% with a mean and standard deviation of 223% and 25%, respectively. Values of θ_s varied from 70% to 90%, with a mean and standard deviation of 83% and 4.3%, respectively. The filter paper method loses accuracy when measuring suction at temperature and stress conditions other than 20°C and 0 kPa because of complications with the calibration. Future research could implement a suction measurement technique that is less sensitive to changes in temperature and stress.

4.3 Determination of Moisture-Suction Relationships for Test Soils

WRCs were developed for the SP, CL, SC1, and SC2 test soils. WRCs were developed for the CL test soil for two compaction conditions, i.e., dry-of-optimum and wet-of optimum. SP and CL test soils were hydrated in tap water, similar to subgrade hydration tests from Olsen (2011). SC1 and SC2 test soils were hydrated in DI water in order to preserve the original pore-water chemistry,

and for comparison of water retention behavior with the exhumed WN2 GCL which was also hydrated in DI water. The intent of this testing was to determine the moisture-suction responses of multiple soils that are often placed adjacent to GCLs in landfill applications. Gravimetric water retention curves of the test soils are presented in Figures 4.19 through 4.21. Moisture-suction behavior was quantified and presented in Table 4.15. The model parameters used to generate the water retention curves are included in the Appendix.

Figure 4.19. Moisture-Suction Relationships for SP Hydrated in Tap Water

Figure 4.20. Moisture-Suction Relationships for CL Hydrated in Tap Water

Figure 4.21. Moisture-Suction Relationships of SC1 and SC2 Hydrated in DI Water

Table 4.15. Gravimetric Values from WRCs (Test Soils)

Hydration Solution	Soil Type	Water Retention Curve	Saturated Moisture Content w_s (%)	Air-entry Suction ψ_{ae} (kPa)	Air-Entry Moisture Content w_{ae} (%)	Residual Suction ψ_r (kPa) ^b	Residual Moisture Content w_r (%)
Tap water	SP	Wetting	19.5	2.0	19.3	9.5	2.5
		Drying	19.5	3.9	19.4	8.9	2.1
	CL Dry-of-Optimum	Wetting	28.0	2.3	23.9	127	11
		Drying	31.2	3.4	26.1	363	8.7
	CL Wet-of-Optimum	Wetting	23.3	1.9	22.8	1200	8.8
		Drying	23.3	65	19.6	6720	6.6
DI water	SC1	Wetting	24.8	2.0	18.2	1150	6.3
		Drying	24.8	4.6	21.6	132	11
	SC2	Wetting	15.1	555	12.6	91900	0.99
		Drying	24.1	44	17.1	52600	2.2

^a Hysteresis is quantified as (Drying – Wetting) for the given parameters

^b Interpreted from straight line intersections of WRCs (as described by Figure 2.23)

The shape of water retention curves for the test soils was a function of particle size, clay content, and compaction conditions. Water retention capacity increased in the following order: SP < CL dry-of-optimum < SC1 < CL wet-of-optimum < SC2. Generally, as particle size decreased, ψ_{ae} increased. Larger particle sizes caused larger voids and correspondingly smaller matric suctions. Greater clay content increased ψ_{ae} and ψ_r values by decreasing void size and by increasing swelling. SC2 soil exhibited the highest water retention capacity due to the effects of small particle size, high clay content, and compaction at near-optimum conditions.

Compaction of CL at wet-of-optimum conditions increased ψ_{ae} with respect to CL that was compacted at dry-of-optimum conditions, consistent with findings by Tinjum et al. (1997). CL compacted at dry-of-optimum conditions likely exhibited a flocculated structure with relatively large voids, whereas CL compacted at wet-of-optimum conditions likely exhibited a dispersed structure with smaller voids (Lambe 1958, Miller et al. 2002).

4.4 Index Tests of Bentonite Component of Conditioned GCLs

Swell tests, liquid limit tests, and scanning electron microscopy (SEM) images obtained of conditioned bentonite provided possible explanations for water retention behavior of GCLs subjected to the conditioning procedures in this test program. The results of the index tests and SEM images indicated a large influence of hydration solution on swell, plasticity, and microfabric of the bentonite in GCLs.

4.4.1 Swell Index of Bentonite Component of Conditioned GCLs

The swell index of conditioned bentonite decreased as a function of cation concentration and corresponding cation exchange. The swell indices of conditioned bentonite that were determined according to Section 3.5.6 and ASTM D5890 are presented in Table 4.16. Virgin bentonite exhibited the highest swell of 26.0 mL/2g, whereas bentonite from the GCL exhumed from the landfill test plot exhibited the lowest swell of 6.5 mL/2g. All conditioned bentonite specimens that were fully-hydrated for 30 days exhibited lower swell than virgin bentonite which indicated that either the long hydration period or the process of oven-drying bentonite reduced subsequent swell. The results of the swell index tests suggest that cation exchange effects were minor for GCLs hydrated in tap water, large for GCLs hydrated in 0.1 M CaCl_2 solution, and largest for long-term exposure of GCLs to soil-water containing high concentrations of multivalent cations. The swell index is presented in Figure 4.22 as a function of the divalent cation concentration of DI water, tap water, and 0.1 M CaCl_2 . The cation composition and concentration of the soil water solution was unknown.

Table 4.16. Swell Index of Bentonite Component of Conditioned GCLs

Conditioning	Swell Index (mL/2g)
No conditioning (virgin bentonite)	26.0 ^a
30-day submersion in DI water	19.0
30-day submersion in tap water	18.0
30-day submersion in 0.1 M CaCl_2	7.0
9 years in landfill cover test plot then 30-day submersion in DI water	6.5

^a Reported minimum swell index for Bentomat type GCLs is 24 mL/2g (CETCO, 2014)

Figure 4.22. Swell Index of Conditioned Bentonite

4.4.2 Atterberg Limits of Bentonite Component of Conditioned GCLs

The liquid limit and plasticity index of conditioned bentonite decreased as a function of cation concentration and corresponding cation exchange. The liquid limit (LL), plastic limit (PL), and plasticity index (PI) are presented in Table 4.17. Virgin bentonite exhibited the highest liquid limit of 638%, whereas bentonite from the GCL exhumed from the landfill test plot exhibited the lowest LL of 137%. The LL of dried bentonite that was previously hydrated in DI water was reduced by 82% compared to the LL of virgin bentonite due to the reduction of swell capacity associated with oven-drying. The results of the LL test suggested that cation exchange effects were minor for GCLs hydrated in tap water, were large for GCLs hydrated in 0.1 M CaCl_2 solution, and were largest for long-term

exposure of GCLs to soil-water containing high concentrations of multivalent cations. The liquid limit is presented in Figure 4.23 as a function of the divalent cation concentration of DI water, tap water, and 0.1 M CaCl_2 .

In contrast to the LL, the PL remained constant regardless of the composition of the hydration solution or oven-drying from fully-saturated conditions. Cation exchange did not affect the PL because the clay structure was dictated by particle-to-particle contact, i.e., not by swelling behavior, which was similar among the conditioned bentonites. PI values followed the same trends as the LL values since the PL was constant.

Table 4.17. Atterberg Limits of Bentonite Component of Conditioned GCLs

Conditioning	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
No conditioning (virgin bentonite)	638	27	611
30-day submersion in DI water	556	27	529
30-day submersion in tap water	567	27	540
30-day submersion in 0.1 M CaCl_2	141	26	115
9 years in landfill cover test plot then 30-day submersion in DI water	137	26	111

Figure 4.23. Atterberg Limits of Conditioned Bentonite

4.5 Microfabric Analysis of Bentonite Component of Conditioned GCLs

The microfabric of conditioned bentonite was analyzed directly with a scanning electron microscope. Interpretations of the SEM images indicated that both wet-dry cycles and hydration fluid impacted the microfabric of the bentonite.

The microfabric of sodium bentonite changed due to wet-dry cycles experienced by the GCL, as presented in Figure 4.24. Virgin sodium bentonite exhibited a uniform microfabric composed of single flocculated montmorillonite platelets. In contrast, bentonite that was subjected to 20 wet-dry cycles in DI water exhibited a non-uniform microfabric composed of single weakly-oriented montmorillonite platelets. Wet-dry cycles appeared to introduce larger inter-particle voids than that of non-cycled bentonite (Hanson et al. 2013).

Figure 4.24. SEM Images of Virgin and Wet-Dry Cycled Bentonite

Results indicated that the microfabric of sodium-bentonite specimens differed from the microfabric of sodium-bentonite that had been hydrated in 0.1 M CaCl_2 solution, as presented in Figure 4.25. These changes were due to cation exchange of Ca^{2+} in place of Na^+ . Virgin bentonite that was subjected to wet-dry cycles in DI water appeared to consist of individually-flocculated montmorillonite platelets, consistent with findings by Yong and Warkentin (1975) and Mitchell and Soga (2005) for sodium bentonite. Bentonite specimens that were subjected to wet-dry cycles in 0.1 M CaCl_2 solution aggregated in thicker platelet groups, consistent with findings by Oster et al. (1980) and Mitchell and Soga (2005) for calcium bentonite. Aggregation of clay platelet groups was not observed for bentonite specimens that were subjected to wet-dry cycles in DI water or tap water. From this observation, it was determined that aggregation of clay platelet groups observed in Figure 4.25 was likely solely due to cation exchange and was

expected to be independent of the effects of wet-dry cycles. Future research could include a microfabric analysis of bentonite removed from GCLs that were exposed to 0.1 M CaCl_2 solution (without wet-dry cycles) or of bentonite removed from GCLs that were exposed to soil water for several years. Based on observations made from Figure 4.25, it is likely that the microfabric of bentonite removed from GCLs in long-term contact with soil water would be similar to the microfabric of calcium bentonite.

Results indicated that a bimodal void distribution, or dual pore network, as described by Yong and Warkentin (1975) and Lloret et al. (2003), was especially pronounced for bentonite samples that were subjected to 20 wet-dry cycles or hydration solutions containing multivalent cations, as presented in Figure 4.25. Cation exchange was likely the cause of the microfabric variations presented in Figure 4.25. Both wet-dry cycles and cation exchange appeared to increase inter-aggregate void space. Intra-aggregate void space did not appear to be influenced by wet-dry cycles in the absence of cation exchange. However, cation exchange may influence intra-aggregate void size by reducing the thickness of the DDL. Future testing should include mercury intrusion porosimetry in order to quantify the change in inter-aggregate and intra-aggregate void space size and distribution of voids due to wet-dry cycles and cation exchange.

Figure 4.25. SEM Images of Conditioned Bentonite Subjected to 20 Wet-Dry Cycles in DI, Tap, and 0.1 M CaCl₂ Solutions

4.6 Bound Cations and Cation Exchange Capacity Tests

Bound cations (BC) and the Cation exchange capacity (CEC) were determined for conditioned bentonite specimens using ASTM D7503. The results are presented in Table 4.18 below. The mole fractions were calculated based on the BC results and are presented in Table 4.19. The CEC ranged from 70 meq/2g to 89 meq/2g. Notable results from Table 4.19 include the replacement of significant amounts of bound sodium with calcium for specimens hydrated in 0.1 M CaCl_2 solution. Higher degrees of sodium replacement with calcium occurred for specimens prepared for the drying WRC compared to the wetting WRC, likely due to more abundant calcium ions due to submergence for drying WRC specimens. Soil water specimens contained nearly zero bound sodium, having been replaced entirely by calcium and magnesium ions.

Table 4.18. BC and CEC Results

Bentonite Moisture Condition ^a	Wetting or drying WRC?	Hydration Solution	GCL Type	Bound Cations (meq / 100 g)				
				Na (meq / 100 g)	K (meq / 100 g)	Ca (meq / 100 g)	Mg (meq / 100 g)	CEC (meq / 100 g)
Air-Dry	None	Virgin	WN2	35.3	1.6	22.4	4.8	73.9
Air-Dry	None	Virgin	WN2	39.3	0.4	18.9	5.3	75.2
Fully-Saturated for 1 month	Drying	DI	WN2	39.3	1.4	18.8	4.8	77.5
Fully-Saturated for 1 month	Drying	DI	NN1	37.8	1.5	27.5	3.9	85.1
Fully-Saturated for 1 month	Drying	DI	WNT	38.4	1.4	20.9	10.8	84.5
Fully-Saturated for 1 month	Drying	Tap	WN2	41.9	1.9	20.4	7.5	80.4
Fully-Saturated for 1 month	Drying	Tap	NN1	34.3	1.6	23.1	1.8	75.4
Fully-Saturated for 1 month	Drying	Tap	WNT	46.0	1.6	25.4	0.2	87.7
Fully-Saturated for 1 month	Drying	CaCl ₂	WN2	4.8	1.4	74.8	5.4	86.6
Fully-Saturated for 1 month	Drying	CaCl ₂	NN1	7.2	1.1	63.4	5.5	89.0
Fully-Saturated for 1 month	Drying	CaCl ₂	WNT	10.1	1.4	61.8	5.1	81.3
Fully-Saturated for 1 month	Drying	Soil water	WN2	0.6	1.4	47.1	21.9	84.8
Saturated for 1 month	Wetting	DI	WN2	35.4	1.7	23.0	4.6	78.6
Fully-Saturated for 1 month	Drying	DI	WN2	39.3	1.4	18.8	4.8	77.5
Saturated for 1 month	Wetting	Tap	WN2	33.4	1.8	23.9	4.8	75.7
Fully-Saturated for 1 month	Drying	Tap	WN2	41.9	1.9	20.4	7.5	80.4
Saturated for 1 month	Wetting	CaCl ₂	WN2	22.8	1.5	30.3	4.2	70.7
Fully-Saturated for 1 month	Drying	CaCl ₂	WN2	3.3	0.5	64.6	0.4	71.7
10-day saturation	Drying	Tap	WN2	28.9	1.8	24.7	9.4	78.2

^a All samples oven-dried prior to BC and CEC testing

^b Soluble cations (SC) were determined for calculating BC. Values of SC are included in the Appendix.

Table 4.19. BC Mole Fractions

Bentonite Moisture Condition ^a	Wetting or drying WRC?	Hydration Solution	GCL Type	Mole Fractions ($BC_x/BC_{Na+K+Ca+Mg}$)				
				Na (meq / 100 g) ^b	K (meq / 100 g) ^b	Ca (meq / 100 g) ^b	Mg (meq / 100 g) ^b	X_m (meq / 100 g) ^c
Air-Dry	None	Virgin	WN2	0.55	0.02	0.35	0.08	0.58
Air-Dry	None	Virgin	WN2	0.61	0.01	0.30	0.08	0.62
Fully-Saturated for 1 month	Drying	DI	WN2	0.61	0.02	0.29	0.08	0.63
Fully-Saturated for 1 month	Drying	DI	NN1	0.54	0.02	0.39	0.06	0.56
Fully-Saturated for 1 month	Drying	DI	WNT	0.54	0.02	0.29	0.15	0.56
Fully-Saturated for 1 month	Drying	Tap	WN2	0.58	0.03	0.28	0.10	0.61
Fully-Saturated for 1 month	Drying	Tap	NN1	0.56	0.03	0.38	0.03	0.59
Fully-Saturated for 1 month	Drying	Tap	WNT	0.63	0.02	0.35	0.00	0.65
Fully-Saturated for 1 month	Drying	CaCl ₂	WN2	0.06	0.02	0.87	0.06	0.07
Fully-Saturated for 1 month	Drying	CaCl ₂	NN1	0.09	0.01	0.82	0.07	0.11
Fully-Saturated for 1 month	Drying	CaCl ₂	WNT	0.13	0.02	0.79	0.07	0.15
Fully-Saturated for 1 month	Drying	Soil water	WN2	0.01	0.02	0.66	0.31	0.03
Saturated for 1 month	Wetting	DI	WN2	0.55	0.03	0.35	0.07	0.57
Fully-Saturated for 1 month	Drying	DI	WN2	0.61	0.02	0.29	0.08	0.63
Saturated for 1 month	Wetting	Tap	WN2	0.52	0.03	0.37	0.08	0.55
Fully-Saturated for 1 month	Drying	Tap	WN2	0.58	0.03	0.28	0.10	0.61
Saturated for 1 month	Wetting	CaCl ₂	WN2	0.39	0.02	0.52	0.07	0.41
Fully-Saturated for 1 month	Drying	CaCl ₂	WN2	0.05	0.01	0.94	0.01	0.05
10-day saturation	Drying	Tap	WN2	0.45	0.03	0.38	0.15	0.47

^a All samples oven-dried prior to BC and CEC testing

^b Soluble cations (SC) were determined for calculating BC. Values of SC are included in the Appendix.

^c X_m is the mole fraction of monovalent cations (i.e., $X_m = (BC_{Na+K} / BC_{Na+K+Ca+Mg})$)

Chapter 5: Engineering Significance

The water retention curves determined from this study may be used as tools to describe unsaturated behavior of GCLs. WRCs are useful for predicting the equilibrium moisture content of a GCL that is placed adjacent to a given soil. WRCs allow for the calculation of the unsaturated shear strength function which contributes to a better understanding of moisture-dependent shear strength for GCLs. WRCs also allow for the calculation of the permeability function which is necessary for calculating the flow through unsaturated soils, e.g., in a water balance calculation of a landfill cover system. The potential uses of GCL WRCs that were determined in this test program are described in the following section.

5.1 Determining Equilibrium Moisture Contents of GCLs Adjacent to Soil

The equilibrium moisture content and the shrinkage susceptibility of GCLs placed adjacent to soils may be predicted by comparing the GCL WRC to the soil WRC. Olsen (2011) indicated that if both the GCL WRC and the soil WRC are known, it is possible to forecast the equilibrium moisture content of a GCL placed on a given soil type. The following section describes the comparison of measured equilibrium GCL moisture contents from Olsen (2011) to predicted values of equilibrium GCL moisture content determined from GCL WRCs from this study.

Olsen (2011) performed subgrade tests with GCLs in order to determine the moisture transfer of the WN2 and WNT GCL types that were placed on top of compacted SP or CL soil specimens hydrated in tap water. The GCLs were placed in contact with the hydrated test soils in sealed tubs for a period of 20

weeks until moisture equilibrium was reached. At moisture equilibrium, the suction imposed by the soil was assumed to be equal to the suction experienced by the GCL, i.e., moisture transfer between the soil and GCL was complete.

The procedure to use the soil WRC and the GCL WRC together to predict the equilibrium GCL moisture content is presented in Figure 5.1. First, a line from the measured equilibrium moisture content of the soil was drawn to the soil WRC, (Line 1). The suction imposed on the GCL by the soil, (Lines 2a, 2b) corresponded with the moisture content intercepts with the soil wetting WRC and the soil drying WRC that were determined from the current study. The range of equilibrium GCL moisture contents from the WRC predictions is given by Lines 3a, 3b. The range of measured equilibrium GCL moisture contents from Olsen (2011) is given by Lines 4a, 4b. A box representing the measured equilibrium soil moisture content, and a range of suction constrained by the predicted suction, is presented for each soil type in Figure 5.1. The prediction process was performed on the WN2 and WNT GCLs with the SP, CL, SC1, and SC2 soil types, as presented in Figures 5.2, 5.3, and 5.4.

The similarity of the predicted equilibrium GCL moisture contents to the measured equilibrium GCL moisture contents varied. At low suction values associated with wet soils, the boxes representing the measured equilibrium GCL moisture contents were close (i.e., comparable) to the predicted GCL moisture contents determined from the wetting WRC. At high suction values associated with dry soils, the boxes and measured equilibrium GCL moisture contents were lower than the predicted GCL moisture contents determined from the wetting

WRC. The measured and predicted moisture contents are presented in Table 5.1.

Figure 5.1. Measurements and Predictions of Equilibrium GCL Moisture Content

Figure 5.2. Determination of Equilibrium Moisture Content of WN2 Placed Adjacent to SP or CL Soils

Figure 5.3. Determination of Equilibrium Moisture Content of WNT GCL Placed Adjacent to SP or CL Soils

Figure 5.4. Determination of Equilibrium Moisture Content of WN2 GCL Placed Adjacent to SC1 or SC2 Soils

Table 5.1. Measured and Predicted Equilibrium GCL Moisture Contents

GCL Type	Soil Type	Measured equilibrium GCL moisture content, (%) Olsen (2011)	Predicted equilibrium GCL moisture content, (%) current study
WN2	Dry SP	58 – 78	150 – 180
	Wet SP	153 – 164	165 – 205
	Dry-of-Opt CL	21 – 25	35 – 90
	Wet-of-Opt CL	122 – 125	130 – 205
WNT	Dry SP	62 – 74	135 – 140
	Wet SP	154 – 164	137 – 190
	Dry-of-Opt CL	21 – 24	35 – 80
	Wet-of-Opt CL	112 – 118	120 – 190
WN2	SC1 and SC2	37 – 45 ^a	50 – 80

^a Moisture content of exhumed GCL

The differences between the measured and predicted equilibrium GCL moisture contents may be due to a variety of mechanisms, including: method of hydration of GCL specimens from Olsen (2011), limitations of the suction test methods in the current study, and cation exchange experienced by the GCL specimens from Olsen (2011).

The differences between the measured and predicted equilibrium moisture contents may be described by the method of hydration associated with the measured data. The test apparatus of Olsen (2011) did not include overburden pressure to provide intimate contact of the GCL with the subgrade, the lack of which is known to inhibit moisture transfer that would otherwise occur via capillary flow (e.g., Southen and Rowe 2007). While some water may have transferred to the GCL via capillary action, the majority of the water probably transferred to the GCL by vapor diffusion, especially for the dry SP and the dry CL tests, where the largest relative differences between measured and predicted equilibrium GCL moisture contents were present. Moisture transfer to the GCL

via vapor diffusion may have been inhibited by moisture losses from the subgrade test apparatus over the 20-week equilibrium period, which varied from 1% to 15% losses of the original water mass, based on total mass measurements over time. Due to moisture losses from the test apparatus, the moist air in contact with the GCL likely exhibited an artificially lower value of relative humidity than the relative humidity in a completely sealed test apparatus. Subsequently, the decrease in relative humidity caused an artificial reduction in moisture transfer via vapor diffusion to the GCL specimen. The inhibited vapor diffusion may explain why measured GCL equilibrium moisture contents in contact with dry soils were less than the predicted GCL equilibrium moisture contents using the WRCs.

The differences between the measured and predicted equilibrium moisture contents also may be described, in part, by the limitations of the suction test methods. For example, the contact filter paper test may slightly over-predict suction values, especially at suction values greater than 1000 kPa (Agus et al. 2011). Overburden adjustments to the filter paper calibration curve increased the suction at a given moisture content on the GCL WRC. The overprediction of suction with the filter paper method and the changes to the calibration curve may partially explain the lower measured equilibrium GCL moisture contents compared to the predicted moisture contents.

Finally, the differences between the measured and predicted equilibrium moisture contents may be described, in part, by the effects of cation exchange. Olsen (2011) determined that GCL specimens hydrated rapidly and swelled

significantly from highly available moisture from wet SP and wet CL soils and retained high moisture content, as presented in Table 5.1. In contrast, GCLs that were adjacent to dry SP or dry CL soils did not hydrate rapidly and did not swell significantly. Cation exchange inhibits osmotic swell in GCLs that are not prehydrated (e.g., Meer and Benson 2007). The lower measured GCL equilibrium moisture content for GCLs placed adjacent to dry SP and dry CL soils is consistent with a GCL that has undergone partial cation exchange, as suggested by the results from the hydration solution tests.

In terms of dimensional stability of GCLs, the ability to forecast the equilibrium GCL moisture content from a given soil suction is important because it allows the engineer to control the GCL moisture content which dictates the hydraulic performance of the GCL barrier system. Desiccation of GCLs could potentially be avoided by maintaining relatively high moisture contents for the soils that apply suction to GCLs. Maintaining high GCL moisture content (greater than 100%) promotes adequate hydraulic performance by preventing GCL panel separation related to excessive shrinkage and by preventing permanent increases to hydraulic conductivity related to cation exchange (Meer and Benson 2007, Olsen 2011). The equilibrium soil moisture contents that correspond with equilibrium GCL moisture contents, as determined by the soil and GCL WRCs, are presented in Table 5.2.

Table 5.2. Estimated Ideal Soil Moisture Contents for Adequate GCL Hydraulic Performance

GCL Type	Soil Type	Ideal Soil Moisture Content for Adequate GCL Hydraulic Performance ^a (%)
WN2 or WNT	SP	> 2
	CL dry-of-optimum	> 10
	CL wet-of-optimum	> 11 – 15

^a WRC-based prediction

WRCs may be appropriate for predicting equilibrium GCL moisture content, provided that careful consideration is used when determining the soil WRC and the GCL WRC. The soil specimens used to determine the soil WRC must be prepared at equivalent molding water content and compactive effort as the field values for the soil. The GCL specimens used to determine the GCL WRC must be prepared at equivalent overburden conditions, hydrated with a solution equivalent to the pore fluid conditions, and conditioned to simulate other long-term effects, such as wet-dry cycles. Finally, when comparing the soil WRC to the GCL WRC, the equilibrium GCL moisture content must be expressed as a range to account for the uncertainty due to hysteresis of the soil WRC and the GCL WRC.

5.2 Using WRCs to Predict the Shear Strength function for GCLs

The unsaturated shear strength of GCLs may be computed from known strength parameters and moisture-suction data from GCL WRCs. The internal shear strength of GCLs has been determined mainly for hydrated GCLs. The peak internal shear strength failure envelope for needlepunched GCLs may be

described by $c'_p = 42.3$ kPa and $\phi'_p = 41.9^\circ$ (Fox 2010). Whereas, the residual internal shear strength failure envelope (i.e., shear strength at high displacement) for GCLs is independent of reinforcement type, is much lower than peak strength, and is essentially the same as hydrated bentonite, i.e. ($c'_r = 1.0$ kPa and $\phi'_r = 4.7^\circ$) as determined by Fox (2010). Since the shear strength of hydrated bentonite is so low, the amount of shear strength that is gained by increasing matric suction may be significant. The shear strength of an unsaturated soil may be calculated using effective strength parameters and moisture-suction values obtained from the WRC, as presented by Eq. 5.1 and component equation Eq. 5.2, as explained by Fredlund et al. (1996).

$$\tau = [c' + (\sigma_n - u_a)\tan\phi'] + (u_a - u_w)[\Theta_e]^K \tan\phi' \quad (5.1)$$

$$\Theta_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \quad (5.2)$$

Where τ is shear strength, c' is the effective cohesion (kPa), σ_n is the applied normal stress, u_a is the pore air pressure (kPa), ϕ' is the effective friction angle ($^\circ$), u_w is the pore water pressure (kPa), $(u_a - u_w)$ is matric suction (kPa), Θ_e is the normalized water content, and K is a soil-specific parameter that increases with plasticity (ranging from 1.0 to 3.0).

The shear strength gained due to matric suction was calculated at several matric suction values using Eq. 5.1 and presented in Tables 5.3 and 5.4. A value of 3.0 was assigned to K due to the high plasticity of bentonite as suggested by

Fredlund et al. (1996) and the θ_r value was set to zero for consistency with Fredlund and Xing (1994).

The shear strength of GCLs depends on the condition of the geosynthetic reinforcement. For GCLs reinforced with needlepunched fibers, the shear strength is inversely related to the degree of fiber pullout caused by excessive swelling or deformation. The shear strength of GCL specimens prepared for the wetting WRC would likely be different than specimens prepared for the drying WRC due to fiber pullout, as presented in Figure 5.5. Unsaturated peak shear strength was calculated using the baseline wetting WRC for WN2 to simulate the shear strength for a GCL for small displacements and intact needlepunched fibers, as presented in Table 5.3. Unsaturated residual shear strength was calculated using the drying WRC for WN2 to simulate the shear strength for a GCL for large displacements or free-swell conditions corresponding to needlepunched fiber pullout (Table 5.4).

Figure 5.5. Effect of Needlepunched Fiber Pullout on Shear Strength

Table 5.3. Peak Shear Strength for Unsaturated GCLs

Matric Suction ($u_a - u_w$) (kPa)	Normalized Moisture Content, θ_e	Unsaturated Peak Shear Strength ^a , τ_p (kPa)
1	1.00	45
10	0.999	53
100	0.997	133
1000	0.624	262
3000	0.363	172

^a Compared to $\tau = 45$ kPa at saturated conditions and $\sigma_n = 2$ kPa

Table 5.4. Residual Shear Strength for Unsaturated GCLs

Matric Suction ($u_a - u_w$) (kPa)	Normalized Moisture Content, θ_e	Unsaturated Residual Shear Strength ^a , τ_r (kPa)
1	0.999	1.2
10	0.999	2.0
100	0.998	5.7
1000	0.375	12.2
3000	0.276	7.7

^a Compared to $\tau = 1.2$ kPa at saturated conditions and $\sigma_n = 2$ kPa

The unsaturated shear strengths, provided in Tables 5.3 and 5.4 are presented in Figures 5.6 and 5.7, for peak and residual shear strengths, respectively. The unsaturated peak and residual shear strengths increase with increasing matric suction approximately until the air-entry suction, then decrease at suction values greater than air-entry suction, consistent with Fredlund et al. (1996). The decrease in shear strength beyond the air-entry suction is associated with the K parameter (Fredlund et al. 1996). Further research is needed to determine the accuracy and applicability of the unsaturated shear strength function for strength analyses for GCLs.

Figure 5.6. Unsaturated Peak Shear Strength Function for WN2 Drying WRC (Baseline Test)

Figure 5.7. Unsaturated Residual Shear Strength Function for WN2 Drying WRC (Baseline Test)

5.3 Using WRCs to Predict the Permeability Function of GCLs

The permeability function of GCLs may be computed from moisture-suction data from GCL WRCs. Alternatively, the permeability function may be determined directly using ASTM D7664 which involves the use of a specialized suction apparatus. Little or no data exist for the unsaturated coefficient of permeability of GCLs determined using ASTM D7664. Numerous models exist for predicting permeability of soils, with varying degrees of complexity. Two common models for predicting the permeability function were proposed by van Genuchten (1980), [VG], and Fredlund et al. (1994), [FX], and are adapted to analyze GCLs in this section. The [VG] model is presented in Eq. 5.4 and the [FX] model is presented in Eq. 5.5. The [VG] and [FX] models calculate the relative permeability, k_r , as presented in Eq. 5.3, which is related to the permeability function, $k(\psi)$ based on the saturated coefficient of permeability, k_{sat} .

$$k(\psi) = k_r * k_{sat} \quad (5.3)$$

$$k_r = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^p \left\{ 1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/m} \right]^m \right\}^2 \quad (5.4)$$

where θ is the volumetric moisture content at a given suction from the van Genuchten (1980) WRC, θ_r is the residual volumetric moisture content, θ_s is the saturated volumetric moisture content, p is a parameter related to pore connectivity, and m is the fitting parameter from the [VG] WRC equation. The value of p is typically equal to 0.5 based on Mualem (1976), and m is typically equal to $1 - (1/n)$ based on van Genuchten (1980).

The [FX] model for relative permeability function is presented in Eq. 5.5, with component equations described by Equations. 5.6 to 5.9 (Fredlund et al. 1994). The equation is an approximation to an integral which allows for a spreadsheet-based solution for k_r .

$$k_r(\psi) \approx \frac{\sum_{i=j}^N \frac{\theta(e^{\bar{y}_i}) - \theta(\psi)}{e^{\bar{y}_i}} \theta'(e^{\bar{y}_i})}{\sum_{i=1}^N \frac{\theta(e^{\bar{y}_i}) - \theta_s}{e^{\bar{y}_i}} \theta'(e^{\bar{y}_i})} \quad (5.5)$$

$$\theta = C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^m} \quad (5.6)$$

$$C(\psi) = 1 - \frac{\ln \left(1 + \frac{\psi}{\psi_r} \right)}{\ln \left(1 + \frac{1000000}{\psi_r} \right)} \quad (5.7)$$

$$\theta'(\psi) = C'(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^m} - C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^n \right] \right\}^{m+1}} \frac{mn \left(\frac{\psi}{a} \right)^{n-1}}{a \left[e + \left(\frac{\psi}{a} \right)^n \right]} \quad (5.8)$$

$$C'(\psi) = \frac{-1}{(\psi_r + \psi) \ln \left(1 + \frac{1000000}{\psi_r} \right)} \quad (5.9)$$

Where N is the number of equally-spaced intervals from $\ln(\psi_{ae})$ to $\ln(1,000,000)$, $\bar{y}^i$ is the natural logarithm of suction at the midpoint of interval i , $\theta(\psi)$ is the [FX]

WRC, ψ is the suction at the interval i , $\theta'(\psi)$ is the derivative of $\theta(\psi)$, $C(\psi)$ and $C'(\psi)$ are correction factors, $\{\psi_r, a, n, m\}$ are fitting parameters of the [FX] WRC, and e is the base of the natural logarithms. The summation occurs only for intervals from ψ_{ae} to 1,000,000 kPa, however the permeability function can be plotted for suction values less than ψ_{ae} . Using $N = 10$ intervals produced the best results. A comparison of the [VG] and [FX] models is presented in Figure 5.8.

Figure 5.8. Comparison of Models for Predicting k_r

Since the [FX] WRC was used in the test program, the [FX] model was used to calculate the relative permeability functions for the GCLs. A sample of the results using the [FX] model is presented in Figure 5.9, and the remaining results are included in the Appendix.

Figure 5.9. Prediction of k_r function for the GCLs from the Hydration Solution Tests

If k_{sat} is known, the permeability function, $k(\psi)$, may be determined from the k_r function. The permeability function was calculated using $k_{sat} = 1.7 \times 10^{-9}$ cm/sec for GCLs hydrated in DI water (Jo et al. 2005). The permeability function is plotted alongside the WRC, as presented in Figure 5.10. The coefficient of permeability decreased by several orders of magnitude at suction values greater than ψ_{ae} . At suction values near 1,000,000 kPa, the coefficient of permeability approached zero.

Figure 5.10. Prediction of $k(\psi)$ for WN2 GCL (Baseline Test)

Similar permeability functions may be calculated from the relative permeability functions presented in Figure 5.9, using published k_{sat} values. Selected values from the permeability functions for the WN2 GCL, and the NN1

GCL subjected to 20 wet-dry cycles, are presented in Table 5.5. The selected $k(\psi)$ values were determined from the wetting $k(\psi)$ curves in each case. A flow ratio was calculated by dividing the coefficient of permeability for a given solution by the coefficient of permeability for DI water. A flow ratio greater than 1.0 represents a condition where flow is higher than the baseline case, whereas a flow ratio less than 1.0 represents a condition where flow is less than the baseline case. The flow ratios for GCLs hydrated in 0.1 M CaCl_2 or soil water are consistently greater than 1.0 which indicates that infiltration rates would be higher than those of GCLs hydrated in DI water. This trend of increasing flow due to exposure of the GCL to solutions containing high concentrations of multivalent cations is consistent with infiltration studies of landfill covers, e.g., Melchior (2002). High flow ratios are also exhibited by the GCL specimens that were subjected to 20 wet-dry cycles. Further research is needed to examine the use of predicting infiltration rates through GCLs in landfill barrier systems using permeability functions estimated from GCL WRCs.

Table 5.5. Selected Values from Permeability Functions for GCLs

Hydration Solution	Suction (kPa)	Relative coefficient of permeability ^f , k_r	Saturated coefficient of permeability, k_{sat} , (cm/sec) ^{a,b,c,d,e}	Coefficient of permeability, $k(\psi)$, (cm/sec)	Flow Ratio $k(\psi)_{\text{solution}}/k(\psi)_{\text{DI}}$
DI	100	0.544	1.7×10^{-9}	9.25×10^{-10}	--
	1000	0.0295	1.7×10^{-9}	5.02×10^{-11}	--
	10000	1.53×10^{-5}	1.7×10^{-9}	2.60×10^{-14}	--
DI, 20 wet-dry cycles	100	0.477	2.9×10^{-9}	1.38×10^{-9}	1.49
	1000	0.00619	2.9×10^{-9}	1.80×10^{-11}	0.356
	10000	1.07×10^{-4}	2.9×10^{-9}	3.11×10^{-13}	12.0
Tap	100	0.0750	1.7×10^{-9}	1.28×10^{-10}	0.138
	1000	0.00529	1.7×10^{-9}	8.99×10^{-12}	0.179
	10000	2.57×10^{-6}	1.7×10^{-9}	4.38×10^{-15}	0.168
0.1 M CaCl_2	100	0.0261	9.5×10^{-7}	2.48×10^{-8}	26.8
	1000	3.54×10^{-4}	9.5×10^{-7}	3.36×10^{-10}	6.70
	10000	3.18×10^{-6}	9.5×10^{-7}	3.02×10^{-12}	116
Soil water	100	1.07×10^{-4}	1.0×10^{-5}	1.07×10^{-9}	1.16
	1000	1.69×10^{-5}	1.0×10^{-5}	1.69×10^{-10}	3.37
	10000	5.06×10^{-8}	1.0×10^{-5}	5.06×10^{-13}	19.5

^a k_{sat} data for GCLs in DI water (Jo et al. 2005)

^b k_{sat} data for GCLs for 20 wet-dry cycles in DI water (Lin and Benson 2000)

^c k_{sat} data for GCLs in tap water (Lin and Benson 2000)

^d k_{sat} data for GCLs in 0.1 M CaCl_2 (Jo et al. 2005)

^e k_{sat} data for GCLs in soil water (Meer and Benson 2007)

^f k_r data was determined from wetting WRCs for this table

5.4 Summary of Engineering Significance

WRCs may be used to predict a variety of unsaturated behavior for GCLs.

The predictions have the potential for aiding GCL specifications involving the optimization of moisture content and long-term GCL performance. Specifications for GCL moisture content must satisfy the variety of long-term performance demands for GCLs (e.g., dimensional stability, low permeability, and high shear strength). The value of 100% gravimetric moisture content was determined to be a point of separation for permeability and shrinkage (Meer and Benson 2007, Olsen 2011). A schematic, as presented in Figure 5.11 may be useful to

conceptualize the relationship between conflicting performance parameters, and assist the designer to specify a GCL moisture content that best satisfies the performance demands.

Figure 5.11. Schematic of GCL Performance in Terms of Moisture Content or Suction

Chapter 6: Summary, Conclusion, and Recommendations

6.1 Summary and Conclusions

An extensive laboratory test program was conducted to evaluate the effects of GCL type, hydration solution chemistry, wet-dry cycles, and temperature on the moisture-suction behavior of GCLs. The testing program was conducted using three types of GCLs. The geosynthetic components of the GCLs were configured in one of three ways: nonwoven/woven (WN2), nonwoven/nonwoven (NN1), or nonwoven/woven with a textured geofilm laminated to the surface of the nonwoven geotextile (WNT). A combination of pressure plate tests, contact filter paper tests, and relative humidity tests were used to obtain moisture-suction data for GCL specimens that were subjected to variable conditions of the test program. WRCs were fitted to the moisture-suction data from tests with varied conditions, and trends in the curves were analyzed and compared to baseline tests. Supplementary tests, including: index tests, SEM microscopy, and bound cation (BC) and cation exchange capacity (CEC) tests were performed on the bentonite from the GCLs tested under different conditions. The GCL WRCs were used to predict the moisture transfer for GCLs placed adjacent to soils, as well as the unsaturated shear strength function and the permeability function for unsaturated GCLs.

For baseline tests, each of the three GCL types were hydrated in deionized water for 30 days with an applied overburden stress of 2 kPa. Hydration was accomplished either by spraying a predetermined amount of water on the GCL specimen or by submerging GCL samples in a bath of DI water.

Moisture-suction data of the wetting WRCs were obtained for GCL specimens that were hydrated by spraying from an initially dry state (i.e., as-received moisture content). In contrast, moisture-suction data for the drying WRCs were obtained using GCL specimens that were hydrated by air-drying from an initially saturated state. Based on the shape of the wetting WRCs and the drying WRCs for the baseline tests, the following conclusions were drawn:

1. The pressure plate test, the contact filter paper test, and the relative humidity test may be used to measure suction of GCLs from 10 to 1500 kPa, from 10 to 1000 kPa (recommended), and greater than 5000 kPa, respectively.
2. The moisture-suction behavior of a multi-component GCL is different from conventional, reinforced GCLs. The WNT GCL exhibited lower ψ_{ae} and higher ψ_r values than that of the WN2 and NN1 type GCLs. The moisture-suction data for WNT was more consistent (i.e., less scatter on the WRC) than the WN2 and NN1 type GCLs.
3. The difference (hysteresis) between wetting WRCs and drying WRCs was high at suction values less than or equal to ψ_{ae} , whereas hysteresis was low at suction values greater than ψ_{ae} . The magnitude of hysteresis among the GCLs ranged from 58 to 71 percentage points in terms of w_s and from 11 to 21 percentage points in terms of θ_s .
4. The macrostructure of wetting WRC GCL specimens consisted of a moderate gel structure with remnant bentonite granules, and intact needlepunched fibers. The macrostructure of drying WRC GCL specimens consisted of a

well-developed gel structure without remnant granules, and evidence of partial pullout of needlepunched fibers.

5. Mechanisms of hysteresis likely included ink-bottle effects, contact angle hysteresis, needlepunched fiber pullout, and macrostructure differences.

Hydration solution tests were conducted on each of the three types of GCLs. The hydration solutions consisted of DI water, tap water and 0.1 M CaCl_2 . Tap water simulated a dilute solution such as soil water, whereas 0.1 M CaCl_2 simulated a concentrated solution that would cause change to the bentonite chemistry and behavior. For WN2 a fourth hydration solution was used, which consisted of soil water that was in contact with a WN2 GCL in a landfill cover test plot. The hydration solution test procedure was identical to the baseline tests with DI water. Based on the results of the hydration solution tests, the following conclusions were drawn:

1. Significant variations were observed in the moisture-suction relationships of the GCLs as a function of hydration solution. The hysteresis between wetting WRCs and drying WRCs decreased progressively from DI water to tap water to CaCl_2 solution. The hysteresis of the NN1 GCL was largest, which decreased from 71 to 62 to 28 percentage points in terms of w_s , with DI water, tap water, and CaCl_2 solution, respectively.
2. The hysteresis between wetting WRCs and drying WRCs was lowest for the exhumed WN2 GCL that was subjected to 9 years of contact with soil water in a landfill cover test plot. Hysteresis was equal to 24 percentage points in

- terms of w_s . The wetting WRCs and drying WRCs were indistinguishable in terms of volumetric moisture content (i.e., no hysteresis was present).
3. The drying WRCs were affected more by the variation in the hydration fluid than the wetting WRCs. The drying WRCs translated downward, and the drying WRCs and wetting WRCs converged as the hydration solution varied from DI water to tap water to CaCl_2 solution.
 4. The water retention capacities of GCLs hydrated in DI water or tap water were greater than the water retention capacity of GCLs hydrated in CaCl_2 solution or soil water. At constant moisture content, the suctions for the tests with DI water and tap water were significantly higher than those for the CaCl_2 solution and the soil water.
 5. At suction values greater than approximately 1000 kPa, moisture-suction relationships were similar, regardless of hydration solution.
 6. The differences in observed behavior were attributed to cation exchange which affected the swelling capacity of the bentonite. Both crystalline swelling and osmotic swelling were assumed to have occurred in the GCL specimens hydrated with DI water or tap water. Only crystalline swelling was assumed to have occurred in the GCL specimens hydrated with CaCl_2 solution or soil water.

A cyclic wet-dry test was conducted using the NN1 GCL. NN1 GCL specimens were hydrated with a fine spray of DI water to 50% gravimetric moisture content for 8 hours and subsequently dried in a 60°C oven for 16 hours. The 24-hour hydration and dehydration process was repeated 20 times. After the

completion of 20 wet-dry cycles, the GCL specimens were prepared for suction testing in the same manner as the baseline tests. Based on the data obtained from the cyclic wet-dry test, the following conclusions were drawn:

1. Wet-dry cycles reduced the hysteresis between the wetting WRC and the drying WRC. The reduction amounted to 17 percentage points in terms of w_s and 11 percentage points in terms of θ_s .
2. Wet-dry cycles increased the swelling capacity of GCL specimens. Values of w_s increased by 30 to 47 percentage points, and θ_s increased by as much as 7 percentage points due to wet-dry cycles. The higher swelling capacity may be attributable to the changes to the bentonite microstructure that were imposed by wet-dry cycles.

Temperature tests were conducted using the WN2 GCL. WN2 specimens were hydrated in a manner identical to the baseline tests at room temperature (20°C). After the 30 day hydration period, the WN2 specimens were subjected to 2°C, 20°C, and 40°C in a temperature-controlled chamber for 24 hours. Suction tests were then performed at 2°C, 20°C, and 40°C, respectively. Based on the data obtained from the temperature tests, the following conclusions were drawn:

1. The test temperature in the range of 2°C to 40°C had a minimal influence on the moisture-suction relationships for GCLs.
2. Increasing temperatures resulted in small decreases in water retention capacity for previously-hydrated GCLs.

Supplementary tests, including: index tests, SEM microscopy, BC tests, and CEC tests were performed on bentonite that was removed from conditioned

GCLs. The swell index test and the determination of the Atterberg Limits were performed for bentonite that was removed from the GCLs from the hydration solution tests. SEM microscopy images were captured at 10,000x magnification for bentonite that was removed from GCLs subjected to varying hydration solutions and wet-dry cycles. The BC and CEC were determined for bentonite from the hydration solution tests. Individual mole fractions of the major bound cations Na, Ca, Mg, and K (X_{Na} , X_{Ca} , X_{Mg} , X_K) were calculated relative to the sum of the major bound cations. Based on the data obtained from the supplementary tests, the following conclusions were drawn:

1. The swell index of conditioned bentonite decreased progressively as a function of cation exchange. The swell index was 19.0 mL/2g for DI water, 18.0 mL/2g for tap water, 7.0 mL/2g for $CaCl_2$ solution, and 6.5 mL/2g for soil water. The swell index of each conditioned bentonite was less than the swell index for virgin sodium bentonite (26.0 mL/2g). The swell index of virgin bentonite was different from the swell index of bentonite conditioned in DI water due to the effect of one full cycle of hydration and oven-drying that was imposed on the conditioned bentonite sample hydrated in DI water.
2. The plasticity of the conditioned bentonite generally decreased as a function of cation exchange. The plasticity index of bentonite was 529% for DI water, 540% for tap water, 115% for $CaCl_2$ solution, and 111% for soil water. The plasticity index of each conditioned bentonite was less than the plasticity index for virgin sodium bentonite (611%). The plasticity index of virgin bentonite was different from the conditioned bentonite hydrated in DI water

- potentially due to the effect of one full cycle of hydration and oven-drying imposed on the conditioned bentonite specimen.
3. The reduction of swell index and plasticity were approximately linear with respect to divalent cation concentration of the hydration solution.
 4. The microfabric of virgin sodium bentonite consisted of single, flocculated montmorillonite platelets. Exposure to CaCl_2 solution caused montmorillonite platelets to aggregate.
 5. Wet-dry cycles caused the microfabric of sodium bentonite to become weakly oriented.
 6. The inter-aggregate void size increased with exposure to CaCl_2 solution or to wet-dry cycles, compared to the inter-aggregate void size of virgin sodium bentonite.
 7. The CEC for the bentonite of the GCLs ranged from 71 to 89 meq/100g.
 8. Sodium dominated the bound cations for GCLs conditioned with either DI water or tap water ($X_{\text{Na}} = 0.58$, $X_{\text{Ca}} = 0.33$), whereas calcium dominated the bound cations for GCLs submerged in 0.1 M CaCl_2 solution ($X_{\text{Na}} = 0.09$, $X_{\text{Ca}} = 0.83$). Calcium and magnesium dominated the bound cations ($X_{\text{Na}} = 0.01$, $X_{\text{Ca+Mg}} = 0.97$) for the exhumed GCL.
 9. The wetting WRC GCL specimens experienced less cation exchange than the drying WRC GCL specimens for the CaCl_2 solution due to the limited amount of calcium available for exchange with wetting WRC specimens. The bound sodium and calcium of wetting WRC specimens ($X_{\text{Na}} = 0.39$, $X_{\text{Ca}} = 0.52$) was less than for drying WRC specimens ($X_{\text{Na}} = 0.05$, $X_{\text{Ca}} = 0.94$). This

contributed to the low hysteresis and cross-over behavior of the wetting WRC and drying WRC of GCLs hydrated in CaCl_2 solution.

The GCL WRCs were used to predict the equilibrium moisture content of GCLs placed adjacent to soils. The WRCs also were used to predict the shear strength function and the permeability function for unsaturated GCLs. Based on the data obtained from the WRC predictions, the following conclusions were drawn:

1. The use of WRCs to predict the equilibrium moisture content of GCLs placed adjacent to soils tended to overestimate the measured equilibrium moisture content, as determined by Olsen (2011).
2. The use of WRCs to predict the equilibrium GCL moisture content may be valuable as a design tool to avoid subjecting the GCL to excessive shrinkage that would otherwise cause panel separation or cause permanent increases to hydraulic conductivity due to the occurrence of cation exchange.
3. WRCs along with known strength parameters may be used to predict the shear strength function for unsaturated GCLs.
4. WRCs along with known values of k_{sat} may be used to predict the permeability function, $k(\psi)$ for unsaturated GCLs. The coefficient of permeability decreased by several orders of magnitude at suction values greater than ψ_{ae} . Unsaturated flow through GCLs permeated with CaCl_2 solutions may be 5 to 100 times greater than the flow through GCLs permeated with DI water, at a given suction.

6.2 Recommendations

Based on results of the test program, recommendations are provided that could potentially improve the performance of GCLs used in landfill barrier systems. Also, opportunities for future research are identified.

WRCs are important for GCLs as they provide indications of engineering properties and response. GCL WRCs are affected by GCL type, cation exchange, wet-dry cycles, and temperature, which must all be considered in design applications. The use of soil WRCs and GCL WRCs tended to over-predict the equilibrium GCL moisture content, compared to measured GCL moisture contents. If WRCs are used for in-situ predictions of suction and moisture content, the hysteresis of the GCL WRCs, the potential of cation exchange from the soil, and the field overburden stress conditions must be known.

The use of GCL WRCs to predict the permeability function of GCLs assumes that the mass of bentonite is evenly distributed within the GCL specimen. Macrofeatures such as desiccation cracks may potentially affect the coefficient of permeability, especially if the self-healing capacity of the GCL has been reduced due to cation exchange. The permeability function of GCLs should be determined experimentally, using ASTM D7664 or a modification thereof.

In consideration of the degree of hydration necessary for long-term GCL performance, the need to ensure hydraulic performance of GCLs must be balanced by the need to provide adequate shear strength in the barrier system.

As a result of the hydration solution test, it was determined that the WRCs of GCLs that were initially hydrated in either CaCl_2 solution or soil water exhibited lower water retention capacity than GCLs that were initially hydrated in DI water or tap water. GCLs in the field may hydrate in dilute solutions and be subsequently subjected to cation exchange over time. Future testing is needed to determine the moisture-suction responses for GCLs that are initially hydrated with dilute solutions, then subjected to cation exchange.

The hydration tests were conducted with dilute solutions containing multiple species of cations or with a highly concentrated solution containing a single species of cation. Future testing is needed to determine the wetting WRCs and drying WRCs for GCLs that are hydrated with solutions of moderate concentration and with solutions containing multiple species of cations.

The cyclic wet-dry test was conducted with deionized water. Moisture-suction relationships have not been determined for GCLs subjected to wet-dry cycles using other solutions. The number of cycles, moisture fluctuation within a cycle, and the concentration of the hydration fluid would all likely contribute to the moisture-suction response of wet-dry cycled GCLs. Future testing is needed to determine the moisture-suction responses for GCLs that are subjected to cation exchange and wet-dry cycles.

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APPENDIX

Table A.1. Gravimetric Fredlund and Xing (1994) parameters (hydration solution tests)

Test Name	Hydration Solution	Water Retention Curve	GCL Type	Ψ_r	w_s	a	m	n
DI water test	DI water	Wetting	WN2	189	142	617	0.353	11.6
			NN1	10000	139	521	0.673	4.85
			WNT	574	145	100000	26.4	0.604
		Drying	WN2	2280	200	270	0.836	3.39
			NN1	1010	210	220	0.673	4.04
			WNT	33500	214	249	1.39	1.61
Tap water test	Tap water	Wetting	WN2	658	167	441	1.54	0.909
			NN1	3050	135	799	0.405	12.9
			WNT	1110	138	525	1.31	1.61
		Drying	WN2	147000	205	354	0.999	3.40
			NN1	134000	197	341	0.707	7.00
			WNT	79800	187	244	0.903	2.84
CaCl ₂ solution test	0.1 M CaCl ₂ solution	Wetting	WN2	2450	81.8	763	0.342	5.01
			NN1	1470	79.6	30700	3.50	0.715
			WNT	1990	79.2	605	0.236	12.2
		Drying	WN2	104	93.5	1510	0.178	9.77
			NN1	2040	108	8790	3.35	0.406
			WNT	1190	103	43500	3.20	0.182
Exhumed GCL Test	Soil Water ^a DI water	Wetting	WN2	8570	58.9	69.1	0.455	1.09
		Drying	WN2	855000	83.0	56.9	1.03	0.676

^a 9 years of prior contact with moist soil in a landfill cover test plot, containing abundant multi-valent cations

Table A.2. Volumetric Fredlund and Xing (1994) parameters (hydration solution tests)

Test Name	Hydration Solution	Water Retention Curve	GCL Type	Ψ_r	θ_s	a	m	n
DI water test	DI water	Wetting	WN2	7580	69.4	586	0.496	4.11
			NN1	89900	63.3	507	0.898	2.03
			WNT	362	63.6	533	0.835	0.955
		Drying	WN2	24600	84.6	430	0.343	20.0
			NN1	40100	84.1	355	0.449	9.28
			WNT	45500	75.3	493	0.708	4.77
Tap water test	Tap water	Wetting	WN2	401	89.0	9990	3.85	0.342
			NN1	2810	62.8	756	0.366	8.72
			WNT	763	70.9	17900	6.49	0.661
		Drying	WN2	362	85.8	433	0.222	24.5
			NN1	131000	76.9	364	0.509	7.85
			WNT	5740	74.0	337	0.707	3.04
CaCl ₂ solution test	0.1 M CaCl ₂ solution	Wetting	WN2	6980	60.0	54.0	0.898	0.671
			NN1	22900	45.7	4610	1.76	0.831
			WNT	9990	50	716	0.496	2.14
		Drying	WN2	509	69.1	995	0.308	3.44
			NN1	1930	70.3	2920	2.04	0.443
			WNT	830	70.5	1390	1.57	0.197
Exhumed GCL Test	Soil Water ^a DI water	Wetting	WN2	2480	3640	51.5	16.2	0.0274
		Drying	WN2	855000	68.0	68.2	1.08	0.641

^a 9 years of prior contact with moist soil in a landfill cover test plot, containing abundant multi-valent cations

Table A.3. Gravimetric Fredlund and Xing (1994) parameters (wet-dry cyclic test, temperature tests)

Hydration Solution	GCL Conditioning	GCL Type	Water Retention Curve	Ψ_r	w_s	a	m	n
DI water	20 wet-dry cycles	NN1	Wetting	1680	186	309	1.61	0.906
			Drying	36000	240	265	1.29	1.93
DI water	2°C	WN2	Wetting	2100	135	1000	0.343	18.2
			Drying	328000	233	402	1.93	0.892
DI water	40°C	WN2	Wetting	80100	140	481	0.979	2.51
			Drying	20000	234	468	1.62	1.24

Table A.4. Volumetric Fredlund and Xing (1994) parameters (wet-dry cyclic test, temperature tests)

Hydration Solution	GCL Conditioning	GCL Type	Water Retention Curve	Ψ_r	θ_s	a	m	n
DI water	20 wet-dry cycles	NN1	Wetting	1680	70.0	320	0.657	1.61
			Drying	106000	80.2	354	0.699	2.91
DI water	2°C	WN2	Wetting	2390	74.0	777	0.276	6.27
			Drying	2000	88.4	318	0.965	1.03
DI water	40°C	WN2	Wetting	2470	69.1	667	0.733	2.47
			Drying	855000	83.0	693	1.17	1.54

Table A.5. Gravimetric Fredlund and Xing (1994) parameters (soil tests)

Hydration Solution	Soil Type	Water Retention Curve	Ψ_r	w_s	a	m	n
Tap	SP	Wetting	8560	19.5	3.65	0.630	10.1
		Drying	33700	19.5	4.70	0.712	9.38
Tap	CL (Dry of Opt)	Wetting	5010	28.0	2.58	0.623	0.967
		Drying	98400	31.2	7.93	1.09	0.702
Tap	CL (Wet of Opt)	Wetting	7.50	23.3	8.52	0.121	3.75
		Drying	100000	23.3	271	1.45	0.588
DI	SC1	Wetting	0.730	24.5	75.5	1.38	0.202
		Drying	9814	24.8	6	0.671	0.948
DI	SC2	Wetting	51500	15.1	482000	13.1	0.429
		Drying	89537	24.1	19700	5.94	0.277

Figure A.1. Degree of saturation and bulk void ratio relationships to suction for WN2 GCL (baseline test)

Figure A.2. Degree of saturation and bulk void ratio relationships to suction for WN2 GCL (Tap water test)

Figure A.3. Degree of saturation and bulk void ratio relationships to suction for WN2 GCL (CaCl₂ solution test)

Figure A.4. Degree of saturation and bulk void ratio relationships to suction for WN2 GCL (Exhumed GCL test)

Figure A.5. Degree of saturation and bulk void ratio relationships to suction for NN1 GCL (baseline test)

Figure A.6. Degree of saturation and bulk void ratio relationships to suction for NN1 GCL (Tap water test)

Figure A.7. Degree of saturation and bulk void ratio relationships to suction for NN1 GCL (CaCl₂ solution test)

Figure A.8. Degree of saturation and bulk void ratio relationships to suction for WNT GCL (baseline test)

Figure A.9. Degree of saturation and bulk void ratio relationships to suction for WNT GCL (Tap water test)

Figure A.10. Degree of saturation and bulk void ratio relationships to suction for WNT GCL (CaCl₂ solution test)

Figure A.11. Degree of saturation and bulk void ratio relationships to suction for NN1 GCL (20 Wet-dry Cycles test)

Figure A.12. Degree of saturation and bulk void ratio relationships to suction for WN2 GCL (2°C Temperature Test)

Figure A.13. Degree of saturation and bulk void ratio relationships to suction for WN2 GCL (40°C Temperature Test)

Table A.6. Moisture-suction data measurements for WN2 GCL (DI water test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
16	144.9	72.6	97.9	2.9	1	264.9	78.6	99.3	3.8
18	135.2	70.9	96.4	2.8	1	171.2	81.3	102.8	3.8
36	149.4	69.0	88.2	3.6	1	185.9	78.2	97.0	4.1
63	122.5	64.8	87.8	2.8	1	195.7	70.4	82.7	5.7
98	139.5	70.3	91.9	3.2	1	189.3	83.2	102.1	4.4
149	128.7	66.3	87.6	3.1	1	222.7	85.6	102.0	5.2
159	133.4				1	252.6	86.7	103.9	5.0
199	130.3	68.7	91.1	3.1	1	226.3	81.5	98.1	4.9
456	122.9				1	208.5	89.5	108.5	4.7
506	117.0	65.8	89.8	2.7	10	216.0			
622	112.5				30	178.5			
657	103.1				30	214.9			
666	85.8				59	219.4	81.5	98.1	4.9
767	96.9	54.8	74.9	2.7	100	182.5			
783	70.4				100	190.7			
833	68.1	43.6	62.3	2.3	110	180.6			
2120	42.3	30.0	45.0	2.0	119	183.9			
18153	18.4	14.0	21.4	1.9	132	203.4	88.3	110.6	4.0
53703	13.9	11.2	17.8	1.7	158	185.5	84.7	108.0	3.6
110443	4.6	3.8	6.3	1.5	225	194.0	82.1	104.0	3.7
228613	1.3				229	228.6	84.8	103.1	4.7
233115	1.0				246	106.1			
					258	138.7			
					300	156.8			
					307	102.7			
					348	181.6	85.3	114.6	2.9
					513	91.1	55.5	76.7	2.6
					561	73.1	45.1	64.0	2.4
					798	56.9	36.7	52.7	2.3
					42638	16.3	12.1	18.8	1.8
					56486	13.7	12.9	22.7	1.3
					87596	12.2			
					90210	10.0			
					130175	8.6			

Table A.7. Moisture-suction data measurements for WN2 GCL (Tap water test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
96	144.7	66.5	85.9	3.4	1	223.8	86.4	106.1	4.4
105	136.0	64.7	83.7	3.4	1	228.9	87.1	106.5	4.5
107	144.5	60.8	76.7	3.8	1	211.9	85.4	105.5	4.2
117	166.7	71.6	90.1	3.9	1	224.2	84.8	103.6	4.5
127	134.5	62.1	80.5	3.4	10	211.3			
156	124.3				30	215.2	87.0	108.1	4.1
200	118.6				62	201.9	84.1	104.8	4.1
268	96.7	49.5	65.7	3.1	96	202.2	76.1	92.3	4.7
318	119.6	58.5	76.9	3.2	204	174.1	76.2	96.2	3.8
339	105.5				275	186.6	78.7	98.8	3.9
468	121.1	57.6	75.2	3.3	297	168.1	72.5	91.4	3.8
471	109.9				301	161.3	76.4	98.1	3.5
556	91.2				306	177.2	73.4	91.3	4.1
782	65.7				322		82.8		
827	96.5	51.0	68.4	2.9	406	135.0	72.4	96.9	3.0
1049	73.0	43.7	60.6	2.6	420	154.9	76.8	95.0	2.9
1370	72.7	46.5	67.0	2.3	441	132.3	70.9	95.0	2.9
1510	47.6	29.5	42.0	2.4	468	122.9	64.8	86.7	2.9
2105	36.4	25.2	37.7	2.0	602	88.5	49.1	66.8	2.8
41926	16.5	4.8	7.5	1.8	879	51.4	33.9	49.7	2.1
83072	6.5	13.0	20.7	1.7	4786	28.8	21.6	33.8	1.8
129100	3.5	2.7	4.3	1.7	13478	24.2	18.9	30.1	1.7
					19682	24.0			
					39435	18.5			
					55366	17.0			
					56936	15.0	13.9	24.8	1.3
					202093	2.3			

Table A.8. Moisture-suction data measurements for WN2 GCL
(CaCl₂ solution test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
10	85.2	54.7	78.7	2.3	1	90.8			
13	77.5	53.5	78.5	2.1	1	96.2			
820	77.6				10	96.7	69.2	110.0	1.7
920	50.7				30	76.5			
1067	64.6				428	80.3	62.8	99.1	1.7
1114	62.9				1474	64.7	50.8	79.6	1.8
1521	45.0				1630	58.3	45.1	71.1	1.7
1876	34.3	18.9	26.0	2.7	2568	45.2	35.0	54.7	1.8
2222	51.9	25.5	34.0	3.0	4315	38.5	31.2	50.6	1.6
3087	40.9	23.4	32.6	2.5	8397	27.5	22.5	36.3	1.6
4698	29.0	21.6	33.6	1.8	44013	16.8	12.9	20.3	1.7
18183	21.2	13.1	18.8	2.3	140787.5	10.4			
65206	14.2	9.1	13.2	2.2					
96811	6.8	4.8	7.2	2.0					
138886	4.0	2.4	3.3	2.5					

Table A.9. Moisture-suction data measurements for WN2 GCL
(exhumed GCL test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
19	56.6				1	84.6	67.9		
49	53.9	46.4	75.8	1.6	1	81.5	66.9		
123	47.9	42.0	70.7	1.5	1		69.3		
174	45.9				10	80.6			
471	40.0	33.5	55.2	1.5	10	73.3			
12117	19.9	16.6	27.1	1.6	13	73.6	58.2	92.8	1.7
40221	16.3	11.9	18.7	1.7	30	70.4			
128439	11.0	11.2	20.4	1.2	33	61.9	57.2	95.3	1.5
					55	62.1	49.6	79.3	1.7
					55	61.7	53.5	88.4	1.5
					75	59.2	51.7	83.8	1.6
					170	53.1	44.3	71.7	1.6
					294	46.7	38.3	61.6	1.6
					319	48.2	39.1	63.5	1.6
					677	39.3	35.1	59.9	1.4
					786	36.1	28.5	45.7	1.7
					19849	18.9	15.6	25.9	1.5
					21440	19.3	18.4	33.0	1.3
					43939	16.2	13.3	21.6	1.6
					92002	12.9	9.9	15.7	1.7

Table A.10. Moisture-suction data measurements for NN1 GCL (DI water test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
28	129.4	60.5	78.1	3.4	1	206.2	80.9		
65	159.6	68.2	86.6	3.7	1	198.2	78.2		
84	132.4	59.4	76.4	3.5	1	205.1	78.3		
195	121.8	57.8	75.4	3.3	1	220.1	84.9		
223	146.3	66.3	85.6	3.4	1	230.1	84.8		
302	92.2	49.5	66.9	2.8	1	226.6	81.7		
305	155.1				1	206.4	79.9		
334	164.3	65.7	81.6	4.1	1	215.9	79.9		
340	147.1				1	216.2	84.3		
407	158.3	65.0	81.0	4.1	1	234.4	84.0		
415	137.4				1	223.9	80.3		
430	116.9				1	200.1	79.1		
432	127.1				1	208.7	79.6		
438	70.2	41.9	59.9	2.3	1	210.1	82.7		
481	96.6				1	204.2	79.5		
531	139.4	57.7	72.2	4.0	10	227.5			
651	111.8	53.3	69.1	3.4	30	217.5			
838	90.3	46.0	61.0	3.1	30	200.2			
842	64.0	35.2	49.4	2.5	100	178.0			
889	40.5	28.8	44.7	1.8	100	172.5			
3944	40.0				102	131.5			
7729	19.6	13.3	19.9	2.0	119	233.8	85.5	104.5	4.5
28840	14.1	9.6	14.3	2.0	145	122.5			
179312	1.7				163	147.2			
285793	0.2				200	129.3			
303792	0.4				227	223.6	82.4	101.0	4.4
					280	94.9			
					300	190.4			
					340	182.6	76.1	95.8	3.9
					386	147.2	69.6	91.4	3.2
					457	106.9	52.8	69.6	3.2
					566	83.6	45.7	62.7	2.7
					793	53.7	31.8	45.1	2.4
					6949	31.6	20.1	29.1	2.2
					10562	24.0	15.2	21.8	2.3
					87744	11.7			
					135161	9.9			

Table A.11. Moisture-suction data measurements for NN1 GCL (Tap water test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
241	145.1	60.2	75.6	3.9	1	225.9	75.1	92.5	4.3
259	153.6	61.4	76.8	4.0	1	212.7	84.3	104.5	4.2
301	139.1				1	204.7	82.5	102.9	4.1
309	132.2	59.5	76.4	3.5	1	214.5	81.7	100.6	4.3
336	143.1				30	199.9	72.3	88.9	4.4
390	114.1				30	181.7	77.6	98.6	3.7
427	125.4				45	190.6	17.4	26.8	1.9
508	104.4				132	181.5	9.9	15.6	1.7
515	136.0	58.2	73.9	3.7	159	216.3	81.1	100.0	4.3
519	146.5	59.4	74.5	3.9	182	205.3	77.2	96.3	4.0
545	155.1	65.5	82.4	3.9	217	201.9	77.6	96.2	4.2
550	92.6				302	193.4			
583	150.3	63.5	80.4	3.8	311	167.2	70.6	89.4	3.8
599	136.9	59.5	75.8	3.7	319	146.1	71.0	90.4	3.7
785	119.9	54.4	69.6	3.6	358	171.4	79.3	98.2	4.2
869	122.5	52.5	67.3	3.5	403	132.3	67.2	86.4	3.5
936	72.4	38.3	51.7	2.9	416	122.8	61.1	78.6	3.5
954	57.9	33.9	47.7	2.5	443	118.2	56.3	73.0	3.4
1055	96.9	46.8	61.1	3.3	559	83.5	55.7	71.9	3.4
1074	93.7	43.9	57.3	3.3	606	59.0	43.1	57.3	3.1
1922	46.6	28.3	40.3	2.4	7677	29.8	7.0	11.5	1.6
2589	37.2	22.6	32.1	2.4	25287	19.5	72.8	90.4	4.1
12117	18.6	12.7	19.0	2.0	77745	12.9	78.2	97.7	4.0
40221	14.1	10.3	15.9	1.8	225765	2.3	33.3	45.6	2.7
79356	6.4	4.2	6.3	2.1					
135161	2.8	2.0	3.1	1.8					

Table A.12. Moisture-suction data measurements for NN1 GCL
(CaCl₂ solution test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
10	84.4	49.6	69.2	2.5	1	100.1	69.5	100.8	2.2
26	69.1	40.6	56.8	2.5	1	106.7	69.2	100.7	2.2
782	78.3				1	105.3	70.3	103.7	2.1
799	70.6				1	106.3	70.9	100.5	2.4
857	61.3				1	113.8	71.8	103.3	2.3
879	70.1				10	94.5			
880	66.2				30	73.0			
960	67.0				203	76.1	51.2	75.5	2.1
1265	66.8	41.4	58.9	2.4	714	73.1	46.4	67.1	2.2
1659	51.3	30.8	43.2	2.5	1422	72.9	48.0	71.1	2.1
5385	43.0	26.4	37.7	2.3	1604	72.7	49.3	73.8	2.0
18122	20.6	13.1	19.0	2.2	1801	57.6	40.2	60.3	2.0
64875	12.9	8.4	12.3	2.1	2387	47.0	32.3	48.6	2.0
99609	5.8	3.9	5.7	2.1	5209	30.2	22.3	34.7	1.8
136779	2.9	1.9	2.7	2.2	9792	24.8	19.0	30.3	1.7
					18122	21.4	16.0	25.2	1.7
					57520	15.8	12.1	19.4	1.7
					142958	9.1	7.0	11.0	1.7

Table A.13. Moisture-suction data measurements for WNT GCL (DI water test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
17		64.0	86.1	2.9	1	221.3	75.8	96.8	3.6
22	136.9	67.3	87.8	3.3	1	207.9	76.8	95.8	4.1
28		59.3	79.0	3.0	1	209.0	81.1	99.8	4.3
29	130.1	67.8	89.5	3.1	1	219.6	77.1	96.1	4.1
31		54.3	74.7	2.7	1	212.8	80.9	99.0	4.5
31	136.7				1	209.9	82.6	100.4	4.6
57	127.7				1	230.0	78.7	95.2	4.8
75		55.2	79.9	2.2	10	219.5			
168	113.7	62.8	84.0	3.0	30	228.5			
179		45.8	66.1	2.3	30	209.2			
191	117.9				49	195.4			
251	106.2				57	185.2	69.0	83.5	4.7
318	95.9				57	193.4	80.0	98.5	4.3
458	93.9	49.3	66.1	2.9	100	166.5			
492	98.8	49.6	66.1	3.0	100	180.5			
550		52.4	71.3	2.8	132	173.8	68.1	83.4	4.4
641		41.7	58.8	2.4	137	202.6	77.3	94.1	4.6
1059		29.5	43.9	2.1	161	187.8	76.9	95.5	4.1
1104	66.9	42.7	61.2	2.3	174	149.5			
1816	43.0	28.3	40.9	2.2	178	207.0	80.9	99.0	4.5
12056	14.1	22.4	31.9	2.4	218	143.4			
226529	1.1				239	123.7			
355111	0.3				300	147.5			
					429	98.7	58.7	81.8	2.5
					444	63.8			
					444	157.7	72.5	92.0	3.7
					585	96.0	57.0	78.6	2.6
					755	56.0	34.1	47.3	2.6
					855	68.7	40.9	56.8	2.6
					16580	15.8	9.0	12.3	2.8
					28257.81	19.0			
					90210.1	11.0			
					166237.4	7.1			
					322906.9	0.4			

Table A.14. Moisture-suction data measurements for WNT GCL (Tap water test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
12	143.5	70.2	91.0	3.4	1	190.6			
49	135.8				1	195.8			
73	132.1	61.8	79.3	3.5	1	187.6			
98	135.3	65.0	84.2	3.4	1	194.1			
130	129.4				1	179.8			
150	119.8	59.0	77.5	3.2	1	184.9			
153	124.3	64.6	85.5	3.1	1	199.3	76.7	98.3	3.5
241	109.6				1	205.9	79.5	101.3	3.6
253	118.7				10	181.4			
430	98.9				30	175.7	72.8	90.2	4.2
474	97.0	57.1	78.9	2.6	57	185.2	69.0	83.5	4.7
650	93.6	58.7	83.0	2.4	71	186.2	77.5	95.7	4.2
816	72.2	48.8	71.3	2.2	76	192.8	77.7	95.3	4.4
860	71.2	47.6	70.5	2.1	99	184.4	75.7	93.2	4.3
1365	45.6	36.5	59.6	1.6	132	173.8	68.1	83.4	4.4
1369	38.5	31.8	51.8	1.6	142	197.3	77.9	94.9	4.6
41926	15.6				214	145.3	67.9	86.7	3.6
72214	6.9				222	150.4	65.0	81.4	3.9
138180	2.9				239	145.0	64.3	80.8	3.9
					252	136.9	69.2	90.2	3.3
					474	83.8	46.2	61.9	3.0
					481	114.4	58.4	77.0	3.1
					717	60.9	35.8	49.3	2.7
					974	42.7	26.7	37.5	2.5
					6973	26.3			
					13455	22.0	14.6	21.6	2.1
					21224	19.8			
					78689	12.7			
					194006	2.5			
					247438	1.1	0.7	1.1	2.1

Table A.15. Moisture-suction data measurements for WNT GCL
(CaCl₂ solution test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w _s (%)	Vol. Moist. Cont., θ _s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e _b	Suction (kPa)	Grav. Moist. Cont., w _s (%)	Vol. Moist. Cont., θ _s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e _b
14	77.9	48.6	68.0	2.5	1	84.4			
30	72.8	48.0	69.1	2.3	1	90.9			
90	84.5				1	96.4			
260	80.9				1	104.8	66.4	95.3	2.3
261	76.9	52.3	78.7	2.0	1	100.9			
443	75.5				1	110.0	73.2	107.4	2.1
602	70.4				1	103.8	71.7	107.2	2.0
659	68.1	47.7	71.3	2.0	10	83.2			
796	59.0				10	79.7	54.8	82.3	2.0
923	50.1				20	73.6	57.3	89.6	1.8
945	38.1	31.1	50.5	1.6	30	75.2			
1424	52.9	40.4	62.8	1.8	544	62.2	44.5	66.8	2.0
1670	40.4	32.2	50.8	1.7	550	70.2	48.9	73.3	2.0
12035	22.5	17.8	28.2	1.7	1489	54.1	38.3	57.3	2.0
57423	14.9	11.9	18.9	1.7	1788	47.0	35.9	56.6	1.7
92718	7.1	5.9	9.6	1.6	2543	60.2	44.5	68.5	1.9
155160	2.6	2.1	3.5	1.6	4072	34.2	25.9	40.3	1.8
					10580	29.5	24.1	39.6	1.6
					95595	11.5	9.1	14.6	1.6

Table A.16. Moisture-suction data measurements for NN1 GCL
(Wet-dry cyclic test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
47	168.4	69.4	86.6	4.0	1	216.2	80.3	97.5	4.7
224	121.7	59.2	76.9	3.3	1	218.8	79.1	98.0	4.2
246	149.3	64.2	80.6	3.9	1	219.2	79.6	97.7	4.4
259	98.6	55.8	76.3	2.7	1	219.3	82.7	102.5	4.2
607	123.6	57.7	75.3	3.3	1	219.3	79.5	98.4	4.2
719	98.6	49.9	67.1	2.9	1	224.8			
762	34.4	23.7	34.9	2.1	1	242.0			
1047	73.1	39.4	53.7	2.7	1	235.0			
1217	66.4	38.4	53.7	2.5	1	210.0			
77754	8.9				10	234.5			
121209	4.0				30	238.2			
151237	2.9				193	241.2	85.0	102.7	4.8
177090	1.5				214	186.7	70.0	85.5	4.5
					226	207.8	77.1	94.2	4.5
					249	83.3			
					251	170.7	67.8	84.0	4.2
					369	152.7	67.9	86.7	3.6
					460	136.3	61.7	79.5	3.5
					486	94.1	49.8	67.5	2.8
					566	122.6	55.8	73.5	3.1
					714	91.2	42.2	54.6	3.4
					723	80.7	47.2	65.9	2.5
					962	51.4	32.2	46.4	2.3
					131530	7.7			

Table A.17. Moisture-suction data measurements for WN2 GCL
(2°C temperature test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
318	131.5	69.6	92.5	3.0	1	253.4	88.5	104.8	5.4
557	133.2	67.3	88.4	3.2	1	229.0	82.8	99.5	5.0
576	133.8				1	219.3	84.4	102.7	4.6
634	125.6	64.3	85.4	3.0	1	239.4	85.0	102.6	4.8
725	111.2	62.3	85.8	2.6	1	232.7	86.8	105.4	4.7
771	133.6	68.1	92.3	2.8	1	225.5	84.2	102.5	4.6
872	130.6	71.9	96.7	2.9	199	235.5	86.8	105.4	4.7
872	130.6				102	234.6	77.6	92.2	5.3
1074	99.7	53.7	73.7	2.7	245	188.9	75.4	92.6	4.4
1230	84.2	49.7	71.3	2.3	161	201.1	79.4	98.0	4.3
1354	66.9	44.1	64.0	2.2	60	168.7	77.4	98.3	3.7
2438	45.6	32.3	49.2	1.9	119	158.5	73.5	94.0	3.6
4573	36.5	39.2	79.0	1.0	172	134.0	69.6	93.3	2.9
51040	14.2				248	108.1	58.7	80.1	2.7
162235	2.4				861	91.4	45.8	60.4	3.1
					2475	57.9	35.9	50.8	2.4
					3684	47.0	27.2	37.7	2.6
					21581	24.9			
					165128	5.9			
					106088	8.8			

Table A.18. Moisture-suction data measurements for WN2 GCL
(40°C temperature test)

Wetting Curve					Drying Curve				
Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b	Suction (kPa)	Grav. Moist. Cont., w_s (%)	Vol. Moist. Cont., θ_s (%)	Deg. of Sat., S (%)	Bulk GCL Void Ratio, e_b
24	146.3	73.1	96.4	3.1	1	251.8	87.7	104.8	5.1
34	127.1	63.9	84.0	3.2	1	224.1	83.5	101.7	4.6
39	144.8	68.5	88.1	3.5	1	223.4	85.3	104.2	4.5
148	139.9	69.1	90.5	3.2	1	239.1	84.3	100.6	5.2
302	131.5	69.5	93.6	2.9	1	207.3	81.6	100.0	4.4
350	114.9	62.3	84.5	2.8	30	235.8			
395	125.5	64.6	86.1	3.0	87	209.6			
397	106.2	58.7	80.4	2.7	94	191.3	78.8	98.7	4.0
670	92.6	55.9	77.6	2.6	100	240.0			
859	71.0	47.5	68.0	2.3	134	204.5	79.0	97.0	4.4
1820	39.9	30.7	48.1	1.8	169	212.4	82.6	101.0	4.5
1882	40.0	29.5	45.3	1.9	268	173.3	73.5	92.6	3.8
39471	16.2				433	84.6	51.3	71.3	2.6
175298	4.1				465	225.4	79.1	95.2	4.9
183083	2.7				537	136.6	68.5	90.2	3.1
					830	61.8	38.4	54.2	2.4
					841	152.0	73.6	95.7	3.3
					1123	121.6	60.1	78.6	3.3
					2202	37.2	23.4	32.9	2.5
					4838	31.2	19.5	27.7	2.4
					26589	22.0	15.0	22.6	2.0
					37830	16.6			
					74016	13.7	9.6	14.6	1.9
					146002	7.2			
					186265	3.6

Figure A.14. Permeability function for WN2 GCL (baseline test)

Table A.19. k_r data for WN2 GCL (baseline Test)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
0.730998	0.550974	1	0.948085
1.602544	0.55003	1	0.948065
3.513204	0.549087	3	0.948044
7.701883	0.548143	6	0.948023
16.88459	0.547201	13	0.948002
37.01553	0.546259	29	0.947982
81.14795	0.545282	66	0.947961
177.898	0.543791	147	0.947941
390	0.529169	327	0.94792
854.9843	0.127116	730	0.005062
1874.354	0.0052	1628	0.000192
4109.086	0.000434	3632	1.95E-05
9008.215	5.7E-05	8105	3.4E-06
19748.42	8.88E-06	18083	7.61E-07
43293.81	1.43E-06	40347	1.73E-07
94911.62	2.29E-07	90025	3.55E-08
208071.7	3.24E-08	200867	5.83E-09

Figure A.15. Permeability function for WN2 GCL (tap water)

Table A.20. k_r data for WN2 GCL (tap water)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	1	1	0.94127
1	1	1	0.90827
4	1	3	0.87546
10	1	6	0.84303
26	0.53979	14	0.81145
69	0.14107	32	0.78161
180	0.03332	70	0.75517
469	0.00644	156	0.73447
1222	0.00095	346	0.72131
3186	0.00011	768	0.00679
8307	1E-05	1703	0.0005
21654	7.6E-07	3779	6.2E-05
56449	4.7E-08	8384	9.3E-06
147153	2.3E-09	18601	1.5E-06
		41270	2.5E-07
		91564	4.3E-08
		203149	6.6E-09

Figure A.16. Permeability function for WN2 GCL (CaCl_2 solution)

Table A.21. k_r data for WN2 GCL (CaCl_2 solution)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	1	1	1
2	1	2	1
6	0.91042	5	1
19	0.2341	11	1
55	0.04306	23	0.90513
164	0.00543	49	0.71577
486	0.00051	105	0.54816
1446	4.4E-05	225	0.41342
4301	4E-06	482	0.30766
12790	3.6E-07	1035	0.16269
38032	2.9E-08	2220	0.01658
113093	2.1E-09	4766	0.00153
		10229	0.00019
		21954	2.9E-05
		47121	4.7E-06
		101138	7.9E-07
		217075	1.2E-07

Figure A.17. Permeability function for exhumed WN2 GCL (soil water)

Table A.22. k_r data for exhumed WN2 GCL (soil water)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	0.37297	1	1
5	0.08017	2	1
19	0.00799	7	0.89814
73	0.00041	20	0.22302
286	1.8E-05	60	0.04027
1114	1.1E-06	177	0.005
4339	8E-08	521	0.00044
16905	4.6E-09	1534	3.1E-05
65869	2.3E-10	4517	2E-06
		13300	1.5E-07
		39164	1.7E-08
		115326	2.5E-09

Figure A.18. Permeability function for NN1 GCL (baseline test)

Table A.23. k_r data for NN1 GCL (baseline test)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	0.54131	1	0.86118
2	0.54127	2	0.86117
4	0.54119	5	0.86116
10	0.54095	11	0.86114
22	0.53997	25	0.86113
50	0.53538	56	0.86112
115	0.51248	127	0.86111
262	0.40835	287	0.861
598	0.14153	649	0.01056
1365	0.01104	1467	0.00035
3113	0.00058	3315	2.8E-05
7100	4.1E-05	7494	4E-06
16196	4.3E-06	16941	7.9E-07
36942	6.2E-07	38296	1.8E-07
84263	1.1E-07	86569	3.7E-08
192203	1.6E-08	195693	6.1E-09

Figure A.19. Permeability function for NN1 GCL (tap water)

Table A.24. k_r data for NN1 GCL (tap water)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	0.7337	1	0.83098
2	0.72975	2	0.83098
3	0.72579	5	0.83098
7	0.72185	11	0.83097
15	0.71792	24	0.83097
32	0.71401	55	0.83097
66	0.71017	125	0.83096
139	0.70645	283	0.83075
292	0.70296	641	0.01569
611	0.6985	1450	0.00043
1281	0.02327	3283	2.9E-05
2684	0.00131	7431	3.2E-06
5626	0.00016	16823	5.5E-07
11793	2.5E-05	38082	1.3E-07
24718	4.3E-06	86206	3.4E-08
51810	7.6E-07	195145	7E-09
108596	1.4E-07		
227619	2.2E-08

Figure A.20. Permeability function for NN1 GCL (CaCl₂ solution)

Table A.25. k_r data for NN1 GCL (CaCl₂ solution)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	1	1	1
2	1	1	1
4	1	3	1
9	1	7	1
18	1	17	1
37	1	39	1
78	1	91	0.46162
161	0.72492	212	0.14717
333	0.41828	494	0.04262
689	0.21234	1151	0.01055
1427	0.08977	2682	0.00209
2955	0.02955	6249	0.00032
6120	0.00713	14560	4E-05
12675	0.00124	33926	4.2E-06
26249	0.00016	79050	3.8E-07
54361	1.7E-05	184190	2.9E-08
112581	1.6E-06		
233155	1.4E-07

Figure A.21. Permeability function for WNT GCL (baseline test)

Table A.26. k_r data for WNT GCL (baseline test)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	1	1	0.6513
1	1	1	0.65127
4	1	3	0.65125
9	1	7	0.65122
21	0.99871	15	0.6512
52	0.58869	32	0.65117
127	0.27615	72	0.65114
311	0.09032	158	0.65106
764	0.01812	351	0.6437
1874	0.00223	778	0.05701
4595	0.0002	1723	0.00131
11269	1.7E-05	3817	7.5E-05
27639	1.4E-06	8456	7.6E-06
67786	1.3E-07	18735	1.1E-06
166250	1.1E-08	41507	2E-07
		91959	3.6E-08
		203733	5.5E-09

Figure A.22. Permeability function for WNT GCL (tap water)

Table A.27. k_r data for WNT GCL (tap water)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	1	1	0.54663
1	1	1	0.54619
3	1	3	0.54575
7	1	7	0.5453
16	1	16	0.54482
38	1	36	0.54412
90	0.51675	85	0.54145
209	0.22276	200	0.50638
488	0.07763	469	0.13494
1138	0.02002	1099	0.00474
2655	0.00351	2575	0.00025
6196	0.00038	6034	2.2E-05
14457	2.3E-05	14142	2.5E-06
33733	7.2E-07	33145	3E-07
78713	1.2E-08	77680	3.7E-08
183666	1.3E-10	182056	4.2E-09
1	1	1	0.54663

Figure A.23. Permeability function for WNT GCL (CaCl_2 solution)

Table A.28. k_r data for WNT GCL (CaCl_2 solution)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	0.51196	0	1
2	0.51047	1	1
4	0.50891	2	1
8	0.5072	5	1
17	0.50507	12	1
38	0.50175	26	1
83	0.49443	59	0.82696
181	0.47141	133	0.25561
397	0.3853	299	0.07959
869	0.16237	673	0.0229
1901	0.02124	1515	0.00568
4161	0.00215	3412	0.0012
9105	0.00028	7681	0.00022
19925	4.4E-05	17292	3.8E-05
43603	7.3E-06	38929	6.2E-06
95420	1.2E-06	87640	9.5E-07
208813	1.7E-07	197303	1.3E-07

Figure A.23. Permeability function for NN1 GCL (cyclic wet-dry test)

Table A.29. k_r data for NN1 GCL (cyclic wet-dry test)

Wetting WRC		Drying WRC	
Suction (kPa)	Relative Coefficient of Permeability, k_r	Suction (kPa)	Relative Coefficient of Permeability, k_r
1	0.67382	1	0.54739
2	0.66565	1	0.54739
4	0.65407	3	0.54738
9	0.63523	8	0.54737
23	0.59999	17	0.54735
55	0.52666	41	0.54722
134	0.3744	94	0.54514
327	0.14593	219	0.50269
797	0.01982	509	0.12379
1945	0.00156	1181	0.00456
4745	0.00013	2744	0.00022
11576	1.2E-05	6372	1.8E-05
28239	1.2E-06	14799	2.3E-06
68886	1.3E-07	34370	4E-07
168043	1.3E-08	79824	8.2E-08
1	0.67382	185391	1.4E-08
2	0.66565	1	0.54739

Table A.24. Soluble Cations (SC) determined for BC and CEC tests

Bentonite Moisture Condition ^a	Wetting or drying WRC?	Hydration Solution	GCL Type	Soluble Cation (meq / 100 g)			
				Na (meq / 100 g)	K (meq / 100 g)	Ca (meq / 100 g)	Mg (meq / 100 g)
Air-Dry	None	Virgin	WN2	17.5	0.2	0.2	0.3
Air-Dry	None	Virgin	WN2	15.1	1.3	0.2	0.2
Fully-Saturated for 1 month	Drying	DI	WN2	19.3	0.6	2.3	1.7
Fully-Saturated for 1 month	Drying	DI	NN1	11.3	0.2	0.5	4.6
Fully-Saturated for 1 month	Drying	DI	WNT	17.3	0.2	0.0	0.0
Fully-Saturated for 1 month	Drying	Tap	WN2	17.5	0.2	1.3	0.7
Fully-Saturated for 1 month	Drying	Tap	NN1	14.2	0.4	1.8	8.2
Fully-Saturated for 1 month	Drying	Tap	WNT	16.6	0.5	0.6	9.8
Fully-Saturated for 1 month	Drying	CaCl ₂	WN2	20.9	0.3	2.1	0.2
Fully-Saturated for 1 month	Drying	CaCl ₂	NN1	17.1	0.4	1.4	0.9
Fully-Saturated for 1 month	Drying	CaCl ₂	WNT	14.9	0.2	0.7	0.2
Fully-Saturated for 1 month	Drying	Soil water	WN2	0.3	0.1	0.4	0.2
Saturated for 1 month	Wetting	DI	WN2	22.4	0.2	0.1	0.1
Fully-Saturated for 1 month	Drying	DI	WN2	19.3	0.6	2.3	1.7
Saturated for 1 month	Wetting	Tap	WN2	23.1	0.2	0.1	0.1
Fully-Saturated for 1 month	Drying	Tap	WN2	17.5	0.2	1.3	0.7
Saturated for 1 month	Wetting	CaCl ₂	WN2	29.9	0.3	0.3	0.1
Fully-Saturated for 1 month	Drying	CaCl ₂	WN2	20.7	1.2	2.6	4.1
10-day saturation	Drying	Tap	WN2	19.6	0.2	0.2	0.5

^a All samples oven-dried prior to testing