Dimensional Stability of Geosynthetic Clay Liners in Landfill Applications

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ABSTRACT

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An investigation was conducted related to the dimensional stability of geosynthetic clay liners (GCLs) in landfill applications. Multiple occurrences of panel separation of overlap seams in GCLs have been documented; however, explanation for the relative contribution of various mechanisms causing shrinkage has been limited. A systematic test program was conducted to determine the effects of a variety of conditions on GCL dimensional stability.

Effects of initial moisture content, permeant type, and overburden pressure were tested by subjecting various GCL products to wet-dry cycles and measuring the dimensional change with each cycle. Different GCL types were each tested under various combinations of initial moisture content (as-received, 50, 75, 100, and 125%), permeant types (tap water, distilled water, and 0.1 M CaCl_2), and overburden pressures (0, 6, and 20 kPa). Thermal expansion tests were conducted by heating or cooling GCL test specimens to temperatures of 0, 10, 40, 60, and 80°C at constant moisture content. Subgrade tests were conducted by placing GCL test specimens on compacted clay and sand subgrades in different orientations and hydration conditions in sealed containers and measuring dimensional change over time. Mechanical necking tests were conducted by subjecting GCL specimens to varying levels of tension and measuring the longitudinal and transverse strains at each load increment. Field simulation tests were conducted by placing specimens on a compacted sand subgrade beneath an exposed geomembrane liner outdoors in late summer.

Initial moisture content tests resulted in shrinkage strains as high as 20% after 20 wet-dry cycles. GCLs ranged from slightly anisotropic [approximately 1.1:1 ratio of machine (MD) to cross-machine (XMD) shrinkage] to highly anisotropic (approximately 3:1 ratio of MD to XMD shrinkage). Most combinations of GCL type and initial moisture content resulted in GCL MD shrinkage strains greater than a value that would cause panel separation (termed panel separation threshold, PST) at roll ends during the first wet-dry cycle. All test specimens contracted beyond the PST in the MD within 3 wet-dry cycles. GCL specimens without attached geomembranes contracted beyond the PST in the XMD within 5 cycles. Permeant type tests demonstrated that hydration with 0.1 M CaCl_2 reduced shrinkage by 50-80% compared to permeation with tap water. Overburden tests demonstrated that applying 6 kPa and 20 kPa reduced specimen shrinkage by at least 60% and 80%, respectively. Thermal expansion tests indicated that temperature changes at constant moisture content had little effect on GCL dimensional stability. Subgrade tests demonstrated that subgrade type and moisture as well as GCL type and orientation had effects on dimensional stability. Tensile necking tests demonstrated that transverse shrinkage occurred due to tensile forces in GCLs, but shrinkage was nearly always less than PST. Field simulation tests demonstrated that wet-dry cycles in the field were less intense and/or less frequent than in the laboratory. Results of this testing provide a basis for GCL overlap specifications necessary to maintain full coverage and future research to confirm a suggested method of preconditioning bentonite to prevent shrinkage.

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Chapter 1: Introduction

Of the more than 220 million metric tons of municipal solid waste generated in the United States annually, nearly 120 million metric tons is discarded in landfills (EPA 2011). For the foreseeable future, a large portion of the waste generated in the U.S. will have to be landfilled, with only certain waste types able to be incinerated or recycled. In addition, the relative abundance of inexpensive open space in the U.S. compared to other countries makes landfilling an economically more favorable option than recycling or incineration. As the amount of waste landfilled continues to increase or at least hold steady, increased attention has been devoted to maximizing available space in landfills while maintaining an adequate barrier to contaminant infiltration into groundwater.

Geosynthetic clay liners (GCLs) are manufactured hydraulic barriers consisting of clay bonded to a layer or layers of geosynthetic materials (ASTM 2011d). GCLs are designed to be a thin (5 to 10 mm thick) alternative to compacted clay liners (CCLs) (at least 600 mm thick). The reduced liner thickness of GCLs in combination with the relative ease of installation has made GCLs an economically superior alternative to CCLs. The additional 0.6 m of depth available for containment of waste by using a GCL instead of a CCL allows for a significant increase in landfill capacity when distributed over hectares of land area. When GCLs perform as designed, they have comparable or superior advective hydraulic performance compared to CCLs.

A concern with the durability of GCL barriers that was first documented within the past decade relates to the dimensional stability of the panels. GCLs are typically seamed by overlapping panels by 500 to 600 mm at the panel ends and 150 to 300 mm along the longitudinal panel edges. Multiple instances have been reported of GCL panels undergoing sufficient shrinkage to cause loss of panel overlap. A gap between panels could compromise the integrity of the liner. Limited systematic research has been conducted to determine the relative importance of soil and geosynthetic conditions that affect GCL dimensional stability. Similarly, limited detailed explanation has been provided for the various mechanisms causing GCL shrinkage.

A laboratory test program was conducted to determine the relative effects of six individual factors on GCL shrinkage. In addition, a field simulation test was conducted to monitor the effects of coupled factors. The effects of initial moisture content, permeant type, and overburden stress on GCL shrinkage were determined for specimens undergoing cyclic wetting and drying. For these tests, specimens were cycled between dry and moist conditions by drying in a convection oven at 60°C and hydrating with liquid to 50% nominal gravimetric moisture content. Initial nominal gravimetric moisture contents of as-received, 50%, 75%, 100%, and 125% were used for initial moisture content tests. Tap water, deionized water, and 0.1 M CaCl₂ were used for permeant type tests. Unconfined, 6 kPa, and 20 kPa pressures were applied in overburden tests. Thermal expansion tests were conducted at 0, 10, 40, 60, and 80°C under constant moisture to test the effects of temperature on GCLs independently from

moisture. Subgrade tests were conducted to determine the effect of subgrade soil type, subgrade moisture, GCL type, GCL moisture, and GCL orientation on shrinkage. Mechanical necking tests were conducted to determine the amount of shrinkage as a result of tensile forces imparted on GCLs. The field simulation test investigated the coupled mechanisms of temperature variation, moisture variation, and subgrade-GCL interaction.

In this thesis, a review of the state of knowledge related to GCL dimensional stability, as well as relevant background information regarding clay mineralogy and structure, bentonite characteristics, and cation exchange is presented in Chapter 2. Description of the tests conducted within the experimental test program is presented in Chapter 3. The results and discussion of each test, followed by a discussion of the significance of the results in engineering applications is presented in Chapter 4. Finally, conclusions and recommendations for future work related to GCL dimensional stability are presented in Chapter 5. References and an Appendix follow the conclusions.

Chapter 2: Literature Review

2.1 Introduction

A review of the current literature related to dimensional stability of geosynthetic clay liners (GCLs) in landfill facilities is presented in this chapter. Additional discussion is included related to clay mineralogy and performance under wet/dry cycling as well as under cation exchange conditions.

Over 220 million metric tons of solid wastes were generated in the United States in 2010 (EPA 2011). Waste may be handled or disposed in three ways: burial, incineration, or reusing/recycling (Qian et al. 2002). Despite increased efforts in the United States to reduce, reuse, and recycle wastes, approximately 54% of solid waste is directly landfilled and approximately 12% is combusted and subsequently landfilled (EPA 2011). The need for landfiling is expected continue in the United States in the long term, as landfiling is still the most economical method of waste disposal in the U.S. because of the relative availability of inexpensive land compared to most developed countries. In addition to economic reasons, not all wastes are suitable for incineration or recycling (Qian et al. 2002).

Engineered landfills are a controlled method of refuse disposal designed to reduce the environmental and public health impacts of waste. The most important issue in landfill design and construction is to contain liquid and gas pollutants such that they do not contaminate their surroundings. An important target for landfills is collecting and properly disposing of leachate. Leachate is the contaminated liquid generated in the landfill, which consists of solutes from the solid waste dissolved in liquid either squeezed from the waste itself or water

that infiltrates into the landfill and percolates through the waste (Qian et al. 2002, Yesiller and Shackelford 2010). If leachate escapes a landfill, it can pollute surrounding groundwater, which poses an environmental and health hazard. For this reason, landfills must have a hydraulic barrier devoid of leaks to collect and properly dispose of leachate. Another area of concern is gas generated by decomposition of waste. Landfills may generate methane and carbon dioxide, both of which are greenhouse gasses. Gas generated in landfills is collected and may be used to produce energy or flared under controlled conditions (Yesiller and Shackelford 2010, Qian et al. 2002). In addition to the management of leachates and gasses, landfills are designed to reduce or eliminate nuisances such as smoke, odor, unsightliness, insects, rodents, and birds (Qian et al. 2002).

Most modern municipal solid waste (MSW) landfills are composed of seven systems:

1. Bottom and lateral side liners system
2. Leachate collection and removal system
3. Gas collection and control system
4. Final cover system
5. Stormwater management system
6. Groundwater monitoring system
7. Gas monitoring system

The above systems are used to ensure that liquid and gas pollutants generated in the landfill waste do not escape the landfill boundaries. The waste

in landfills may be placed in a variety of configurations. Some common geometrical configurations for waste placement are presented in Figure 2.1. Area fills involve placing waste on areas with little to no excavation. This type of landfill is used in areas with high groundwater tables or where the terrain does not allow for excavation (Qian et al. 2002). Trench fills are series of deep and narrow trenches. Because of their geometry, trench fills are generally only used to contain small quantities of waste compared to other types of landfills. Trench fills are commonly used for hazardous wastes in some states. Above and below ground fills generally consist of a large excavation with waste placed below grade initially and then placed above grade until the height reaches the maximum allowed by local regulations. The depth of the excavation generally depends on the depth of the groundwater table. Canyon or valley fills consist of waste placed between hills or rolling terrain (Qian et al. 2002).

Landfills are lined with systems that consist of alternating layers of low and high permeability materials that perform barrier functions and drainage/filtration functions, respectively. The two basic types of liner systems are single and double liner systems. Single liner systems include a hydraulic barrier layer overlain by a high permeability layer known as the leachate collection system. Double liner systems include two hydraulic barrier layers that are separated by a drainage layer, called the leak detection system, and overlain by the leachate collection system. Examples of single liner systems are presented in Figure 2.2 and Figure 2.3. An example of a double liner system is presented in Figure 2.4.

Figure 2.1. Common Landfill Configurations (Qian et al. 2002)

The barrier component of the liner system is the component that performs containment functions and has two types: single and composite. Single liners consist of a geosynthetic clay liner (GCL), single compacted clay liner (CCL), or a geomembrane (GM). Examples of single liners are presented in Figure 2.2. Composite liners consist of a paired GCL and GM or a paired CCL and GM. An example of a composite liner is presented in Figure 2.3. Composite liners combine the advantages and eliminate the disadvantages of single liners. The geomembrane component of the GCL is virtually impermeable to liquids and

serves to restrict the overall area that flow may occur through to small defects in the membrane. The GCL (or CCL) beneath the geomembrane minimizes the impact of holes in the geomembrane by serving as a low permeability material that is relatively resistant to formation of holes or macrovoids when hydrated.

Figure 2.2. Single Liner Systems with Single Liners (Qian et al. 2002)

Figure 2.3. Single Liner System with Composite Liner (Qian et al. 2002)

Figure 2.4. Double Liner System with Composite Liners (Qian et al. 2002)

Composite liners are now required in all landfills constructed in the United States under the Resource Conservation and Recovery Act (RCRA) of 1976. Federal regulations stipulate that a single composite liner must be used for MSW landfills, while a double composite liner must be used for hazardous waste landfills (Qian et al. 2002).

According to RCRA, the geomembrane in a composite liner must be at least 1.5 mm thick if it is made of high density polyethylene (HDPE), or at least 0.75 mm thick if it is made from a different polymer resin (Electronic Code of Federal Regulations 2011). The clay component in a composite liner must have a minimum thickness of 0.6 m and a hydraulic conductivity of less than or equal to 1.0×10^{-7} cm/s. A GCL with equivalent performance may be used in place of a compacted clay liner. State and local regulations may be stricter, depending upon the location of the landfill (Qian et al. 2002). These types of regulations are termed prescriptive criteria and are common in United States landfill regulations.

A second type of regulation is called performance criteria. Performance criteria may allow for more flexibility in design while still requiring adequate protection. Performance criteria generally stipulate the magnitude of the flux of contaminants at a given time, the cumulative or average flux over a period of time, or the length of time needed to reach a given magnitude of flux. Performance criteria generally relate to the rate of contaminant release or the detection of excessive amounts of contaminants beyond landfill boundaries (NRC 2007).

Landfills may vary significantly in size, depending on the landfill location and type. Landfills may have one or many sectors for containing waste, termed cells. A typical cell may be on the order of several hectares or more in area and have a depth on the order of tens of meters. Side slopes typically vary in steepness and depend upon whether the waste is placed below or above grade. Waste may be placed several tens of meters above grade. Once the landfill cell is closed, a final cover is placed in the same manner as it was lined in the bottom. This final cover is typically a composite liner and serves to prevent additional generation of leachate (i.e., infiltration of precipitation) subsequent to closure of the cells.

The performance of landfill barrier systems is critical for short, medium, and long term time periods. In MSW landfills, wastes may potentially generate contaminants at unacceptably high levels for hundreds of years (NRC 2007). This waste must be properly contained within this timeframe in order to ensure environmental health and safety throughout the area surrounding a landfill. Though waste may pose a risk to the environment for hundreds of years, landfills

in the United States are generally only required by regulation to be monitored for 30 years after closure (NRC 2007). As landfills built according to modern regulatory standards are now beginning to reach the end of the 30 year post-closure monitoring requirement, liability and responsibility for prevention of contamination of groundwater and air from landfill waste is not fully established. The long-term performance of geosynthetics is not entirely known either, as high strength polymer materials have been in existence for well under 100 years (NRC 2007).

The primary liner in a double-liner system is the only type of engineered barrier that allows for direct measurement of post-construction effectiveness because it allows for direct collection of leachate in the leak detection layer below. The absence of monitoring of barrier integrity for other system types may be attributed to (NRC 2007):

- Difficulty in directly monitoring barrier system effectiveness beneath tens to hundreds of meters of waste or soil.
- A philosophy that the integrity individual barrier elements are less important than the overall containment system performance.
- The reluctance of designers, owners, operators, and regulators to monitor something that will be impossible or exceedingly expensive to fix if a problem is discovered.

2.2 Geosynthetic Clay Liners

GCLs have become a popular alternative to thick CCLs in barrier applications for economic reasons. ASTM D4439 defines a Geosynthetic Clay

Liner as “a manufactured hydraulic barrier consisting of clay bonded to a layer or layers of geosynthetic materials” (ASTM 2011d). Essentially, most GCLs consist of a bentonite clay core held between two geotextiles. Often the top geotextile is referred to as the cover geotextile, while the bottom geotextile is referred to as the carrier geotextile. The geotextiles may be woven or nonwoven, depending on the desired strength characteristics. The geotextiles are held together by adhesive bonding (Figure 2.5a, Figure 2.6a), needle punching (Figure 2.5d; Figure 2.6b, c), or stitch bonding (Figure 2.5c). Some GCLs also contain a plastic film or geomembrane component, either adhered to a geotextile encased GCL (Figure 2.6) or bonded directly to bentonite clay by an adhesive (Figure 2.5b).

Figure 2.5. Conventional GCLs (Yesiller and Shackelford 2010)

Figure 2.6. GM-Backed, GT Encased GCLs (Yesiller and Shackelford 2010)

The main advantages of GCLs include their low thickness and ease of installation. A GCL of approximately 5-10 mm thickness has comparable advective flux to a CCL of about 1 m thickness. The reduced thickness allows for greater economy, as the difference in thickness can be used as airspace (i.e., volume for waste placement) in a landfill with a thinner barrier. GCLs also are easy to install, as they are flexible and are manufactured in large rolls. GCLs can be installed by a small crew of workers unrolling the product from a large spool. This compares to transporting loads of clay to a landfill site and then compacting the clay in lifts with a sheepfoot compactor and smoothing the surface of the

clay with a heavy smooth drum roller, as would be required for a CCL (Koerner 2005, Wagner and Schnatmeyer 2002). Major disadvantages of GCLs are high levels of diffusive flux due to the low thickness and sensitivity to temperature cycling, wet-dry cycling, and cation exchange. The sensitivity to temperature cycling, wet-dry cycling, and cation exchange factors has caused problems with GCL panels shrinking in addition to hydraulic conductivity increasing (Thiel and Richardson 2005, Koerner and Koerner 2005a,b). Moisture and cation exchange have significant effects on the integrity of the clay in GCLs due to the type of the clay material.

2.3 Clay Mineralogy and Structure

Clay mineralogy plays a key role in the effectiveness of clay liners (including GCLs) as a hydraulic barrier. Clay minerals are defined by Holtz et al. (2010) as “very tiny crystalline substances that are evolved primarily from chemical weathering of certain rock-forming minerals.” These minerals are categorized as colloids, which is a common term used for materials with a diameter smaller than 1 μm . Clays are composed of crystal sheets with a repeating atomic structure. Clays contain two fundamental structural units: silica and alumina. Silica is composed of four oxygen atoms at the corners surrounding a single silicon atom in a tetrahedral shape. The tetrahedral units are joined together to form planar sheets (Figure 2.7). Alumina is composed of six oxygen atoms or hydroxyls surrounding an aluminum atom in an octahedral shape. The octahedral units are joined together to form planar sheets, similar to

silica (Figure 2.8) (Mitchell and Soga 2005, Holtz et al. 2010). The configuration of the silica and alumina sheets dictates the clay type and behavior.

Figure 2.7. Schematic of Silica Tetrahedra (Mitchell and Soga 2005)

Figure 2.8. Schematic of Alumina Octahedra (Mitchell and Soga 2005)

Clay particles have a negative charge due to isomorphous substitution. Isomorphous substitution is the substitution of ions of one kind with ions of another, while maintaining the same crystal structure. For example, Al^{3+} in the octahedral units may be replaced by Mg^{2+} , Fe^{2+} , Zn^{2+} , Ni^{2+} , or Li^{+} . In the tetrahedral sheet, Al^{3+} may replace Si^{4+} . The substitutions mentioned above all involve a cation of low valence substituting for a cation of higher valence, which creates a net negative charge on the clay particle (Mitchell and Soga 2005).

To preserve neutrality in clay particles and balance the negative charge of the clay particles, cations are attracted to the surfaces and edges of particles as

well as between mineral layers within the clay particles. Many of the attracted cations are exchangeable, meaning that they may be replaced by cations of a different type. The quantity of exchangeable cations is termed the cation exchange capacity (CEC) and is expressed as milliequivalents (meq) per 100 g of dry clay. One equivalent contains a charge equal to 1 Faraday, which is equal to 6.023×10^{23} electron charges and 96,500 Coulombs (Mitchell and Soga 2005). Cation exchange capacity has a significant effect upon clay behavior, as is discussed later in this chapter.

The clay used for GCLs typically consists of bentonite. Bentonite refers to any material that is composed mainly of montmorillonite (also called smectite) minerals and has properties and behavior similar to those of montmorillonite. Montmorillonite is a clay mineral characterized by a high cation exchange capacity, large specific surface area, high swelling potential, and low hydraulic conductivity to water (Gleason et al. 1997). Bentonite is a 2:1 mineral because it is composed of an alumina octahedral sheet located between two silica tetrahedral sheets. The tips of the tetrahedrons combine with the hydroxyls of the octahedral sheet to form a single layer as presented in Figure 2.9. This layer has an approximate thickness of 0.96 nm.

Figure 2.9. Schematic of Montmorillonite Mineral (Mitchell and Soga 2005)

The bonding between 2:1 layers in montmorillonite is largely due to attraction of negatively charged clay particles to exchangeable hydrated cations in the interlayer regions between 2:1 units (Yesiller and Shackelford 2010). Most of the isomorphous substitution in montmorillonite particles is located in the octahedral sheet, which is relatively far from the interlayer region of the crystal structure where the exchangeable cations are present. Because the negatively charged area of the clay particle is located so far from the positively charged cations, the bond between 2:1 layers is relatively weak (Yesiller and Shackelford 2010). The presence of weak bonds results in crystals smaller than the crystals of other types of clay minerals. The weak bonds also give the crystals a strong

attraction for water (Yesiller and Shackelford 2010, Mitchell and Soga 2005). The cations are held loosely and are very easily exchanged because the negative charges are so far away from cations in the interlayer regions (Yesiller and Shackelford 2010).

Hydrated exchangeable cations and bound water in both the interlayer space within clay minerals and the space between individual clay particles is held in place by the negative charge in the clay particles. The combination of the cations/water and the charge deficiency of the clay particles is referred to as the electrostatic double layer, or diffuse double layer (DDL) (Yesiller and Shackelford 2010). The thickness of the DDL has a significant impact on the properties and behavior of bentonite. A thicker DDL causes montmorillonite particles to swell substantially, which makes water flow paths significantly more tortuous than other soil types and gives bentonite a lower hydraulic conductivity than virtually all other soils.

The thickness of the DDL can be described by:

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

where t_{DDL} is the DDL thickness, ϵ is the dielectric constant of the liquid in the clay soil voids, v is the valence of the cations in the pore liquid, and n_o is the number of ions in the pore liquid. Pore fluids with low dielectric constants (such as hydrocarbons) result in a much thinner DDL than fluids with high dielectric constants (such as water). Also, pore fluids with higher concentrations of high valence cations cause thinning of clay DDLs. DDL thickness also decreases with

increasing temperature and decreasing pH and anion adsorption (Yesiller and Shackelford 2010).

The hydraulic and dimensional properties of clay are further influenced by the orientation of the particles. First introduced by Lambe (1958), the particle-orientation theory describes two orientations for clay particle arrangements: flocculated and dispersed. Clay particles in the flocculated structure resemble that of a card house as illustrated in Figure 2.10a,b. Increased tendency towards flocculation occurs as a result of increasing electrolyte concentration, ion valence, and temperature, as well as decreasing dielectric constant, hydrated ion size, pH, and anion adsorption (Lambe 1958).

Flocculated orientations result in clay with larger pores and lower densities in comparison to dispersed structures and usually result when clays are compacted dry of optimum moisture content. This dry moisture content is labeled point A in Figure 2.11. The flocculated structure gives the clay high hydraulic conductivity because of the large air voids. Adding water to the point where the clay reaches optimum moisture content (labeled point B in Figure 2.11) tends to lubricate the clay particles by expanding the double layers around the soil particles and also reducing the electrolyte concentration. This lubrication allows the particles to slide past each other into a more oriented, dispersed structure, as illustrated in Figure 2.10c (Lambe 1958).

a) Salt Flocculation

b) Non-salt Flocculation

c) Dispersion

Figure 2.10. Flocculated and Dispersed Clay Structure (Lambe 1958)

Figure 2.11. Particle Orientation Theory (Lambe 1958)

Adding more water beyond optimum moisture content (indicated by point C in Figure 2.11) results in further expansion of the diffuse double layer and creates an even more orderly arrangement of particles. The density of clays compacted wet of optimum moisture content reduces due to the fact that water begins to replace the soil particles in a given volume. From point A to point B, density increases due to a rearrangement of particles and thus a reduction of air voids. From point B to point C, the reduction in density is not due to an increase in air voids, but rather from water starting to displace the soil solids (Lambe 1958).

Due to the water deficiency in unsaturated clays, the water present in the clay is subject to tension as the colloids try to draw water towards them. In the flocculated orientation at point A the water deficiency is greatest, so pore water tension is greatest at this orientation. With increasing water and a dispersed orientation, the pore water tension is reduced (Lambe 1958).

Clay particles tend to group together to form clods. These clods may vary significantly in size. The size of clay clods dictates how the entire mass of clay will perform. The clod theory, as proposed by Olsen (1960), suggests that most of the water flow in clays occurs in the relatively large pores between clods of clay, rather than between the individual clay particles within the clods. According to the clod theory, soft, wet clods of soil are easier to remold than hard, dry clods. Therefore, when clays are compacted wet of optimum moisture content, the soft clods are easy to remold and break down, which reduces the size of interclod voids. Dry of optimum moisture content, clods may remain large, which leaves

large interclod voids in the structure. The larger the interclod voids, the easier it is for water to pass through the clays, providing another explanation for why soils compacted dry of optimum moisture content have high hydraulic conductivity (Benson and Daniel 1990). While the particle-orientation theory and the clod theory both offer different explanations for why water flows more readily through clays compacted dry of optimum moisture content than wet of optimum moisture content, the two theories are not mutually exclusive, and may both be applicable. As discussed in Chapter 4, GCL shrinkage as a result of wet-dry cycling may be attributable to changes in clay fabric and structure.

2.4 Characteristics of Bentonite Clay

There are two major types of bentonite: sodium and calcium. Bentonite is categorized by the type of external cation that is adsorbed to the surface of the clay particle during bentonite processing or particle formation, thus sodium is adsorbed to sodium bentonite clay particles and calcium is adsorbed to calcium bentonite. Sodium bentonite is the more commonly used of the two major types, as it tends to swell more and has a lower hydraulic conductivity to water than calcium bentonite. When exposed to chemicals with high valence cations, the hydraulic conductivity of sodium and calcium bentonite becomes comparable (Gleason et al. 1997, Wagner and Schnatmeyer 2002).

Bentonite swells when it is hydrated with water and certain other liquids. The main mechanism for GCL hydration in the field is uptake of water from moisture in the surrounding subgrade soils. Therefore, knowledge of how certain soils will affect GCL moisture content is necessary. The equilibrium water

content of the bentonite in a GCL is related to the soil suction of the surrounding subgrade soil (Daniel et al. 1993, Beddoe et al. 2010, 2011). Subgrades that are wet have low suctions, which results in GCLs drawing in more water. Conversely, dry subgrades have increased suctions and thus do not allow water to be sorbed as readily. Daniel et al. (1993) determined approximate values for the correlation between the soil suction and the approximate water content of the bentonite in the GCL placed over the soil. These data are presented in Table 2.1.

Table 2.1. Relationship between Water Content and Suction 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 to 100
Moist soil that will support growth of lush vegetation (0 kPa ≤ Suction ≤ 100 kPa)	100 to 140
Wet (Practically Saturated) Soil (Soil Suction = 0)	> 140

Data in Table 2.1 demonstrate that bentonite may be present over a wide range of moisture contents; therefore, swelling of bentonite can vary greatly depending on site conditions (Daniel et al. 1993). Recently, research has focused on defining a more precise relationship between suction and GCL moisture content. Studies by Beddoe et al. (2010, 2011) have focused on

defining the water retention curve, also known as the soil-water characteristic curve, of several types of GCL. Beddoe et al. (2010, 2011) determined that the configuration and structure of the GCL affected its soil-water characteristic curve. The ingress and egress of water to GCLs follows a hysteretic soil-water characteristic curve. The shape of the soil water characteristic curve (SWCC) fits well with previously published unsaturated soil mechanics modeling, notably the Fredlund and Xing (1994) model. The Fredlund and Xing (1994) model is given by:

$$\theta = \theta_s \left[1 - \frac{\ln(1 + \psi/\psi_r)}{\ln(1 + 10^6/\psi_r)} \right] \left[\frac{1}{\ln(e + (\psi/a_f)^{n_f})} \right]^{m_f} \quad (2.2)$$

where θ is the volumetric moisture content (m^3/m^3), θ_s is the saturated volumetric moisture content (m^3/m^3), ψ is the soil suction (kPa), ψ_r is the residual soil suction (kPa), e is the numerical constant approximately equal to 2.718, and a_f (kPa), n_f , and m_f are fitting parameters unique to the soil. Unsaturated soil mechanics models such as these could be helpful in determining how much water GCLs will hydrate in the field and thus help predict shrink-swell behavior of the bentonite in the GCL.

Two types of swelling may occur in bentonite: the crystalline phase and the osmotic phase. Crystalline swelling occurs first as water molecules move into the interlayer portion of the diffuse double layer to hydrate the mineral surface and associated adsorbed cations. Crystalline swelling causes the interlayer to separate by several water molecules and thus causes minor swelling (Scalia and Benson 2011). Crystalline swelling occurs until the bentonite is

hydrated to approximately 35% gravimetric water content. At water contents beyond 35% osmotic swelling occurs, provided that the water is not high in concentration of multivalent cations. Osmotic swelling occurs when water molecules flow into the interlayer region because of a cation concentration gradient between the interlayer region and the free pore water in the bentonite clay (Scalia and Benson 2011). Osmotic swelling produces much greater swelling of the two phases because it allows additional water to flow into the interlayer region between particles, which has implications for the hydraulic conductivity of GCLs as well as dimensional stability. Bentonites that have undergone osmotic swelling tend to have water contents exceeding 35%, and in many cases in excess of 100%. Osmotic swelling only occurs when the cations in the interlayer space of the diffuse double layer are predominantly monovalent. When multivalent cations are predominant, only crystalline swelling can occur (Scalia and Benson 2011).

2.5 Cation Exchange in GCLs

Permeants with lower ionic charge cause greater swelling in DDLs because more water molecules or cations are required to be sorbed to balance the negative charge of the clay particle. Exchange of Ca^{2+} or Mg^{2+} for Na^+ is thermodynamically favorable in clays (Benson et al. 2007). If a sodium bentonite is exposed to permeants with Ca^{2+} and Mg^{2+} in the pore water of the GCL, cation exchange will occur as one divalent cation will replace two sorbed monovalent cations, unless a far greater abundance of monovalent ions exist in the permeant fluid to offset the influence of the divalent cations (Benson et al. 2007). This

process will in turn reduce the amount of swelling that the clay particles undergo, which can increase the hydraulic conductivity of the GCL by a significant amount in a relatively short amount of time.

Cation exchange can increase the hydraulic conductivity of a GCL by several orders of magnitude in a matter of years, which is relatively short term considering that liners are expected to effectively contain wastes for hundreds of years to maintain environmental safety (NRC 2007). Quaranta et al. (1997) documented the hydraulic conductivity of a GCL to increase from 4×10^{-9} cm/s to 4×10^{-6} cm/s after exposure to a 0.2 M calcium carbonate+0.03 M acetic acid solution, yet the hydraulic conductivity decreased from 2×10^{-8} cm/s to 3.3×10^{-9} cm/s when exposed to acetic acid alone. This difference of three orders of magnitude brings the GCL from compliance with regulations to noncompliance and thus cation exchange is a significant concern. Multivalent cations can be supplied from various sources. Most test data simulate the multivalent cations being supplied by leachate moving downward into the GCL. Multivalent cations can come from the soil underneath the GCL as well (Touze-Foltz et al. 2006). This is certainly a concern when placing GCLs above soils rich in calcium carbonate. Care needs to be taken to ensure that sources of multivalent cations, both above and below the liner system, are accounted for whenever designing a landfill liner with a GCL component.

Wet-dry cycling tends to enhance the negative effects of cation exchange. Bentonite that has undergone osmotic swelling as described in the previous section can retain a hydrated structure and relatively low hydraulic conductivity

under a relatively low confining stress (10-30 kPa), even if the Na^+ is replaced by divalent cations. The hydrated structure remains in GCLs as long as the bentonite in the GCL does not desiccate because cation exchange alone does not provide sufficient energy to remove the tightly bound water molecules in the interlayer space. If the water molecules are removed from the interlayer space by a high energy source, such as heating to the extent of desiccation, then the swelling potential will be permanently reduced when cation exchange occurs. Once cation exchange occurs, any swelling after desiccation will only be crystalline, which does not allow for as much swelling and thus an increased hydraulic conductivity (Scalia and Benson 2011).

Prehydration of GCLs is a proposed method to ensure that GCLs maintain low permeability when permeated with fluids containing multivalent cations. Prehydration is the hydration of GCLs with water prior to the GCL being exposed to chemicals (Jo et al. 2004). Prehydration ensures that GCLs have undergone osmotic swelling before cation exchange can occur, which allows the hydraulic conductivity of the GCL to remain low. The Comité Français des Géosynthétiques (1998) recommended prehydration to 100% moisture content prior to GCL exposure to chemicals (Barroso et al. 2006, Touze Foltz et al. 2006). Some GCLs manufactured in Europe are prehydrated in the factory to improve hydraulic performance (Mazzieri 2011, Mazzieri and Pasqualini 2011). Prehydration may be ineffective when wet-dry cycles are intense, as the benefits of osmotic swelling are lost if desiccation is severe (Mazzieri 2011).

Wet dry cycles may occur in the field seasonally, as a GCL is hydrated by pore water which may contain divalent cations such as calcium and magnesium in the rainy season, which subjects the GCL to cation exchange. When the seasons change and the bentonite is subjected to dry summers on an annual basis, the bentonite, subsequent to repeated wet-dry cycles, may progressively become more brittle, less plastic, and thus swell less when hydrated in the next rainy season. (Lin and Benson 2000, Bouazza et al. 2006, 2007). Cation exchange coupled with wet-dry cycling will makes the GCL more permeable because the particles will not swell as much and desiccation cracks will be present (Lin and Benson 2000, Bouazza et al. 2006, 2007).

The effect of wet-dry cycling and cation exchange in GCLs is illustrated in Figure 2.12 as obtained from Bouazza et al. (2007). GCLs tend to have the ability to self heal in the absence of cation exchange when they are wetted and dried without the cation exchange. The self healing ability is illustrated by the upper line in Figure 2.12, as the swell of the bentonite particles remains relatively constant when wetted and rewetted with deionized (DI) water. Rehydrating a dry, cracked GCL with pure water will cause the clay particles in the GCL to swell and fill all of the desiccation cracks. With cation exchange however, the particles tend to swell less when hydrated and thus do not fill the desiccation cracks, which has a severely detrimental effect on the hydraulic conductivity of the GCL. The detrimental effect of cation exchange on self healing is illustrated in Figure 2.12. The GCLs hydrated with 0.0125 M CaCl_2 swelled progressively less as the specimens were further wetted and dried. The microstructure of the GCL wetted

with the strong 0.125 M CaCl_2 solution basically broke down after the first wetting cycle because the Ca^{2+} content was sufficiently high for cation exchange to destroy all swell potential quickly, reaching the minimum swell potential of the GCL in only two wetting cycles.

Figure 2.12. Effect of Cation Exchange and Wet-Dry cycling on GCL Swell (Bouazza et al. 2007)

2.6 Dimensional Stability of GCLs

Bentonite within GCLs can shrink and swell significantly as a function of various operational and environmental factors. These factors include temperature, moisture content, and cation content. The temperature of GCLs can vary due to atmospheric conditions for GCLs in cover systems or GCLs in uncovered bottom liners. The temperature of GCLs covered by waste may change due to variation in the temperatures of the overlying wastes. Moisture content in GCLs can change due to changes in atmospheric temperature for uncovered bottom liners, and changes in moisture in the soil beneath a liner and above a final cover. Moisture content in GCLs also depends on the adjacent soil

conditions (e.g., soil suctions), as described in Daniel et al. (1993). Cation concentration can change due to cation exchange between the GCL and subgrade if the subgrade is a clayey soil rich in multivalent cations, as well as between the GCL and permeants such as leachate and rainwater.

Significant potential is present for large scale shrinkage and swelling of bentonite, and therefore GCLs, has led to concerns regarding the dimensional stability of GCLs. Currently, ASTM D6102, the standard guide for installation of GCLs, requires a minimum overlap of GCL panels of at least 150 mm (unless otherwise specified) (ASTM 2011j). Depending on the product, GCL manufacturers recommend an overlap between 150 mm to 300 mm. If GCLs are covered by a geomembrane and left exposed to the elements without being overlain by cover soils, they can potentially shrink to an extent that the overlap that was present at installation is lost. This would leave gaps in GCL coverage beneath the geomembrane and destroy the composite action of the liner system at the GCL seams. This scenario has been documented in field studies, notably by Thiel and Richardson (2005) and Koerner and Koerner (2005a,b).

Thiel and Richardson (2005) documented five cases over two years where separation of GCL seams was observed. All five instances involved reinforced fabric (i.e., needlepunched) GCLs installed on a slope and subsequently overlain by an HDPE geomembrane, but not covered by any protective cover soil. Each case had unique circumstances as to why the geomembrane had to be removed from above the GCL, which allowed the GCL to be inspected. In each case, the geomembrane had been left exposed for months or even years. While this is not

standard practice, it also is not uncommon for the slopes to remain uncovered for several months due to operational reasons (Thiel and Richardson 2005). In one case where one of the authors had significant involvement, the GCL panels were originally overlapped by at least 150 mm and after about four months of being left exposed underneath the geomembrane, the panels had gaps of 50 to 75 mm between them.

Thiel and Richardson (2005) listed 5 potential mechanisms for seam separation: moisture loss, tensile necking, thermal expansion of overlying GM, cation exchange, and stress relaxation. The first mechanism is shrinkage related to moisture loss in the GCL. As the clay component of the GCL absorbs moisture, it expands, and when it loses moisture, it shrinks, directly influencing the behavior of the entire GCL. The second potential shrinkage mechanism is necking resulting from tension in the GCL panels caused by different levels of interface friction above and below GCLs installed on slopes. The third mechanism is the expansion and contraction of the overlying geomembrane. Movement of the overlying membrane can cause shifting and pulling on the GCL below. GM expansion and contraction would generally not cause dimensional changes in the GCL, unless the movement brings the GCL into tension and creates necking as mentioned above. A fourth potential mechanism is cation exchange, which causes bentonite to shrink due to a collapse of the diffuse double layer, as described in the previous section. The final proposed mechanism is shrinkage of the geotextile component of the GCL due to thermal

strains and stress relaxation as the geotextile is allowed to relax in the unrolled configuration (Thiel and Richardson 2005).

Thiel and Richardson (2005) proposed a possible sequence of events to explain the observed GCL desiccation and associated shrinkage. The process is cyclical with the following four steps. While Thiel and Richardson (2005) proposed that this cycle could repeat daily, other studies published since 2005, such as Bostwick et al (2008), have proposed that the cycles could instead be seasonal.

1. The GCL is placed beneath an exposed, black geomembrane during the daytime or during summer, which can reach temperatures of 50°C to 70°C depending on the local climate conditions.
2. The hot geomembrane causes evaporation of the moisture directly below the geomembrane, which will draw water out of the GCL.
3. During the night (or cooler seasons), the temperature decreases significantly, causing the vaporized moisture to condense and form droplets between the GCL and the geomembrane.
4. Gravity causes the droplets to run down to the toe of the slope. The cycle then repeats from step 1 either the next day or in the next warm season.

Koerner and Koerner (2005a, b) also cited five cases where GCL panels were left beneath an exposed geomembrane for an extended period of time and underwent significant shrinkage. It is unclear whether all or any of these cases are the same as those documented in Thiel and Richardson (2005). Most of the

conditions in the cases reported by Koerner and Koerner (2005) were similar to those described in Thiel and Richardson (2005). Therefore, only the notable exceptions are described herein. Four of the five cases had needlepunched nonwoven geotextiles as the upper geotextile placed against the overlying textured geomembrane. One of the cases was for a GCL placed along the base of a landfill, while the other four included GCLs placed on side slopes of bottom liners under geomembranes prior to placement of cover soil or waste. The as-manufactured moisture content of the GCLs was 24 to 44%, which is approximately the upper end of the range of normal GCL moisture contents. Three configurations of GCLs were involved: adhesive bonded nonreinforced GCL with woven GTs on both sides; needle punched GCL with nonwoven GT up and slit film woven GT down; and needle punched nonwoven GT up with nonwoven GT down. None of the geotextiles had any type of woven scrim reinforcement (Koerner and Koerner 2005a,b). Scrim reinforcement is a method of reinforcing a nonwoven geotextile by needlepunching a woven and nonwoven geotextile together and using the resulting composite woven-nonwoven material as either the top or bottom layer of the GCL (von Maubeuge and Herlin 2011).

A summary of field observations from Thiel and Richardson (2005) and Koerner and Koerner (2005a,b) is presented in Table 2.2. This table includes the type of GCLs, slope angle, maximum panel separation, and exposure duration for GCLs beneath the exposed GMs. As GCLs are typically manufactured in approximately 4.5 m wide rolls and are overlapped by 150 mm to 300 mm, the

maximum separation for the cases reported in Table 2.2 corresponds to shrinkage strains of 8 to 33%.

Table 2.2. Summary of Field GCL Shrinkage Observations

GCL Type (Top GT/Bottom GT)	As-Manufactured Moisture Content (%)	Slope (°)	Exposure duration (months)	Maximum separation (mm)
Woven/Woven unreinforced	Approximately 20	22	60	300
Nonwoven/Woven reinforced	25-30	18	15	200
Nonwoven/Woven reinforced	Not Reported	4	2	300
Nonwoven/Nonwoven reinforced	25-29	34	36	1200
Nonwoven/Nonwoven reinforced	25-31	18	5	300
Nonwoven/Nonwoven reinforced	29-44	2-4	2	150

The proposed mechanisms in Koerner and Koerner (2005a,b) for shrinkage generally agree with those provided in Thiel and Richardson (2005). Koerner and Koerner (2005a,b) provided five recommendations to prevent and detect seam separation:

- Backfill at least 300 mm of soil over the GM in a timely manner to prevent exposing the GCL to dramatic temperature fluctuations.
- Prevent using GCLs with needle punched nonwoven geotextiles on both sides unless one of the geotextiles is scrim reinforced.
- Increase the GCL overlap to 250 to 450 mm instead of 150 mm depending on the GCL product used.

- Protect the GM/GCL composite with thermal blankets, geofoam, or other insulation techniques.
- Develop a nondestructive test to detect panel separation.

Significant seam separation has not occurred in all instances reported in literature where a GCL is left beneath an exposed geomembrane. Gassner (2009) investigated a site in Australia where a GCL liner with overlaps of 300 mm had been left under an exposed geomembrane for 18 months and only underwent shrinkage of approximately 50-80 mm at the seams.

The mechanisms responsible for the dimensional changes of GCLs are not well understood, with the mechanisms listed above mainly constituting educated guesses. Relative contributions of the separate mechanisms related to panel shrinkage have not been reported. As the dimensional stability problem only has been documented recently, laboratory testing for GCL dimensional stability is still under development and standardized test procedures (e.g., ASTM standards) are not available to quantify the dimensional stability of a GCL.

2.7 Laboratory Testing of GCL Dimensional Stability

The initial laboratory research regarding GCL dimensional stability was published by Koerner and Koerner (2005a, b). These tests focused mainly on the mechanical strains of GCLs caused by tension in the longitudinal direction. The properties of the GCLs tested and the results were not presented in detail as both publications were brief white papers (Koerner and Koerner 2005a,b). The papers documented that nonwoven/nonwoven reinforced GCLs exhibited the greatest transverse strain, with up to 70% transverse shrinkage. GCLs with a

woven/woven or woven/nonwoven configuration exhibited less than a 10% transverse shrinkage. As the length to width aspect ratio increased, transverse shrinkage increased as well. Stress strain relationships were not published (Koerner and Koerner 2005a,b).

The effects of wetting and drying on dimensional stability of GCLs were initially investigated by Thiel et al. (2006). Further studies have been conducted by Bostwick et al. (2007, 2008, 2010) and Rowe et al. (2011). The studies have documented the effects of aspect ratio, specimen size, GCL type, edge confinement, hydration amount, bentonite mass per unit area, initial moisture content, bentonite granularity and bentonite type on specimens undergoing cyclic wetting and drying. Laboratory and field testing also was conducted to develop a solution to the GCL dimensional stability problem by heat tacking seams to prevent separation (Rowe et al. 2009, 2010). A summary of all tests performed in these investigations is presented in Table 2.3.

A variety of GCL types have been tested in the aforementioned studies. Several of the studies tested nominally the same GCL types, allowing for investigation of variation within a given GCL type. A summary of the GCL types studied in laboratory tests is presented in Table 2.4. The GCLs were all reinforced by needlepunching and had varying bentonite mass per unit areas, geotextile types, and geotextile mass per unit areas. Some of the GCLs contained elements proprietary to their specific manufacturer. Those proprietary elements include incorporating (a) scrim reinforcement to one of the nonwoven geotextiles in the GCL to improve the geotextile strength and perhaps also

improve GCL dimensional stability (Thiel et al. 2006), (b) a heat treatment process intended to improve the strength of the needlepunched fibers and provide increased internal shear strength and long term creep resistance (Terrafix 2007), and (c) addition of a uniform polypropylene geofilm coating applied to the woven bottom geotextile intended to lower the hydraulic conductivity of the GCL (Terrafix 2007).

Table 2.3. Summary of GCL Tests Performed in Laboratory Studies

Variable Tested	Testing Type	Reference
Aspect Ratio	Tension	Koerner and Koerner (2005a,b)
	Cyclic Wet/Dry	Bostwick et al. (2007, 2010)
Specimen Size	Cyclic Wet/Dry	Bostwick et al. (2007, 2010)
GCL Type	Tension	Koerner and Koerner (2005a,b)
	Cyclic Wet/Dry	Thiel et al. (2006), Bostwick et al. (2007, 2008, 2010), Rowe et al. (2011)
End Boundary Conditions	Cyclic Wet/Dry	Bostwick et al. (2008, 2010)
Hydration Amount	Cyclic Wet/Dry	Thiel et al. (2006) Rowe et al. (2011)
Mass per Unit Area	Cyclic Wet/Dry	Bostwick et al. (2010)
Initial Moisture Content	Cyclic Wet/Dry	Rowe et al. (2011)
Bentonite Type and Granularity	Cyclic Wet/Dry	Rowe et al. (2011)

Table 2.4. Summary of GCL Types Tested in Laboratory Studies

Product	Top GT Type [Weight] (g/m ²)	Bottom GT Type [Weight] (g/m ²)	Bentonite Granularity	Thermally Treated	Reference
N/W1 ^a (GCL 3)	Nonwoven [280]	Woven [130]	Coarse	No	Thiel et al. (2006) Bostwick et al. (2008) Rowe et al. (2011)
N/W2 ^a (GCL 1)	Nonwoven [240]	Woven [120]	Fine	Yes	Thiel et al. (2006) Bostwick et al. (2008) Rowe et al. (2011)
N/N1 ^a (GCL 4)	Nonwoven [260]	Nonwoven [230]	Coarse	No	Thiel et al. (2006) Bostwick et al. (2007) Bostwick et al. (2008) Bostwick et al. (2010) Rowe et al. (2011)
N/S-N1 ^a (GCL 2)	Nonwoven [230]	Scrim reinforced nonwoven [260]	Fine	Yes	Thiel et al. (2006) Bostwick et al. (2008) Bostwick et al. (2010) Rowe et al. (2011)
N/S-N2 ^a	Nonwoven ^b	Scrim reinforced nonwoven ^b	N/A ^c	Yes	Thiel et al. (2006)
N/W-C1 ^a	Nonwoven ^b	PP coated woven ^b	N/A ^c	No	Thiel et al. (2006)
GCL 5	Nonwoven [410]	Scrim reinforced nonwoven [500]	Powdered	Yes	Rowe et al. (2011)
GCL 6	Nonwoven [310]	Scrim reinforced nonwoven [440]	Powdered	Yes	Rowe et al. (2011)
GCL 7	Nonwoven [410]	Woven [220]	Powdered	Yes	Rowe et al. (2011)
GCL 8	Nonwoven [240]	Woven [140]	Powdered	Yes	Rowe et al. (2011)

^aDesignation in Thiel et al. (2006); designation in parentheses corresponds to designation in later publications.

^bGeosynthetic mass per unit area not provided by Thiel et al. (2006).

^cBentonite granularity not provided by Thiel et al. (2006).

2.7.1 Basic Laboratory Testing Procedure

The testing procedures used by Thiel et al. (2006) have served as a basic template for all subsequent GCL laboratory tests. This procedure also was considered for a potential ASTM standard that was never officially adopted. Specimens for this test were cut to dimensions of 350 mm (cross-machine direction, XMD) by 600 mm (machine direction, MD). The specimens were clamped in a relaxed state to an aluminum pan using 25-mm-wide bar clamps screwed directly to the pan and running in the transverse direction along the ends of the specimen. Clamping the specimens was intended to simulate field conditions where the GCLs are anchored at the ends. Each specimen was marked with a frame drawn 25 mm from the edges of the specimen and clamped ends. At the midpoint of the framing lines, an additional marking was placed for taking strain measurements. These markings resulted in a gauge length of 500 mm, a gauge width of approximately 300 mm, and thus an aspect ratio of 1.7 (500 : 300 mm).

The specimens were hydrated by spraying a prescribed amount of water evenly over the specimen and then covering the specimen with a plastic sheet at room temperature for approximately 8 hours. After the 8-hour hydration period, the specimens were measured at the gauge marks and then placed in an oven at 60°C and allowed to dry. After approximately 15 hours of drying time, the specimens were removed from the oven, allowed to cool to room temperature, and again measured at the midpoints. Each cycle lasted approximately 24 hours, as measuring and handling the specimens took approximately one hour.

Specimens were hydrated and dried in this manner for 40 cycles (Thiel et al. 2006). This basic testing procedure was adopted by other researchers in subsequent tests, with modifications made to the procedure to test the effects of aspect ratio, specimen size, edge confinement, hydration amount, and initial moisture content.

2.7.2 Baseline Behavior

GCLs tended to experience shrinkage upon desiccation due to heating. During wetting at room temperature, the GCLs swelled as they regained the moisture they had lost upon heating; however, cyclic wetting/drying induced shrinkage strains that were not entirely recoverable. Each time a specimen desiccated and contracted, the specimen recovered only a fraction of its original size upon subsequent rehydration and swelling. With each cycle, the total amount of shrinkage increased. The total strain increased significantly from cycle to cycle in the stages and began to increase less steadily as the number of cycles increased. Eventually, the wetting and drying strains stabilized. In general the maximum shrinkage strain occurred near the midlength of tested specimens (Thiel et al. 2006, Bostwick et al. 2007, 2008, 2010, Rowe et al. 2011).

The amount of shrinkage during the initial 10 cycles of wetting and drying was higher than the amount of shrinkage over the later cycles. The reduced amount of shrinkage between cycles with increasing numbers of wetting/drying cycles indicate that the rate of shrinkage decreases with the number of cycles and a limiting value of shrinkage is reached. Depending on the GCL type and

testing conditions, GCLs may take as few as 15 wet-dry cycles (for select GCL types with granular bentonite) or more than 75 wet-dry cycles (for GCLs with powdered bentonite) for the accumulated shrinkage to stabilize (Thiel et al. 2006, Bostwick et al. 2007, 2008, 2010, Rowe et al. 2011).

2.7.3 Effects of Aspect Ratio and Specimen Size

Specimens of GCL type N/N1 were tested according to the basic procedure outlined in Section 2.7.2, with the exception that specimen sizes and shapes varied, and that the hydration and drying times and temperatures were changed to accommodate some large specimen sizes (Bostwick et al. 2007). The aspect ratios and specimen sizes tested are presented in Table 2.5.

Table 2.5. Aspect Ratios and Sample Sizes (Bostwick et al. 2007)

Aspect Ratio	Specimen Width (mm)	Gauge Width (mm)	Length (mm)
1	300	250	300
1.7	350	300	550
5	100	50	500
5	300	250	1500
5	600	550	3000
10	300	250	3000

Three of the specimens had approximately the same width to test the effects of aspect ratio, while three of the specimens had the same aspect ratio but different sizes in order to test the effects of specimen size. Rather than drying at 60°C like all other wet-dry tests the specimens were dried at 40°C because they were dried in a temperature controlled room rather than a convection oven. The decreased temperature required an adjustment of wet-dry

cycle timing to six hours of hydration with 65 hours of drying (Bostwick et al. 2007).

Shrinkage strains generally increased with aspect ratio at aspect ratios of less than 5. No significant difference was found in shrinkage between specimens with an aspect ratio of 5 and 10. At small aspect ratios, a specimen is highly influenced by the restraint at the ends, whereas this effect is less pronounced for higher aspect ratios. As the specimen became longer in length relative to its width, the end restraints had less of an effect on the shrinkage and the midpoint of the specimen thus had more freedom to move relative to the ends. Beyond an aspect ratio of 5, end restraints had negligible effects. The three specimens with an aspect ratio of 5 all had a relatively similar maximum strain. Therefore, specimen size did not appear to have a significant effect on specimen shrinkage (Bostwick et al. 2007, 2010).

2.7.4 Effects of GCL Type

A total of 10 GCL types have been tested in the studies listed in Table 2.3. Four of the GCL types were tested in multiple studies by different authors. Tests were conducted on a variety of GCL types to determine the effects of configuration, mass per unit area (bentonite and geosynthetics), bentonite granularity, and presence of proprietary technology, such as scrim reinforced geotextiles and heat treatment. In addition, individual geotextiles were tested to determine whether shrinkage was a result of wet-dry cycling of the textiles or the bentonite component of the GCL. Before wet-dry cycling, each specimen was hydrated by adding a constant amount of water with a garden sprayer. This led

to unequal water contents being applied to the specimens, as some GCLs had higher initial moisture contents than others.

In tests conducted on GCLs, when no scrim reinforcement was present, specimens with nonwoven/woven construction tended to shrink less than those with nonwoven/nonwoven construction (20.6% and 14.5% for the two nonwoven/woven versus 23% for the nonwoven/nonwoven). Scrim reinforcement in nonwoven/nonwoven GCLs tended to greatly reduce shrinkage. The scrim reinforced GCL, however, also contained a heat treated carrier geotextile, which was not present in the unreinforced nonwoven/nonwoven, and the initial moisture content of the reinforced GCL was lower than the water content of the unreinforced GCL (Thiel et al. 2006). Both of these factors also would serve to reduce shrinkage and may cause an overestimation of the benefits of scrim reinforcement. Needle punch density had a significant impact on shrinkage. The specimen with the higher needle punch density experienced less shrinkage than the specimen with lower needle punch density (Thiel et al. 2006). The specimen with a polypropylene geofilm coating improved dimensional stability, especially in the initial cycles, compared to the other specimens tested (Thiel et al. 2006).

Thiel et al. (2006) tested five different types of geotextiles in addition to the testing of GCLs that contained the five geotextile types. This was done to determine whether the geotextiles caused the shrinkage, or whether shrinkage resulted mainly from the bentonite component of the GCL composite. The geotextiles were the same as those used in the GCLs and were tested under

identical conditions to the corresponding complete GCLs. Geotextiles experienced minimal shrinkage and stabilized in less than seven cycles, thus it was determined that geotextile shrinkage was not the driving mechanism of GCL shrinkage (Thiel et al. 2006).

2.7.5 Effects of End Confinement

In previous investigations, several specimens were tested without clamping the ends to determine whether or not edge confinement affected the overall shrinkage as well as to allow for measurement of shrinkage in the machine direction of the specimen. The unconfined specimens were cut to dimensions of 550 by 350mm, which allowed for a similar gauge area (500 by 300 mm) (Bostwick et al. 2008, 2008, Rowe et al. 2011).

Specimens that were restrained tended to shrink slightly more in the transverse direction than specimens of the same GCL type that were unrestrained, with approximately 1.1 times as much shrinkage strain. In unrestrained specimens, the difference in shrinkage between the machine and cross-machine direction depended on GCL type. Specimens with a scrim reinforced nonwoven geotextile (N/S-N1 in Table 2.4) displayed no significant difference between shrinkage in the longitudinal and transverse direction. Specimens without scrim reinforcement (N/N1 in Table 2.4) displayed a statistically significant difference between longitudinal shrinkage and transverse shrinkage. Specimens of this type underwent more shrinkage in the longitudinal direction to a variable extent (Bostwick et al. 2010).

2.7.6 Effects of Mass per Unit Area

Mass per unit area tended to vary significantly between specimens in all previous test programs, even when specimens were taken from similar locations on a larger GCL roll. In order to test the effects of mass per unit area on GCL shrinkage, multiple specimens of GCL type N/N1 were tested under identical conditions, such that the only difference between the specimens was their mass per unit area (Bostwick et al. 2010).

In general, GCL shrinkage was high if the mass per unit area was below a certain threshold value. At very low dry mass per unit areas ($3700\text{--}4000\text{ g/m}^2$), shrinkage was severe, at about 12.5%. Specimens with mass per unit areas of $4000\text{--}5000\text{ g/m}^2$ experienced significantly less shrinkage, with about 7.3%. Within the range of $4000\text{--}5000\text{ g/m}^2$ there was little variance in shrinkage between specimens, except in specimens with irregular distributions of bentonite. Specimens with non-uniform distributions of bentonite experienced greater shrinkage than specimens that were uniform, regardless of the specimen mass. All specimens with low mass per unit area and some specimens with high mass per unit area had a non-uniform distribution of bentonite and thus experienced high degrees of shrinkage. As the uniformity of the bentonite distribution decreases, the GCLs became increasingly susceptible to shrinkage. In areas with less bentonite, shrinkage was more pronounced. Unrestrained specimens were as susceptible to localized shrinkage as restrained specimens in thin areas (Bostwick et al. 2010).

2.7.7 Effects of Hydration Amount

Most of the specimens in the previously published studies were sprayed with a constant amount of added water equivalent to 500 mL of water in each cycle over a GCL area of 0.193 m^2 (approximately 65% gravimetric moisture content). One of the specimens in Thiel et al. (2006), however, was sprayed with 300 mL of water on a 0.193 m^2 specimen in each cycle (approximately 40% gravimetric moisture content) to determine whether hydration amount affected the magnitude of GCL shrinkage. Testing of hydration amount was continued by Rowe et al. (2011), with some specimens hydrated using 1000 mL of water on a 0.193 m^2 specimen (100-125% gravimetric moisture content) and others hydrated to a target gravimetric water content of 60% and 100% in addition to the 500 mL of each previous test (Rowe et al. 2011).

Hydration amount tended to have a greater effect on shrinkage at lower degrees of hydration than higher degrees. Specimens hydrated with low amounts of water experienced less shrinkage than specimens hydrated with the baseline amount of water. Specimens hydrated to approximately 40% gravimetric moisture content tended to experience overall shrinkages about 25% less severe than specimens hydrated with the baseline of approximately 65% gravimetric moisture content. It is unknown whether specimens at low moisture contents would eventually reach equilibrium at the same degree of shrinkage as the baseline because testing ceased after 40 cycles before specimens of that specific GCL type had reached stable shrinkage behavior (Thiel et al. 2006).

Specimens hydrated with more water than the baseline amount of approximately 65% gravimetric moisture content tended to shrink the same

amount as specimens hydrated to the baseline amount. Adding more water increased the rate of shrinkage, as the specimens hydrated with 100-125% gravimetric moisture reached shrinkage equilibrium in fewer cycles than those hydrated with 65% (Rowe et al. 2011).

While Thiel et al. (2006) observed that adding less water than the baseline results in significantly less shrinkage than the baseline specimen, Rowe et al. (2011) determined that adding more than the baseline results in no significant change in overall shrinkage than the baseline. Both results may be valid, as the tests between both studies were conducted on different GCL types. Another explanation for the observed effect of hydration amount was that baseline hydration was wetter than the plastic limit and the reduced hydration was drier than the plastic limit. Reduced hydration also may not have been sufficient to evenly spray the specimens, which would lead to decreased shrinkage (Rowe et al. 2011). It is possible that there is some threshold between 40% and 65% gravimetric moisture content that specimens must be hydrated to in order to experience maximum shrinkage.

2.7.8 Effects of Initial Moisture Content

The effects of initial moisture content were tested in Rowe et al. (2011) by adding sufficient water to artificially raise the moisture content from the as-received moisture content (5% gravimetric moisture content) to 19%, 64%, and 72% to cover an extreme range of possible initial conditions. Rowe et al. (2011) only tested the effects of initial moisture content in one GCL type (N/N1). After specimens were sprayed with sufficient water to reach the above moisture

contents, the specimens were allowed to equilibrate before adding 500 mL of water according to the basic procedure outlined in Section 2.7.1. All subsequent hydration and drying phases followed the outline in Section 2.7.1 (Rowe et al. 2011).

The initial moisture content of the GCL was not found to have significant correlation to the final observed shrinkage in the GCL. Specimens with a higher initial moisture content displayed more shrinkage in the first wet-dry cycle than specimens with lower initial moisture content, which contributed to a higher accumulated strain in the first few cycles. After a number of cycles, the effect of initial moisture content was minimal, and at equilibrium there was no apparent effect on ultimate maximum shrinkage (Rowe et al. 2011).

2.7.9 Effects of Bentonite Type and Granularity

To test the effect of granularity and bentonite type on GCL dimensional stability, the products tested by Rowe et al. (2011) had three different granularities and three different compositions of sodium bentonite. The bentonites tested ranged in granularity from coarse granular (D_{50} approximately 0.08 mm) to fine granular (D_{50} approximately 0.03 mm) to powdered (D_{50} approximately 0.003 mm).

Bentonite granularity and type had little effect on the dimensional stability of GCLs in the first five wet-dry cycles. After about the fifth cycle, when shrinkage with each cycle began to decline in specimens with granular bentonite, specimens with powdered bentonite continued shrinking at a high rate. GCLs with granular bentonite reached a relatively constant shrinkage by about 30

cycles, where GCLs with powdered bentonite did not reach constant shrinkage, even after 75 cycles. Because the rate of shrinkage in the first several cycles between powdered bentonite and granular bentonite were similar, GCLs with powdered bentonite experienced higher final shrinkages than those with granular bentonite (Rowe et al 2011).

Though the total shrinkage of the GCLs is of scientific interest, if wet-dry cycles are seasonal rather than daily in the field, shrinkage within the first 5 to 10 cycles is of greater relevance to field situations, unless the composite liner is to be left uncovered for considerable periods of time. After covering the GCL with at least 0.3 m of soil, wet-dry cycles are assumed to decrease significantly in severity. At 10 wet-dry cycles, the shrinkage for the powdered and granular bentonites was similar, so the differences between shrinkage in granular and powdered bentonites may be less significant in the field than the laboratory results imply (Rowe et al. 2011).

2.7.10 Summary of Results from Previous Studies

A summary of the results of previous investigations [(Thiel et al 2006), (Bostwick et al. 2007, 2008, 2010), (Rowe et al. 2011)] is presented in Table 2.6. This table includes most of the parameters tested in the five studies; however it does not include the effects of initial moisture content and mass per unit area because these variables would add excessive complexity to the table. For simplicity, when duplicate or follow-up tests were conducted by the same authors in two papers, only the later results are presented.

Table 2.6. Summary of Results from Dimensional Stability Laboratory Tests

GCL Type	Approximate Hydration Water Content (%)	Maximum Machine Shrinkage (%)	Maximum Cross Machine Shrinkage (%)	Number of Cycles to Reach Equilibrium	Specimen Dimensions (mm)	Edge Restraint	Reference
N/W1	65	N/A ^a	20.1	25-30	350 x 550	Restrained	Thiel et al. (2006)
	50	N/A ^a	Approx. 11	20-25	350 x 550	Restrained	Bostwick et al. (2008)
	50	N/A ^a	Approx. 11	30-35	350 x 550	Restrained	Rowe et al. (2011)
N/W2	65	N/A ^a	14.5	30-40	350 x 550	Restrained	Thiel et al. (2006)
	50	N/A ^a	10.1	25-30	350 x 550	Restrained	Rowe et al. (2011)
	105	N/A ^a	10.4	10-15	350 x 550	Restrained	Rowe et al. (2011)
N/N1	65	N/A ^a	23	25-30	350 x 550	Restrained	Thiel et al. (2006)
	55	N/A ^a	9.9	15-35	300 x 300	Restrained	Bostwick et al. (2010)
	55	N/A ^a	10.5	15-35	350 x 550	Restrained	Bostwick et al. (2010)
	55	N/A ^a	11.7	15-35	100 x 500	Restrained	Bostwick et al. (2010)
	55	N/A ^a	12.2	15-35	300 x 1500	Restrained	Bostwick et al. (2010)
	55	N/A ^a	13.5	15-35	600 x 3000	Restrained	Bostwick et al. (2010)
	55	N/A ^a	13.4	15-35	300 x 3000	Restrained	Bostwick et al. (2010)
	65	N/A ^a	11.4	15-20	350 x 550	Restrained	Bostwick et al. (2010)
	65	8.6	7.79	15-20	350 x 550	Unrestrained	Bostwick et al. (2010)
	60	N/A ^a	7.8	20-25	350 x 550	Restrained	Rowe et al. (2011)
	60	N.A. ^b	6.7	15-20	350 x 550	Unrestrained	Rowe et al. (2011)
	100	N/A ^a	8.9	20-30	350 x 550	Restrained	Rowe et al. (2011)
	100	N.A. ^b	8.3	15-20	350 x 550	Unrestrained	Rowe et al. (2011)

GCL Type	Approximate Hydration Water Content (%)	Maximum Machine Shrinkage (%)	Maximum Cross Machine Shrinkage (%)	Number of Cycles to Reach Equilibrium	Specimen Dimensions (mm)	Edge Restraint	Reference
N/S-N1	65	N/A ^a	12.9	>40	350 x 550	Restrained	Thiel et al. (2006)
	65	N/A ^a	9.94	N/A ^b	350 x 550	Restrained	Bostwick et al. (2010)
	65	7.4	7.8	N/A ^b	350 x 550	Unrestrained	Bostwick et al. (2010)
	60	N/A ^a	9.6	30-40	350 x 550	Restrained	Rowe et al. (2011)
	125	N.A. ^b	11.3	30-40	350 x 550	Unrestrained	Rowe et al. (2011)
N/S-N2	65	N/A ^a	19.2	>40	350 x 350	Restrained	Thiel et al. (2006)
	40	N/A ^a	14.4	>40	350 x 550	Restrained	Thiel et al. (2006)
N/W-C1	65	N/A ^a	12.8	30-40	350 x 550	Restrained	Thiel et al. (2006)
GCL 5	60	N/A ^a	14.8	>75	350 x 550	Restrained	Rowe et al. (2011)
GCL 6	65	N/A ^a	18.5	>75	350 x 550	Restrained	Rowe et al. (2011)
GCL 7	60	N/A ^a	13.6	>75	350 x 550	Restrained	Rowe et al. (2011)
GCL 8	60	N/A ^a	19.9	>75	350 x 550	Restrained	Rowe et al. (2011)

^a N/A: Not Applicable

^b N.A.: Not Available

2.7.11 Assessment of Testing Variability

Variations were observed between replicate GCL specimens in the tests reported by Thiel et al. (2006), Bostwick et al. (2007, 2008, 2010), and Rowe et al. (2011) even though the testing conditions were essentially the same for certain specimens. The variation in shrinkage was related to the location on a roll that a specimen was taken from in the reported tests. Specimens removed from similar parts of the roll exhibited similar shrinkage and specimens from dissimilar parts of the roll exhibited different shrinkage, especially for GCL type N/N1 (Bostwick et al. 2010).

In addition to variability within a roll, a high degree of variability between rolls also was observed. Large discrepancies in test results were reported between the studies conducted by Thiel et al. (2006), Bostwick et al. (2007, 2008, 2009), and Rowe et al. (2011), even though the same GCL material (same type and manufacturer) was used in the tests. Each of the testing programs in the five aforementioned studies had control specimens that were tested under identical conditions to the other studies. However, differences from one study to the next in nominally the same product ranged from 3-12%. These discrepancies indicate that a wide range of shrinkage can be expected for nominally the same product. Bostwick et al. (2010) reported that such variations may be due to the manufacturer changing production variables which are not generally published, such as pretensioning of the geotextile components, compression of the bentonite component, degree of needle punching, and heat treatment, while retaining the same product name, appearance, and certain index properties.

2.8 Additional Dimensional Stability Tests

In addition to the laboratory investigations detailed in the previous section, field research is currently underway to study GCL shrinkage and associated loss of overlap as well as geomembrane wrinkling. Full size GCL rolls were installed on a native silty sand in Kingston, Ontario beneath an exposed geomembrane. Specimens of GCLs were removed 42 days after installation, and water content was measured to range from 59-115% gravimetric moisture content (Brachman et al. 2007). Field shrinkage in a Canadian climate was not as extreme as in a laboratory setting, indicating that GCL shrinkage is a result of seasonal wet-dry cycles rather than daily. After one year of observation, shrinkage strains in the panels were less than 1.5% (Bostwick et al. 2008). Further results of the investigation have not been published.

A proposed solution to reducing GCL shrinkage is to bond the GCL sheets together by heat tacking. If proven to be effective, heat tacking would be more economical for landfill owners than increasing panel overlaps, which would require purchase of additional GCL materials for the same coverage. At a field site, GCL panels were overlapped by 150 mm, then heat-tacked using a flame torch, and pressed together using a sand-filled bag (Rowe et al. 2009, 2010). After placement beneath an exposed geomembrane for over two months, the heat tacked seams had not separated. Since all of the overlaps at the site were heat tacked, it is unknown whether the heat tacking of the GCL overlaps prevented separation, or if the panels would not have undergone shrinkage without the heat bonding. This study alone was therefore not able to confirm that

the heat-tacking is sufficiently strong to withstand GCL shrinkage (Rowe et al. 2009).

Laboratory tests on heat tacked seams concluded that in most cases, the heat bonded seams were at least as strong as the GCL itself. Also, the strength of the seam did not tend to decrease after wet-dry cycling in the laboratory. While these tests indicate that heat tacking is a viable solution to reducing loss of panel overlap, they were performed under idealized conditions on small-scale specimens (Rowe et al. 2009, 2010). Field-scale tests comparing heat-tacked seams to overlap seams are necessary to prove the viability of heat-tacking to prevent loss of panel overlap.

2.9 Summary

The aforementioned studies provided a good foundation for researching dimensional stability of GCLs; however a more systematic approach is needed to determine the relative effects of all possible causes of GCL panel shrinkage. The effects of aspect ratio, specimen size, GCL type, constraint type, mass per unit area, hydration amount, initial hydration amount, and bentonite granularity on dimensional stability were studied in laboratory settings. Moisture content changes in these tests were coupled with temperature changes.

Several aspects of dimensional stability have not been investigated in the previous studies. Independent analysis of temperature and moisture content change was not studied. Another limitation of the previous laboratory studies is in determining effects of initial GCL moisture content on dimensional stability. Rowe et al. (2011) tested only one type of GCL at four different initial moisture

contents ranging from 5% to 72%. This is a relatively wide range of initial moisture contents for the one GCL type tested by Rowe et al. (2011) under normal conditions. However, other GCL types may be prone to more initial hydration by placement on wet subgrades (Daniel et al. 1993), improper installation that results in the GCL being rained upon prior to covering, or deliberate prehydration to improve hydraulic performance. Initial moisture content testing should be expanded to include a broader range of GCL types and moisture contents.

The aforementioned studies also are limited in that only the effects of GCL hydration with water were tested. Previous studies of bentonite have demonstrated that GCLs lose much of their original swell potential when wetted with calcium solutions, as cation exchange of calcium for sodium is coupled with desiccation and rewetting. This is an area where testing is warranted, as native soils in many regions are high in calcium and leachates reaching the GCL may have high concentrations of multivalent cations. Studies have not been conducted on dimensional stability of intact GCLs hydrated with calcium salt solutions.

Furthermore, tests in the five mentioned studies were conducted on specimens with no overburden pressure. While GCLs may be left beneath an exposed geomembrane for extended periods of time, they generally are covered beneath at least 300 mm of soil in a timely manner in a bottom liner application prior to waste placement. In final cover applications, GCLs are typically covered

by at least 1 m of soil. The dimensional stability of GCLs under overburden confinement has yet to be investigated.

The GCLs in previous studies of dimensional stability were tested by spraying a specified amount of water directly on the specimen and allowing it to hydrate prior to drying. This method of directly spraying the specimen with water is convenient for index testing; however it is not representative of the method of hydration in the field. GCLs hydrate in the field by soaking up moisture from the surrounding soils. Recent studies (Beddoe et al. 2010, 2011) have indicated that different GCL types have different water retention curves and hence uptake water differently in the field, which could influence the drying and wetting history of GCLs (Bostwick et al. 2010).

The effects of tensile loading on GCL dimensional stability have been tested by Koerner and Koerner (2005a,b), however the properties of the specimens tested and the results of the testing were not published in detail, as both studies were published as brief white papers. No stress-strain behavior aimed at quantifying transverse strain or Poisson's ratio of GCLs has been published.

Furthermore, temperature in the laboratory was only cycled between 20°C and 40°C or between 20°C and 60°C. GCLs in certain climates are subject to cooling to sub-freezing temperatures when used in landfill covers, and heating to temperatures of at least 70°C when left underneath an exposed geomembrane (Rowe 2006). Furthermore, 24 hour or 48 hour cycling is convenient because it

results in faster tests, but long-term, slower-rate cycling also is warranted to simulate heating and cooling in seasonal cycles, rather than just diurnal cycles.

This investigation was conducted as a systematic approach to determine the effects of initial moisture content, permeant type, and overburden stress on the dimensional stability of GCLs undergoing cyclic wetting and drying. The isolated effects of temperature, subgrade type, and tensile necking also were investigated. In addition, outdoor tests in which GCLs were placed over a compacted soil subgrade and beneath an exposed geomembrane were conducted to simulate field conditions. Coupled and individual effects of the various factors on dimensional stability of GCLs were investigated.

Chapter 3: Experimental Test Program

3.1 Introduction

A laboratory test program was undertaken to evaluate the individual effects of GCL type, initial moisture content, permeant type, overburden pressure, temperature, underlying soil properties, and mechanical necking on GCL dimensional stability. In addition, the combined effects of GCL type, underlying soil properties, and local temperature variations were tested in a simulated field environment. The objectives of the test program were: (a) to isolate the individual mechanisms that may be responsible for changes in dimensions of GCLs by testing each mechanism individually and (b) to investigate dimensional stability due to the influence of coupled mechanisms.

The test program was designed to provide a systematic analysis of GCL dimensional stability. Initially, the test materials are described. Then, the individual dimensional stability tests are described in detail. Finally, the field simulation test with coupled mechanisms is presented.

3.2 Materials Tested

A total of five types of GCLs were tested in the experimental program. The GCLs were all manufactured by the same company, CETCO, and part of the Bentomat line of GCLs. CETCO is one of the prominent GCL manufacturers in the United States. Testing GCLs from the same manufacturer prevented potential differences in bentonite type and in the type of specific geosynthetic components. The only nominal variable separating the products was the

configuration of the GCLs. In addition, two types of soils were used in tests that were conducted to measure the effects of underlying soils beneath the GCLs.

3.2.1 GCLs Tested

Five different types of GCLs were tested with three basic configurations:

- A layer of granular bentonite between a nonwoven and woven geotextile
- A layer of granular bentonite between two nonwoven geotextiles
- A layer of granular bentonite between a nonwoven and woven geotextile with a geomembrane laminated to the nonwoven geotextile

All GCLs tested have a reported swell index of at least 24 mL/2g per ASTM D5890, and fluid loss of no more than 18 mL per ASTM D5891 (IFAI 2011). The as-manufactured GCLs have reported bentonite moisture contents of between 20% and 40% (CETCO 2009). All of the GCLs are bonded together using needlepunching. None of the GCLs tested incorporate any of the proprietary scrim reinforcement, thermal treatment, or geofilm coating discussed in Section 2.7, as those features are unique to a different manufacturer. Some of the GCLs tested contained adhered geomembrane components, which will be described in further detail on a product-specific basis. The five products tested were all Bentomat series products, including 200R, ST, DN, CL, and CLT.

200R is a lightweight GCL consisting of a layer of bentonite between a lightweight slit-film woven geotextile and a lightweight nonwoven geotextile. The GCL is held together by needlepunching the fibers of the nonwoven geotextile through the apertures of the woven geotextile. 200R is intended to be a low cost

liner placed beneath a geomembrane on slopes that are no steeper than 10H : 1V, or in instances that do not require high internal shear strength (CETCO 2009).

ST is a mid-weight GCL consisting of a layer of bentonite between a lightweight slit-film woven geotextile and a heavier weight nonwoven geotextile. ST is similar in configuration to the aforementioned 200R, except for having a heavier weight nonwoven geotextile. Similar to the other GCLs with woven-nonwoven configuration, ST is held together by needlepunching the fibers of the nonwoven geotextile through the apertures of the woven geotextile. The mid-range performance and cost of this GCL make ST the most commonly specified GCL in the world and allow it to be used in a wide variety of hydraulic barrier applications with slopes of up to 3H : 1V (CETCO 2009).

DN is a heavier weight GCL consisting of a layer of bentonite placed between two heavier weight nonwoven geotextiles. The GCL is held together by needlepunching the fibers of one nonwoven geotextile through the fibers of the other nonwoven geotextile. DN is intended to be used in more demanding locations, such as canyon landfills with slopes as steep as 1.5H : 1V, or in instances that require high internal and interface shear strength (CETCO 2009).

CL is a special type of GCL consisting of bentonite placed between a lightweight slit-film woven geotextile and a heavier weight nonwoven geotextile, with an additional thin, smooth flexible membrane liner laminated to the outer surface of the nonwoven geotextile. The component with the bentonite placed between two geotextiles is held together by needlepunching the fibers of the

nonwoven geotextile through the apertures of the woven geotextile. This GCL is intended to have better hydraulic performance than GCLs without the additional membrane, and improved puncture and tensile performance than geomembranes by themselves. CL is suitable for landfill covers, ponds, and liquid containment applications with slopes of 3H: 1V or less (CETCO 2009).

CLT also is a special type of GCL consisting of a layer of bentonite between a lightweight slit-film woven geotextile and a heavier weight nonwoven geotextile, with an additional thicker, textured geomembrane liner laminated to the outer surface of the nonwoven geotextile. Table 3.1 gives some of the mechanical properties of the geomembrane component of CLT, provided by Poly-Flex (2001).

Table 3.1. Properties of Geomembrane Component in CLT

Property	Test Method	Typical Value	Minimum Allowable Roll Value (MARV)
Thickness (mm)	ASTM D1593	0.51	0.51
Yield Strength (kN/m)	ASTM D1593	7.36	6.66
Break Strength (kN/m)	ASTM D638	7.36	4.90
Yield Elongation (%)	ASTM D638	13	10
Break Elongation (%)	ASTM D638	200	100

In CLT, the component with the bentonite placed between two geotextiles is held together by needlepunching the fibers of the nonwoven geotextile through the apertures of the woven geotextile. Similar to CL, CLT also is intended to

have better hydraulic performance than traditional GCLs and improved puncture and tensile performance than conventional plastic liners. The textured geomembrane in CLT also provides improved interface shear characteristics and allows for use of the product on landfill covers, bottom liners, and liquid containment applications with steep slopes (CETCO 2009).

The dimensional, strength, and hydraulic properties of the aforementioned GCL types are presented in Table 3.2. Before commencing the test program, a representative amount of the granular bentonite was obtained from each sample roll and was used to determine the as-received gravimetric moisture content. An additional specimen was cut to the dimensions provided above and used to determine mass per unit area of dry bentonite in accordance with ASTM D5993. Both the as-received moisture content and mass per unit area of the GCLs are also provided in Table 3.2. These two parameters allowed for an estimate of the amount of water needed to be added to reach the target moisture content for each test specimen.

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

GCL Type	Panel Width/Length ^a (m)	Average Roll Weight ^a (kg)	Minimum GCL Peel Strength ^a (N/m)	MARV Tensile Strength ^a (N/m)	Internal Shear Strength ^{a,b} (kPa)	Maximum Index Flux ^a (m ³ /m ² -s)	Maximum Hydraulic Conductivity ^a (cm/s)	Bentonite Mass per Unit Area ^c (g/m ²)	As-Received Moisture Content ^c (%)
200R	4.6 / 45.7	1200	175	5300	7.2	1 x 10 ⁻⁸	5 x 10 ⁻⁹	3750	23
ST	4.6 / 45.7	1200	610	5300	24	1 x 10 ⁻⁸	5 x 10 ⁻⁹	4220	20 19 ^d
DN	4.4 / 45.7	1220	610	8800	24	1 x 10 ⁻⁸	5 x 10 ⁻⁹	4590	28
CL	4.6 / 45.7	1250	440	7800	24	1 x 10 ⁻⁹	5 x 10 ⁻¹⁰	4320	22
CLT	4.6 / 45.7	1340	440	7000	24	1 x 10 ⁻⁹	5 x 10 ⁻¹⁰	4330	24 28 ^d

^a Values provided by CETCO (2009)

^b Test performed with GCLs hydrated at 10 kPa confining pressure

^c Values determined in laboratory

^d Two sample rolls provided by CETCO. Values provided are the as-received moisture content of each sample.

3.2.2 Subgrade Soils

A poorly graded sand (SP) and a sandy lean clay (CL) were used as subgrade soils in tests conducted to determine the effects of underlying soil type on dimensional stability of GCLs. The grain size distribution of the SP soil is presented in Figure 3.2. The SP soil had a coefficient of uniformity (C_u) of 4.5 and a coefficient of curvature (C_c) of 0.95. The CL soil had a plastic limit (PL) of 13, a liquid limit (LL) of 32, and a plasticity index (PI) of 19.

Figure 3.1. Grain Size Distribution of Sand Subgrades

The compaction characteristics of both soils were determined using ASTM D1557, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort. The compaction curves are presented in Figure 3.2. The objective of determining the compaction characteristics of the soil was to ensure

that half of the subgrades were compacted wet of optimum moisture content, while the other half were compacted dry of optimum moisture content.

Figure 3.2. Compaction curves for SP and CL soils used in subgrade testing

The sand exhibited an unusual compaction curve, inverse of typical compaction curves. Maximum dry unit weight was observed at low and high moisture contents. This observation is supported by a technical note in ASTM D1557 which states: “For cohesionless soils, the optimum water content is typically close to zero or at the point where bleeding occurs” (ASTM 2011b). As neither of these conditions are likely in the field, 97% relative compaction, corresponding to a dry unit weight of 17.3 kN/m^3 was selected as the target compacted dry density of sand for all subgrade testing. The 17.3 kN/m^3 unit

weight is obtained at low and high water contents of 3 and 11%, respectively. These moisture contents were targeted in the testing program.

The clay soil had an optimum moisture content of approximately 10%, with a maximum dry unit weight of 19.2 kN/m^3 . A 95% relative compaction, which corresponds to a dry density of 18.2 kN/m^3 , was selected as the target density for all the tests. The soil was therefore compacted at 6% and 16% moisture content for specimens dry and wet of optimum moisture content, respectively.

Due to the somewhat flexible nature of the plastic containers used in the testing program, some of the compactive energy from the hammer impact in compaction was absorbed by the container deformation. This energy absorption is attributed with reducing the compactive effort applied to the soil, which resulted in dry densities below the target values. The sand specimens were compacted to a relative compaction of 91% on average (16.3 kN/m^3). The dry of optimum moisture content clay specimens were compacted to a relative compaction of 76% (14.6 kN/m^3), while the wet of optimum moisture content clay specimens were compacted to a relative compaction of 89% (17.0 kN/m^3).

As-prepared moisture contents tended to be close to the target moisture contents. Moisture of the sand subgrade before tests began was 2.4% and 10.1%, for dry and wet soil types, respectively. The moisture content of the clay subgrade before tests began was 6.8% and 18.6%, dry and wet of optimum moisture content, respectively. After 140 days of subgrade testing, moisture in the sand subgrade was 2.0% and 8.3% for dry and wet soil types, respectively.

Moisture in the clay subgrades after 140 days of subgrade testing was 8.5% and 16.3% wet and dry of optimum moisture content, respectively.

3.3 Specimen Preparation

Specimens of a given GCL type were obtained from either a 0.3 x 4.27 m sample or a 1.83 x 2.44 m sample, provided by the manufacturer. The samples had been obtained from the end portion of a full size roll. Care was taken in labeling each specimen to keep track of the machine direction and cross-machine direction. A 150 x 150 x 6 mm steel plate was used as a template for cutting the specimens in all tests except the overburden tests (Section 3.4.3) and the mechanical necking tests (Section 3.7). The specific sizes of specimens in those tests are described in detail in the corresponding sections of the tests. The 150 x 150 mm size was selected because it was large enough to be representative, yet small enough that a large number of specimens could be tested in a laboratory convection oven at the same time. A square shape was selected to effectively test anisotropy in specimens by allowing for measurement in both the machine and cross-machine direction without potential effects of aspect ratio. The specimens were cut with a utility knife. To prevent loss of granular bentonite while cutting, each specimen was wetted around the edges of the template. The amount of water added at each edge was recorded and used in the estimate for the initial moisture content of each specimen. Half of the water used for wetting the test specimens was assumed to remain within the specimen, while half was assumed to be cut away with the scrap materials. Each cut specimen was then placed on an individual thin aluminum tray to

prevent any bentonite loss during testing. The specimens and trays were stored in plastic zipper bags (one specimen per bag) at all times when they were outside of the oven to prevent any potential changes in moisture content due to interaction with ambient conditions.

Similar to the studies on dimensional stability of GCLs reported in literature, gauge markings were drawn 25 mm away from the edge of the specimens. This resulted in a gauge area of 100 mm by 100 mm on each specimen. Each mark was a simple dot drawn into the GCL with either ink or paint-based marker depending upon the color of the GCL. The marks were located midway along the length of each side of a GCL specimen, spaced approximately 25 mm away from the edge of the specimen.

Before water was added to any of the specimens, each specimen was weighed. The distance between the gauge marks was measured manually with a digital caliper with a 0.01 mm resolution. To maintain consistency, measurements were always taken between the closest points on the dots.

After all of the initial measurements were taken, specimens were hydrated to the pre-selected initial moisture contents using the permeant liquid pertaining to that specimen by spraying with a continuous spray, air atomizing sprayer. The sprayer used compressed air to spray water in a fine mist similar to an aerosol can. The conditioning period with which specimens were allowed to hydrate varied by test type, but was always at least 8 hours.

3.4 Cyclic Wet-Dry Tests

Cyclic Wet-Dry tests involved spraying GCLs with a predetermined amount of water, allowing a hydration period of 8 hours (12 for first cycle), and then subjecting specimens to oven-drying at 60°C. This basic cycle was repeated until specimens displayed stable shrinkage behavior. Cyclic wetting and drying tests followed a similar general concept as the cyclic wet-dry testing by Thiel et al. (2006), Bostwick et al. (2007, 2008, and 2010), and Rowe et al. (2011) with several key differences, such as specimen size, aspect ratio, and lack of end clamping.

After specimens were prepared according to the procedure in Section 3.3, the specimens were left to hydrate at room temperature for 12 hours. This initial hydration period was longer than all subsequent hydration periods (which were 8 hours in duration) because some of the specimens were hydrated to high moisture contents (up to 125%), and required adequate time to thoroughly absorb the applied moisture.

After the initial hydration phase, dimensional measurements were taken on each specimen between the gauge marks. The specimens were weighed to determine the actual moisture content of the specimen. Then, the specimens were placed in a convection oven at 60°C until they reached dry conditions. Specimens were considered dry when there was no more than 0.1% change in mass between repeated measurements taken at intervals of at least one hour. Drying generally took approximately 16 hours, but sometimes took as many as 24 hours or as few as 12 hours, depending upon how many specimens were in

the oven at one time and how freely dry air could flow over the specimens. An effort was made to keep drying time consistent, and 16 hours was used for the great majority of the tests. Upon completion of the drying phase, specimen dimensions were measured and the mass of the specimens was recorded.

For all wetting cycles after the initial hydration phase, all specimens were wetted to a bentonite moisture content of approximately 50%. This moisture content was selected because it was indicated by Scalia and Benson (2011) to be a common GCL moisture content from field exhumations and also a threshold for GCLs to which GCLs must be hydrated to maintain low hydraulic conductivity. Also, GSE, another manufacturer of GCLs, specifies 50% gravimetric moisture content in its product literature as the level at which a GCL is considered hydrated (Richardson et al. 2002). The specimens were sprayed in individual plastic bags in the same manner that was used at the beginning of the first cycle, but each subsequent hydration phase had a duration of 8 hours, which resulted in a wet-dry cycle of approximately 24 hours. Each specimen was subjected to 20 wet-dry cycles, as the changes in dimensions of the specimens ceased within the first 20 cycles for the various GCL types and hydration conditions. The specimens used in the cyclic wet-dry tests were unrestrained, and thus could change dimensions in both the machine and cross-machine directions.

3.4.1 Initial Moisture Content Tests

First, the effects of initial moisture content on the dimensional stability of the five different types of GCLs were determined. The initial moisture content tests of the cyclic wet-dry test program followed the basic procedure outlined in

Section 3.4. Specimens of all five types of GCLs were each tested at initial bentonite moisture contents of as-received, 50%, 75%, 100%, and 125%. Two iterations (duplicate specimens) of each combination of moisture content and GCL type were tested and distinguished by labeling with an A and B. In the initial moisture content tests, tap water was the only permeant liquid used. After the initial hydration period, the GCLs were hydrated to 50% moisture content.

All tests following the initial moisture content tests were conducted on types ST and CLT. These GCL types were chosen because ST is the most commonly specified GCL of the five GCL types used in the test program and displayed an intermediate level of shrinkage, and CLT exhibited the greater shrinkage of the two GCL types with a geomembrane component.

Specimens in the initial moisture content tests were designated using three groups of letters and numbers as presented in Table 3.3. The groups represented the following three parameters, respectively:

1. GCL type (200R, ST, DN, CL, or CLT)
2. Nominal initial moisture content, in percent [as-received (AR), 50, 75, 100, or 125]
3. Iteration (A or B)

Table 3.3. Summary of Initial Moisture Content Tests

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Initial Bentonite Moisture Content (%) ^b	Overall Mass per Unit Area (g/m ²) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
200R-AR-A	Nonwoven	105	Woven	105	44	3870	3660
200R-AR-B	Nonwoven	105	Woven	105	45	3760	3550
200R-50-A	Nonwoven	105	Woven	105	45	3850	3640
200R-50-B	Nonwoven	105	Woven	105	49	4120	3910
200R-75-A	Nonwoven	105	Woven	105	72	3920	3710
200R-75-B	Nonwoven	105	Woven	105	81	3520	3310
200R-100-A	Nonwoven	105	Woven	105	98	3860	3650
200R-100-B	Nonwoven	105	Woven	105	95	4290	4080
200R-125-A	Nonwoven	105	Woven	105	113	4140	3930
200R-125-B	Nonwoven	105	Woven	105	120	4240	4030
ST-AR-A	Nonwoven	200	Woven	105	34	4530	4230
ST-AR-B	Nonwoven	200	Woven	105	33	4580	4270
ST-50-A	Nonwoven	200	Woven	105	54	4410	4110
ST-50-B	Nonwoven	200	Woven	105	51	4640	4330
ST-75-A	Nonwoven	200	Woven	105	71	4940	4630
ST-75-B	Nonwoven	200	Woven	105	80	4060	3750
ST-100-A	Nonwoven	200	Woven	105	96	4710	4400
ST-100-B	Nonwoven	200	Woven	105	95	4720	4410
ST-125-A	Nonwoven	200	Woven	105	127	4370	4060
ST-125-B	Nonwoven	200	Woven	105	110	5220	4910
DN-AR-A	Nonwoven	200	Nonwoven	200	34	4910	4510
DN-AR-B	Nonwoven	200	Nonwoven	200	38	4620	4220
DN-50-A	Nonwoven	200	Nonwoven	200	41	5580	5180

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Initial Bentonite Moisture Content (%) ^b	Overall Mass per Unit Area (g/m ²) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
DN-50-B	Nonwoven	200	Nonwoven	200	44	4860	4460
DN-75-A	Nonwoven	200	Nonwoven	200	55	5540	5140
DN-75-B	Nonwoven	200	Nonwoven	200	60	5000	4600
DN-100-A	Nonwoven	200	Nonwoven	200	67	5630	5230
DN-100-B	Nonwoven	200	Nonwoven	200	84	4530	4130
DN-125-A	Nonwoven	200	Nonwoven	200	95	4960	4560
DN-125-B	Nonwoven	200	Nonwoven	200	109	4280	3880
CL-AR-A	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	33	5030	4570
CL-AR-B	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	32	4810	4350
CL-50-A	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	45	5410	4950
CL-50-B	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	47	4650	4180
CL-75-A	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	75	4790	4330
CL-75-B	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	76	4600	4130
CL-100-A	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	91	4770	4300
CL-100-B	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	99	4420	3960
CL-125-A	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	121	4600	4140

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Initial Bentonite Moisture Content (%) ^b	Overall Mass per Unit Area (g/m ²) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
CL-125-B	Woven	105	Nonwoven w/ smooth GM	GT: 200 GM: 158	113	4700	4240
CLT-AR-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	29	5680	4770
CLT-AR-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	32	5420	4510
CLT-50-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	52	5490	4580
CLT-50-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	52	5370	4460
CLT-75-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	76	5360	4450
CLT-75-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	83	4920	4010
CLT-100-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	94	5260	4350
CLT-100-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	102	5220	4310
CLT-125-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	109	5080	4170
CLT-125-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	134	5040	4130

^a Provided by IFAI (2011) and/or Athanassopoulos (2011)

^b Calculated and/or measured in laboratory

3.4.2 Permeant Type Tests

The permeant type tests followed the same cyclic wetting and drying procedure as outlined in Section 3.3. In the permeant type tests, which were conducted only on ST and CLT, each specimen was hydrated to 50% moisture content for all cycles. Two iterations (duplicate specimens) were hydrated with deionized (DI) water and two iterations were hydrated with a solution of 0.1 M CaCl_2 . These tests were directly comparable to the cyclic wet-dry tests conducted using tap water at an initial moisture content of 50%.

These tests were used to determine the effects of cations in the water used to hydrate GCLs on GCL dimensional stability. GCLs hydrate in the field by drawing water from the subgrade. Some subgrades may have high concentrations of multivalent cations that may cause cation exchange over long spans of time. In addition, leachates with various cations may contact the GCL in a landfill liner through defects in the overlying membrane.

The solution with 0.1 M CaCl_2 is a higher concentration of CaCl_2 than likely to be encountered in the field. However, these tests were conducted to determine the effects of cation exchange and therefore a high concentration was necessary to ensure that cation exchange occurred within the 20 cycle testing period. Tests at or above this concentration have been conducted by Lee and Shackelford (2005) and Bouazza et al. (2006, 2007) in order to test the effects of cation exchange in an accelerated time frame. Specimens were wetted with their selected permeant liquid type throughout the duration of the tests.

Specimens in the permeant type tests were designated using three groups of letters and numbers as presented in Table 3.4. The groups represented the following three parameters, respectively:

1. GCL type (ST or CLT)
2. Permeant type [tap water (TW), deionized water (DI), or 0.1 M CaCl_2 (Ca)]
3. Iteration (A or B)

Table 3.4. Summary of Permeant Type Tests

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Permeant Liquid	Initial Bentonite Moisture Content (%) ^b	Overall Mass per Unit Area (g/m ²) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
ST-TW-A	Nonwoven	200	Woven	105	Tap Water	54	4410	4110
ST-TW-B	Nonwoven	200	Woven	105	Tap Water	50	4640	4330
ST-DI-A	Nonwoven	200	Woven	105	DI Water	52	4370	4070
ST-DI-B	Nonwoven	200	Woven	105	DI Water	49	4580	4280
ST-Ca-A	Nonwoven	200	Woven	105	0.1 M CaCl ₂	48	4590	4280
ST-Ca-B	Nonwoven	200	Woven	105	0.1 M CaCl ₂	51	4430	4130
CLT-TW-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	Tap Water	51	5490	4580
CLT-TW-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	Tap Water	52	5370	4460
CLT-DI-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	DI Water	48	5410	4500
CLT-DI-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	DI Water	52	5130	4220
CLT-Ca-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	0.1 M CaCl ₂	53	5000	4090
CLT-Ca-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	0.1 M CaCl ₂	50	5580	4670

^a Provided by IFAI (2011) and/or Athanassopoulos (2011)

^b Calculated and/or measured in laboratory

3.4.3 Overburden Tests

The influence of overburden pressure on the dimensional stability of GCLs was determined by placing loads over GCLs undergoing wet-dry cycling. The overburden tests followed the basic cyclic wet-dry testing outline discussed in Section 3.4, with the exception that the specimens were smaller than those used in all other tests and took much longer to dry due to the reduced specimen surface exposure to air. Specimens were 100 x 100 mm in size. The gauge markings were spaced 75 mm apart instead of the 100 mm used in all other tests. The smaller specimen size was selected to facilitate greater surcharge pressures with less weight, as the drying oven could only accommodate limited weight, and using greater weights also presented safety concerns.

Overburden tests were conducted on ST and CLT specimens. Each specimen was loaded with either 6 kg or 20 kg of flat steel weights during both wetting and drying cycles. The weights had to be removed temporarily between wetting and drying stages to facilitate displacement measurements and hydration by spraying. Specimens were estimated to be uncovered by weights for less than one hour each day due to handling, measurement, and spraying. To ensure that roughness in the weights did not disrupt shrinkage behavior, a piece of thin, smooth aluminum sheet was placed between the weights and the specimen. The loads were used to simulate an overburden loading of 0.3 to 1m of soil above the GCL generating an overburden pressure of 6 to 20 kPa. These pressures were selected because they modeled the pressure exerted by the drainage and insulation layer of a bottom liner prior to waste placement and the

erosion control and vegetative layer of a final cover for the 6 kPa and 20 kPa stresses, respectively. Two specimen iterations were used for each GCL type and overburden pressure.

Specimens in the overburden tests were designated using three groups of letters and numbers as presented in Table 3.5. The groups represented the following three parameters, respectively:

1. GCL type (ST or CLT)
2. Overburden pressure, in kPa [Unconfined (UC), 6, or 20]
3. Iteration (A or B)

Table 3.5. Summary of Overburden Tests

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Initial Bentonite Moisture Content (%) ^b	Confining Pressure (kPa)	Overall Mass per Unit Area (g/m ²) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
ST-UC-A	Nonwoven	200	Woven	105	54	0	3630	3330
ST-UC-B	Nonwoven	200	Woven	105	50	0	3630	3320
ST-6-A	Nonwoven	200	Woven	105	56	6	4160	3850
ST-6-B	Nonwoven	200	Woven	105	56	6	3420	3120
ST-20-A	Nonwoven	200	Woven	105	52	20	5100	4190
ST-20-B	Nonwoven	200	Woven	105	57	20	5230	4310
CLT-UC-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	51	0	5490	4580
CLT-UC-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	52	0	5370	4460
CLT-6-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	53	6	5100	4190
CLT-6-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	51	6	5230	4310
CLT-20-A	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	50	20	5070	4150
CLT-20-B	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	52	20	4970	4060

^a Provided by IFAI (2011) and/or Athanassopoulos (2011)

^b Calculated and/or measured in laboratory

3.5 Thermal Expansion Tests

The purpose of thermal expansion tests was to determine the effects of temperature alone on GCLs at constant moisture content. Tests were conducted at temperatures of 0, 10, 20, 40, 60, and 80°C. This was accomplished by keeping the specimens in plastic bags while placing them in the oven at different temperatures. Specimens were placed in bags, wetted with tap water to a moisture content of 50%, and allowed to hydrate for 12 hours at room temperature. The specimens were then removed from the bags for measurement of dimensions and weight. After measuring, they were placed back in bags and then the bagged specimens were placed in an oven or refrigerator.

Six specimens of each GCL type were used in the tests. One specimen was an indicator specimen with an embedded thermocouple wire. This specimen was used only to monitor the internal temperature of the specimens. Heating tests were conducted at 40, 60, and 80 °C. The oven temperature was set to 40°C and the indicator specimen and three additional specimens were placed in the oven. Once the indicator specimen reached 40°C, one of the three other specimens was removed and measured. The oven temperature was then increased to 60°C. Once the indicator specimen equilibrated at 60°C, another specimen was removed from the oven and measured. The oven temperature was then increased to 80°C, and the final specimen was removed from the oven and measured once the indicator specimen reached this temperature. In a similar manner, the indicator specimen and two other specimens were placed in

a refrigerator set to 10°C. Once the indicator specimen reached 10°C, one specimen was removed and measured. Then, the indicator and remaining specimen were placed in a colder refrigerator set to 0°C, and the remaining test specimen was measured upon the indicator specimen reaching 0°C. Measurements were made outside of the plastic bag to ensure accuracy, and were made as quickly as possible upon removal to prevent cooling and moisture loss or gain. Plastic bags performed marginally in preventing moisture loss during heating, as steam from specimens was visible inside the bag, and specimens lost some mass in balance readings conducted after heating was performed. In order to maintain temperature of the specimens for a longer period of time after removal from the oven and refrigerator for measurement, large pieces of steel were placed in the oven and refrigerator. These steel pieces maintained the temperature of the oven/refrigerator for several minutes after removal from the oven/refrigerator. The pieces of steel were taken out of the oven/refrigerator with the specimens and placed beneath them to help keep the specimens closer to the oven/refrigerator temperature while strain measurements were taken.

Specimens in the thermal expansion tests were designated using three groups of letters and numbers as presented in Table 3.6. The groups represented the following three parameters, respectively:

1. GCL type (ST or CLT)
2. Orientation of the woven component of the GCL [top (T) or bottom (B)]
3. Temperature, in °C, (0, 10, 40, 60, 80)

Table 3.6. Summary of Thermal Expansion Tests

Specimen Designation*	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Temperature (°C)	Initial Bentonite Moisture Content (%) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
ST-T-0	Woven	105	Nonwoven	200	0	39	4250
ST-B-0	Nonwoven	200	Woven	105	0	39	4250
ST-T-10	Woven	105	Nonwoven	200	10	42	4350
ST-B-10	Nonwoven	200	Woven	105	10	42	4350
ST-T-40	Woven	105	Nonwoven	200	40	48	4400
ST-B-40	Nonwoven	200	Woven	105	40	48	4400
ST-T-60	Woven	105	Nonwoven	200	60	43	4850
ST-B-60	Nonwoven	200	Woven	105	60	43	4850
ST-T-80	Woven	105	Nonwoven	200	80	45	4180
ST-B-80	Nonwoven	200	Woven	105	80	45	4180
CLT-T-0	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	0	45	4290
CLT-B-0	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	0	45	4290
CLT-T-10	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	10	48	3950
CLT-B-10	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	10	48	3950
CLT-T-40	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	40	52	4030
CLT-B-40	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	40	52	4030

Specimen Designation*	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Temperature (°C)	Initial Bentonite Moisture Content (%) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
CLT-T-60	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	60	47	4300
CLT-B-60	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	60	47	4300
CLT-T-80	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	80	49	4120
CLT-B-80	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	80	49	4120

^a Provided by IFAI (2011) and/or Athanassopoulos (2011)

^b Calculated and/or measured in laboratory

3.6 Subgrade Tests

The subgrade tests consisted of placing GCLs on a compacted soil subgrade in a sealed plastic container in a laboratory climate. The soil specimens were prepared in a 0.006 m³ plastic container with lid (approximately 0.25 x 0.25 x 0.1 m). The soil was compacted such that a target of 0.004 m³ of soil was in the container (approximately 0.02 m from top of container). The container configuration allowed sufficient clearance for the GCL specimen to sit upon the subgrade without making contact with the lid. The SP soil specimens were compacted with static tamping, while the CL soil specimens were compacted with impact compaction with a modified compaction hammer. The sand was tamped in thin lifts with a 100 mm diameter metal disk pressed firmly into the sand to achieve the desired density and moisture content. In order to achieve modified compaction effort in the clay soil, a total of 530 blows were imparted to the clay in four lifts. The soils were attempted to be compacted to the dry density and moisture content described in Section 3.2.2 (i.e., 17.3 kN/m³ dry density at 3 and 11% moisture contents for sand and 18.2 kN/m³ dry density at 6 and 16% moisture contents for clay). Due to flexibility of the containers and associated energy loss, the dry density of the compacted soil was less than targeted (i.e. 16.3 kN/m³ dry density at 2 and 8% moisture contents for sand; 14.6 kN/m³ dry density at 8% moisture content for clay dry of optimum moisture content; 17.03 kN/m³ dry density at 16% moisture content for clay wet of optimum moisture content).

GCL specimens with dimensions of 150 x 150 mm were used in the tests, as described in Section 3.3. The specimens were placed in plastic bags prior to placement on subgrades. Half of the specimens were hydrated to 50% moisture content by directly spraying with water and placed in plastic bags for approximately 36 hours. Subsequent to this 36 hour hydration period, all specimens were placed on their respective subgrades and sealed. An airtight seal was ensured by closing the container with the lid and wrapping around the lid-base interface with industrial strength plastic stretch wrap. Measurements were taken prior to prehydration, immediately prior to placement on the subgrade (subsequent to hydration), and periodically for 140 days after placement on the subgrade.

Specimens in the subgrade testing portion of the test program were designated using five groups of letters and numbers as presented in Table 3.7. The groups represented the following five parameters, respectively:

1. GCL type (ST or CLT)
2. Orientation of the woven component of the GCL [top (T) or bottom (B)]
3. Subgrade soil type (SP or CL)
4. Subgrade moisture condition [dry (D) or wet (W) of optimum moisture content]
5. Nominal specimen initial moisture content, in percent [as-received (AR), or 50]

Table 3.7. Summary of Subgrade Tests

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Subgrade Soil Type	Initial Subgrade Moisture Content (%) ^b	Initial Bentonite Moisture Content (%) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
ST-T-SP-D-AR	Woven	105	Nonwoven	200	SP	3	22	5370
ST-T-SP-D-50	Woven	105	Nonwoven	200	SP	3	46	4520
ST-B-SP-D-AR	Nonwoven	200	Woven	105	SP	3	22	4580
ST-B-SP-D-50	Nonwoven	200	Woven	105	SP	3	48	4590
ST-T-SP-W-AR	Woven	105	Nonwoven	200	SP	10	23	4620
ST-T-SP-W-50	Woven	105	Nonwoven	200	SP	10	57	3630
ST-B-SP-W-AR	Nonwoven	200	Woven	105	SP	10	23	4310
ST-B-SP-W-50	Nonwoven	200	Woven	105	SP	10	50	4440
ST-T-CL-D-AR	Woven	105	Nonwoven	200	CL	7	22	3100
ST-T-CL-D-50	Woven	105	Nonwoven	200	CL	7	57	3670
ST-B-CL-D-AR	Nonwoven	200	Woven	105	CL	7	23	4860
ST-B-CL-D-50	Nonwoven	200	Woven	105	CL	7	53	3960
ST-T-CL-W-AR	Woven	105	Nonwoven	200	CL	18	23	4850
ST-T-CL-W-50	Woven	105	Nonwoven	200	CL	20	53	4330
ST-B-CL-W-AR	Nonwoven	200	Woven	105	CL	17	26	3630
ST-B-CL-W-50	Nonwoven	200	Woven	105	CL	19	58	3780
CLT-T-SP-D-AR	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	SP	3	26	4560
CLT-T-SP-D-50	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	SP	2	44	4710
CLT-B-SP-D-AR	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	SP	2	25	4010
CLT-B-SP-D-50	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	SP	2	44	4200

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Subgrade Soil Type	Initial Subgrade Moisture Content (%) ^b	Initial Bentonite Moisture Content (%) ^b	Bentonite Mass per Unit Area (g/m ²) ^b
CLT-T-SP-W-AR	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	SP	10	29	4410
CLT-T-SP-W-50	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	SP	10	48	4100
CLT-B-SP-W-AR	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	SP	11	27	4670
CLT-B-SP-W-50	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	SP	10	43	4740
CLT-T-CL-D-AR	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	CL	7	28	4330
CLT-T-CL-D-50	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	CL	7	44	4540
CLT-B-CL-D-AR	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	CL	6	30	3870
CLT-B-CL-D-50	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	CL	7	46	3910
CLT-T-CL-W-AR	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	CL	19	30	4410
CLT-T-CL-W-50	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	CL	18	50	4010
CLT-B-CL-W-AR	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	CL	19	29	4650
CLT-B-CL-W-50	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	CL	19	49	4440

^a Provided by IFAI (2011) and/or Athanassopoulos (2011)

^b Calculated and/or measured in laboratory

3.7 Mechanical Necking Tests

Mechanical necking tests were conducted by hanging steel weights from GCL strips. In this case, the GCL specimens were 1500 mm by 150 mm in size between clamps, to represent the 10:1 aspect ratio of full length rolls installed in the field. Care was taken to orient the GCL specimen such that the machine direction was parallel to the long direction of the specimen and in line with the direction of loading. Only ST and CLT GCLs were investigated in this phase of the test program. Duplicate specimens of each type were tested, for a total of four specimens. Gauge markings were drawn 100 mm apart using the same template that was used for the specimens in other tests. The markings were centered 375 mm, 750 mm, and 1125 mm from the top clamp to measure strain at the midpoint and quarter points of the specimen.

Before hanging the GCLs, each specimen was hydrated to a bentonite gravimetric moisture content of 50%. As the specimens were too large to fit in plastic bags, they were hydrated by spraying tap water in the same manner as the other specimens, and then wrapping the specimens with thin plastic stretch wrap. Specimens were allowed to hydrate for 8 hours.

Specimens were hung from a large steel frame by clamps made of 2x4 pieces of lumber bolted together tightly to prevent slippage. The configuration of the top clamp is shown in Figure 3.3a. The bottom clamp was fabricated similarly and connected the GCL strip to the hanging weights. The configuration of the bottom clamp is shown in Figure 3.3b.

Figure 3.3. Clamps Used in Mechanical Necking Tests

After being clamped in place, loads were hung from the GCL incrementally until the GCL underwent ultimate failure. After each load increment, the GCL was measured in both the longitudinal and transverse directions for both the overall length and width. The dimensions between the gauge markings at 375, 750, and 1125 mm from the top clamp also were measured in the longitudinal and transverse directions. Loads were placed at stages with hanging masses of 10, 20, 40, 80, 120, 160, 200, 240, and 280 kg.

3.8 Field Simulation Testing

The final phase of testing was intended to represent the combined effects of natural temperature cycles, desiccation, and subgrade moisture in a more realistic simulation of field conditions. GCL specimens were placed on the SP

soil described in Section 3.2.2 at a 3:1 slope and covered with a black 1.5 mm textured geomembrane.

The first step in this phase of testing was to construct two plywood boxes to hold the sand subgrades. The inner dimensions of the box were approximately 2.5 m long by 270 mm wide by 150 mm deep. Sand in the boxes was filled and tamped to a depth of 100 mm with the target density and moisture contents specified in Section 3.2.2 (i.e., 17.3 kN/m^3 dry unit weight, 3% and 11% moisture contents). The wet sand was compacted at a lower moisture content than the target (i.e., 8% rather than 11%) because the temperature was very high on the day the boxes were filled, leading to unavoidable soil desiccation while filling. The boxes had an inclined base that allowed for a 3:1 slope, which is representative of typical landfill covers. To prevent the plywood from absorbing water the boxes were lined with a polyethylene sheet as shown in Figure 3.4.

GCL specimens similar to Section 3.6 were used. Similar to Section 3.6, half of the GCL specimens were prehydrated to 50% moisture content before placement on the subgrade. Specimens were weighed and measured before any prehydration took place and then immediately before placement on the SP soil subgrade. Subsequent to this step, the GCLs were covered by a black geomembrane simulating a landfill liner installation. The geomembrane was sealed along the outer sides of the box to create a watertight seal. The geomembrane was lifted each time the GCL specimens were measured and then replaced and resealed. A photograph of the test setup is presented in Figure 3.5.

Figure 3.4. Plastic Liner inside Plywood Box

Figure 3.5. GCL Specimens on Sand in Field Simulation Testing

The boxes were oriented facing south on a rooftop to ensure that they were exposed to sunlight for as long as possible throughout the day. The tests were conducted from mid-August to early October in San Luis Obispo, CA, which is traditionally the warmest period of the year for this region.

Specimens in the subgrade testing portion of the test program were designated using four groups of letters and numbers as presented in Table 3.8. The groups represented the following four parameters, respectively:

1. GCL type (ST or CLT)
2. Orientation of the woven component [top (T) or bottom (B)]
3. Subgrade moisture condition [dry (D) or wet (W) of optimum moisture content]
4. Specimen initial moisture content, in percent [as-received (AR), or 50]

Table 3.8. Summary of Field Simulation Tests

Specimen Designation	Top Geosynthetic Type	Top Geosynthetic Weight (g/m ²) ^a	Bottom Geosynthetic Type	Bottom Geosynthetic Weight (g/m ²) ^a	Initial Subgrade Moisture Content (%) ^b	Target Initial GCL Moisture Content (%)	Bentonite Mass per Unit Area (g/m ²)
ST-T-D-AR	Woven	105	Nonwoven	200	3	19	4670
ST-T-D-50	Woven	105	Nonwoven	200	3	50	4670
ST-B-D-AR	Nonwoven	200	Woven	105	3	19	4670
ST-B-D-50	Nonwoven	200	Woven	105	3	50	4670
ST-T-W-AR	Woven	105	Nonwoven	200	8	19	4670
ST-T-W-50	Woven	105	Nonwoven	200	8	50	4670
ST-B-W-AR	Nonwoven	200	Woven	105	8	19	4670
ST-B-W-50	Nonwoven	200	Woven	105	8	50	4670
CLT-T-D-AR	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	3	28	4000
CLT-T-D-50	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	3	50	4000
CLT-B-D-AR	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	3	28	4000
CLT-B-D-50	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	3	50	4000
CLT-T-W-AR	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	8	28	4000
CLT-T-W-50	Nonwoven w/ textured GM	GT: 200 GM: 605	Woven	105	8	50	4000
CLT-B-W-AR	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	8	28	4000
CLT-B-W-50	Woven	105	Nonwoven w/ textured GM	GT: 200 GM: 605	8	50	4000

^a Provided by IFAI (2011) and/or Athanassopoulos (2011); ^b Calculated and/or measured in laboratory

Chapter 4: Results and Discussion

4.1 Introduction

Results of the test program described in Chapter 3 are presented in this chapter. Effects of cyclic wetting and drying on dimensional stability under different initial moisture contents using tap water are described, followed by the results of cyclic wetting and drying using different permeant types (tap water, deionized water, and 0.1 M CaCl₂), and different levels of confining stress (unconfined, 6 kPa, and 20 kPa). Effects of temperature on dimensional stability are then provided, followed by effects of subgrade type and axial tension. Finally, the results of a field simulation test are presented.

4.2 Cyclic Wet-Dry Tests

Cyclic wetting and drying had significant effects on GCL dimensional stability. The following three subsections present the effects of GCL type, initial moisture content, permeant type, and overburden pressure on GCL dimensional stability.

4.2.1 Initial Moisture Content Tests

Strain in each specimen was calculated based on measurements made after wetting and after drying. Strain was defined according to Equation 4.1:

$$\varepsilon_{Ti} = \frac{(L_i - L_0)}{L_0} \quad (4.1)$$

where ε_{Ti} is the total accumulated strain in the i^{th} cycle, L_0 is the initial distance between gauge markings in the as-received condition for each specimen, and L_i is the measured length between gauge markings after the i^{th} cycle.

In each cycle, specimens swelled upon wetting and contracted upon drying, except during the initial hydration, when swell was minimal. However in the initial cycles, specimens contracted after drying more than they swelled after wetting, which led to a net shrinkage. This net shrinkage began to reach a stable level at which the shrinkage from drying and swelling from wetting were approximately equal. This stable shrinkage behavior was reached within 8 to 20 cycles, depending on GCL type and initial moisture content. Therefore, tests were ended after 20 cycles as stable response was determined to be reached between desiccation-related shrinkage and hydration-related swelling. The results of initial moisture content testing are presented in Figure 4.1. The data points in Figure 4.1 represent the average of the strains in the two duplicate specimens for each initial moisture content.

The tests indicated that initial moisture content has an effect on GCL shrinkage in the first 1 to 2 wet-dry cycles. During the initial drying cycles, specimens that were hydrated to higher initial gravimetric moisture contents (nominally 100 to 125%) displayed more severe shrinkage than specimens that were hydrated to lower initial moisture contents (30 to 50%). The effects of high initial moisture contents diminished as the number of cycles increased, as the lines representing each initial moisture content in Figure 4.1 began to cross after the first or second cycle.

Figure 4.1. Initial Moisture Content Tests

Specimens displayed anisotropic strain behavior, with generally greater shrinkage strain in the machine direction than in the cross-machine direction. The degree of anisotropy varied with GCL configuration. GCLs with a laminated membrane component (CL and CLT) displayed the highest degree of anisotropy, with total strains in the machine direction approximately 3 times the magnitude of the cross-machine direction strain on average. GCLs without a membrane component displayed small amounts of anisotropy, with total strains in the machine direction ranging from 1.0 to 1.1 times the cross-machine direction strain. The degree of anisotropy had a high variability throughout the test program. Histograms showing the distribution of the ratio of machine to cross-machine strains are presented in the Appendix.

In addition to the increases in the overall shrinkage strain of the GCLs with each cycle, the amplitude of the waves in Figure 4.1 also increased. The increase in wave amplitude suggests that the incremental strain increased in addition to the total strain as the GCL experienced more wet-dry cycles. The incremental strain is calculated as:

$$\varepsilon_i = \frac{(L_i - L_{i-1})}{L_{i-1}} \quad (4.2)$$

where ε_i is the strain in the increment between either wetting and drying or drying and wetting in a given cycle, L_i is the gauge length at measurement i , and L_{i-1} is the space gauge length in the measurement before measurement i . The incremental strains in each GCL type are provided in the Appendix.

A plot of the incremental machine direction strain of ST specimens at 50% initial moisture content is presented in Figure 4.2. Average strains for 2 duplicate specimens are presented in the figure.

Figure 4.2: Incremental Strain versus Cycle Number

The magnitude of shrinkage and swelling increased quickly in the initial cycles and stabilized as the number of cycles increased. In specimens with higher initial moisture content, the increase was more rapid in the initial cycles, whereas the incremental strain was similar between specimens of low and high initial moisture contents as the number of cycles increased.

Initial moisture content did not have significant effect on the maximum shrinkage of GCLs at the end of 20 cycles. However, the initial moisture content had a significant impact on shrinkage in the first cycle. The effect of initial

moisture content on the first cycle of shrinkage is presented in Figure 4.3. There was a positive correlation between the amount of shrinkage strain in the first cycle and the initial moisture content of the GCL.

Figure 4.3. Effect of Initial Moisture Content on First Cycle Shrinkage

The GCL types in this study are manufactured and sold in rolls 45.7 m in length by 4.4 to 4.6 m in width. For the products studied in this program, the manufacturer specifies a minimum panel overlap of 600 mm in the machine direction at the roll ends. Manufacturer specifications for 200R, DN, and ST stipulate an overlap at least 150 mm in the cross-machine direction, while manufacturer specifications for CL and CLT stipulate an overlap at least 300 mm in the cross-machine direction. The amount of strain required to cause loss of overlap in GCL panels according to manufacture specifications for a specific GCL type is termed the panel separation threshold (PST) for that GCL type. All GCL types had a PST of 1.3% in the machine direction. GCLs with no membrane component had a PST of 3.3% in the cross-machine direction, while GCLs with a membrane had a PST of 6.6% in the cross-machine direction.

Most concern for panel separation has focused on strain in the cross-machine direction as a majority of the reported laboratory values from previous investigations in Table 2.6 are for cross-machine strain. However, shrinkage in the machine direction could be of greater concern in large landfills that require seaming at the ends of rolls. Less strain is required to cause separation based on current recommendations, and the GCLs tended to contract more in the machine direction than the cross-machine direction. The number of cycles required for panel separation in the machine direction and cross-machine directions are presented in Table 4.1 and Table 4.2 , respectively. In instances when PST was not exceeded, the cell in the table was labeled N/A (Not Applicable) and the maximum strain that the specimen experienced was recorded.

In all GCL types tested, shrinkage in the machine direction was greater than PST after the first wet-dry cycle when initial moisture content was greater than 75%. In all combinations of GCL type and initial moisture content, shrinkage in the machine direction exceeded PST within 3 wet-dry cycles. GCLs generally recovered some, but not all strain upon wetting. Shrinkage in the machine direction was greater than PST, even after wetting, within 8 wet-dry cycles for all combinations of initial moisture content and GCL type.

In the cross-machine direction, the number of cycles required to reach PST varied by GCL type. GCL types with no membrane component required 1 to 5 wet-dry cycles to reach PST. For types without a membrane, PST was exceeded within 2 to 13 cycles after wetting. Even if the PST was doubled for

these types, panel separation would occur within 8 cycles after drying. GCL types with a membrane component had the smallest shrinkage strain in the machine direction and also the highest PST; therefore, shrinkage in GCLs with a membrane component never exceeded PST.

Table 4.1. Cycles Needed to Cause Loss of Overlap (MD)

GCL Type	Nominal Initial Moisture Content	Strain in First Cycle (%)	Cycles Required to Exceed 1.3% Strain (Drying)	Cycles Required to Exceed 1.3% Strain (Wetting)
200R	As-Received	-2.00	1	3
	50%	-2.78	1	2
	75%	-5.35	1	2
	100%	-9.36	1	2
	125%	-12.38	1	2
ST	As-Received	-0.27	2	4
	50%	-0.51	2	4
	75%	-2.62	1	3
	100%	-4.99	1	2
	125%	-6.63	1	2
DN	As-Received	-0.63	2	4
	50%	-2.52	1	3
	75%	-1.95	1	4
	100%	-5.41	1	2
	125%	-3.41	1	2
CL	As-Received	-0.32	2	8
	50%	-0.37	2	7
	75%	-1.83	1	7
	100%	-1.79	1	4
	125%	-2.02	1	3
CLT	As-Received	-0.48	3	7
	50%	-1.32	1	3
	75%	-2.11	1	3
	100%	-2.30	1	3
	125%	-2.10	1	5

Table 4.2. Cycles Needed to Cause Loss of Overlap (XMD)

GCL Type	Nominal Initial Moisture Content	Strain in First Cycle (%)	Cycles Required to Exceed 3.3% Strain (Drying)	Cycles Required to Exceed 3.3% Strain (Wetting)	Cycles Required to Exceed 6.6% Strain (Drying)	Cycles Required to Exceed 6.6% Strain (Wetting)
200R	As-Received	-0.63	2	5	4	13
	50%	-2.35	2	3	4	10
	75%	-4.55	1	4	2	10
	100%	-5.42	1	3	2	12
	125%	-9.11	1	2	1	9
ST	As-Received	-0.42	3	8	5	17
	50%	-0.85	5	8	8	19
	75%	-1.80	2	6	4	17
	100%	-3.60	1	3	3	14
	125%	-4.65	1	3	2	6
DN	As-Received	-1.53	2	13	7	N/A; Max. Strain: -4.67% wetting
	50%	-1.27	2	10	4	N/A; Max. Strain: -5.60% wetting
	75%	-2.14	3	9	7	N/A; Max. Strain: -4.90% wetting
	100%	-6.21	1	2	2	9
	125%	-3.10	3	9	7	N/A; Max. Strain: -4.67% wetting
CL	As-Received	-0.03		N/A; Maximum Strain: -2.17% drying, -0.25% wetting		
	50%	-0.21		N/A; Maximum Strain: -1.92% drying, -1.19% wetting		
	75%	-0.70	14	N/A; Maximum Strain: -3.94% drying, -1.46% wetting		
	100%	-0.90	7	N/A; Maximum Strain: -5.77% drying, -1.53% wetting		
	125%	0.22	20	N/A; Maximum Strain: -3.30% drying, -0.00% wetting		
CLT	As-Received	-0.04	14	N/A; Maximum Strain: -4.30% drying, -1.40% wetting		
	50%	-0.08	13	N/A; Maximum Strain: -4.62% drying, -1.06% wetting		
	75%	-0.92	13	N/A; Maximum Strain: -3.62% drying, -2.00% wetting		
	100%	0.12	15	N/A; Maximum Strain: -3.78% drying, -1.50% wetting		
	125%	0.03	14	N/A; Maximum Strain: -4.19% drying, -2.08% wetting		

The mechanism for GCL shrinkage strain accumulation under wet-dry cycling has not been fully described. Explanation has not been provided for the higher degrees of shrinkage of GCLs than swelling in the first several cycles. Changes in macrostructure and microstructure may both have an effect. In the GCLs tested, the bentonite was present in the GCL in small granules with large macrovoids between the granules. When the individual granules shrink and swell without contacting each other, they have little impact on the overall dimensions of the GCL as the voids between the granules get larger and smaller to accommodate the change in granule dimensions. Eventually, when the granules swell to the extent that they are in direct contact, the granules join together into a more uniform structure. As the uniform body of clay swells and contracts, it has a direct effect on the dimensions of the entire GCL panel.

In order for the macrovoids to disappear and render the GCL an effective barrier, the GCL must hydrate such that the bentonite granules swell and fill the voids. In the first cycle, the individual granules did not swell sufficiently to fully fill all the macrovoids. With each cycle, the individual granules swell progressively, which leads them to bond together because the needle punching in the GCL restricts swelling to a large degree in the out-of-plane direction. The number of cycles to reach this bonded state depended on the amount of water added to the GCL during initial water addition. Hydrating the GCLs with 100 to 125% gravimetric water content in the first cycle resulted in bonding the bentonite granules in fewer cycles than initially hydrating with 50 or 75% gravimetric water content. This explains why the GCLs with higher initial moisture content reached

equilibrium faster. Under this hypothesis, reaching stable cyclic response is a function of the number of cycles required to convert the granular bentonite macrostructure with many macrovoids to a uniform structure with a low number of macrovoids.

Another explanation for the shrinkage behavior of the GCL relates to the clay fabric at the microstructural level. If two specimens of a given clay are at the same initial moisture content but have different fabrics, the one that is more deflocculated and dispersed will shrink the most (Mitchell and Soga 2005). In deflocculated clay, the average pore sizes are smaller than in flocculated clay, which results in development of greater capillary stresses in the voids. These increased capillary stresses cause greater tension and hold the particles closer together. In deflocculated fabrics, the particles are also easier to move (Mitchell and Soga 2005).

Though no tests or imaging was done to monitor the clay microstructure, the shrinkage behavior of the GCLs allows for educated conjecture as to a possible mechanism for shrinkage. The specimens were hydrated to nominally the same moisture content in each cycle after the first cycle. Incremental shrinkage (and swelling) increased with each cycle, as shown in Figure 4.2. This suggests that the fabric of the clay in the GCL was flocculated in the as-delivered state and became more deflocculated and dispersed with each cycle. At the same initial moisture content (50% for all cycles after the first cycle), the deflocculated and dispersed specimen is expected to shrink to a greater extent than if the same specimen were flocculated (Mitchell and Soga 2005). The

transition from a flocculated structure to a dispersed structure can be explained with the particle orientation theory described in Section 2.3. Clays compacted wet of optimum moisture content tend to remold into a dispersed fabric. GCLs were not compacted in the traditional sense in any of these tests. However the bentonite was subjected to confining pressures provided by the needlepunch fibers when the bentonite was hydrated and not allowed to deform under swelling pressures. The confinement occurs when the GCL specimen is at high moisture content, thus contributing to a more dispersed structure with each wetting cycle. Therefore, the increasing shrinkage with each cycle can possibly be attributed to an increased level of dispersion with each wetting cycle. Under this assumption, once the soil fabric becomes fully dispersed, the strain with each cycle becomes constant.

Similar to the particle orientation theory and clod theory in Section 2.3, both of the proposed hypotheses for GCL shrinkage may be applicable. Both suggested explanations can be used to describe the results published in Thiel et al. (2006), Bostwick et al. (2010), Rowe et al. (2011), and the current investigation. The proposed hypotheses for non-recoverable GCL shrinkage strains can also explain the low shrinkage in the GCL hydrated with a low amount of water in the study presented by Thiel et al. (2006). The GCL hydrated with the low amount of water in Thiel et al. (2006) may never have received sufficient water for the bentonite to become dispersed and/or eliminate the granular macrostructure. Confirmation of the mechanism(s) causing GCL shrinkage due to wet-dry cycling would be beneficial in that it may allow for the bentonite to be

preconditioned during manufacturing to have a lower potential for shrinkage. For example, if the transition from a flocculated fabric to a dispersed fabric is demonstrated experimentally to be a mechanism for shrinkage, the bentonite can potentially be dispersed and dried to low moisture content prior to use in the manufacture of a GCL. If the GCL with preconditioned bentonite was kept at low moisture content prior to installation in the field, shrinkage could not occur upon deployment, because the bentonite would have already transitioned from flocculated to dispersed during preconditioning. More research is needed to confirm these suggested GCL shrinkage/swelling behavior mechanisms.

The effect of cyclic wetting and drying on total shrinkage was observed to be mainly a function of GCL type. GCLs with a membrane laminated to the nonwoven geotextile component exhibited significantly less shrinkage than GCLs without the membrane component. The average maximum shrinkage of each GCL type after 20 wet/dry cycles of permeation with tap water is presented in Table 4.3. The maximum shrinkage of a GCL specimen was defined by its greatest change in dimension divided by its original dimension. Since initial moisture content was determined to have minimal effect on overall GCL shrinkage, the maximum shrinkage for each specimen of a given GCL type was averaged to give the average maximum shrinkage for the specific GCL type.

Table 4.3. Average Maximum Shrinkage of Each GCL Type

GCL Type	Average Maximum Shrinkage (%)	
	Machine Direction (MD)	Cross-Machine Direction (XMD)
200R	17.5	16.5
ST	15.3	14.4
DN	12.1	11.6
CL	10.4	3.5
CLT	11.3	4.3

Mass per unit area of the specimens had a significant impact on the maximum shrinkage of the GCL, similar to the observations made by Bostwick et al. (2010). The relationship between the average overall mass per unit area of the specimens of each GCL type (including bentonite and geosynthetic components) and the average maximum shrinkage of each GCL type is presented in Figure 4.4. The average maximum shrinkage of each GCL type is plotted versus the average overall mass per unit area.

Figure 4.4. Overall Mass per Area versus Average Maximum Shrinkage

Specimens with higher mass per unit areas tended to exhibit lower shrinkage strains than those with lower masses per unit area. The reason for this trend could be twofold. Higher overall mass per area can either imply

greater bentonite mass per unit area or higher geosynthetic mass per unit area. A higher bentonite mass per unit area would mean that for approximately the same surface area of bentonite, there would be greater mass. This would imply that the specific surface of the clay mass is lower, which would tend to reduce the expected shrinkage. A higher geosynthetic mass per unit area would also reduce shrinkage because the greater weight geotextiles would be stiffer and have higher resistance to dimensional changes associated with wet-dry cycling of the GCL.

The overall mass per unit area and maximum shrinkage were related through a linear relationship in GCL types without an attached geomembrane. Types with an attached geomembrane did not follow such trends. In addition, meaningful trends were not observed when relationships were sought for all GCLs together. This suggests that the presence of a laminated geomembrane component alters the dimensional stability of the GCL.

An analysis was conducted to determine whether bentonite mass per unit area or geosynthetic mass per unit area had a greater effect on GCL dimensional stability. The relationship between the average bentonite mass per unit area of the specimens in each GCL type and average maximum shrinkage is presented in Figure 4.5.

Figure 4.5 Bentonite Mass per Area versus Average Maximum Shrinkage

Bentonite mass per unit area was inversely related to shrinkage for products with no attached geomembrane, even though one of the products (DN) had a different configuration than the other two products (200R and ST). GCLs with an attached geomembrane exhibited virtually identical shrinkage to each other, and did not follow the same linear trend as the products without an attached geomembrane.

The relationship between geosynthetic mass per unit area and average maximum shrinkage is presented in Figure 4.6. For GCLs with no membrane component, an inverse linear relationship between mass per unit area of the geosynthetic components in the GCL and shrinkage was observed, even among products with different configurations. This observation contrasted with findings in Thiel et al. (2006) and Bostwick et al. (2010), which implied that GCL configuration had greater effect on dimensional stability than mass per unit area, as the specimen with the nonwoven/nonwoven configuration in those studies displayed the most shrinkage, despite having heavier geotextiles than other specimens. Studies conducted by Thiel et al. (2006) and Bostwick et al. (2010),

however, used GCLs from different manufacturers within their test programs, so differences in dimensional changes may have been a result of different bentonite types rather than geotextile type.

Figure 4.6. Geosynthetic Mass per Area versus Average Maximum Shrinkage

Quantification of the relative effects of bentonite mass per unit area and geosynthetic mass per unit area on GCL dimensional stability is not entirely possible based on results of this study. Of the products tested, the GCL types with the lightweight geosynthetics also had a lower bentonite mass per unit area and the GCL types with the heavyweight geosynthetics had a higher bentonite mass per unit area. The trend in Figure 4.6 has the best fit to a straight line; however this does not confirm that geosynthetic mass per unit area has greater influence on dimensional stability than total mass per unit area or bentonite mass per unit area. More testing on GCL products with the same type, granularity, and mass per unit area is warranted to design more dimensionally stable products. If a clear relationship can be illustrated between either bentonite mass per unit area or geosynthetic mass per unit area and dimensional stability, it would allow

for optimizing the two variables (bentonite weight and geosynthetic weight) for improved dimensional stability.

The GCLs with an attached geomembrane exhibited similar strains even though the CLT GCL had a heavier geomembrane than the CL GCL. This was likely because the geomembrane component of the GCL types prevented shrinkage of the entire GCL. GCLs with membrane components exhibited unique behavior compared to those without membranes in that they did not begin to display significant shrinkage until the bentonite shrinkage and swelling mobilized a sufficient force to separate the geomembrane component from the rest of the GCL. Once the geomembrane component separated from the rest of the GCL, the remaining GCL began to shrink independently of the geomembrane. Photographs of a specimen where the geomembrane component separated from the remainder of the GCL are presented in Figure 4.7.

Figure 4.7. Shrinkage Behavior of GCL with a Geomembrane Component

Shrinkage of the GCLs with membrane components was less than those without membranes, even after the membrane and the rest of the GCL

separated. Shrinkage in GCLs with membranes was likely governed more by the residual strength of the adhesive bond between the membrane and the rest of the GCL than by the mass per area of the geotextiles in the GCL.

Separation between the geomembrane and the GCL could be problematic from a quality control and inspection standpoint if the GCL is oriented with the geomembrane component facing up. GCLs of type CL are not recommended by the manufacturer to be oriented with the membrane facing upward, while recommendations for orientation of CLT are site specific. Regardless of manufacturer recommendation, a scenario in which the membrane component of CL or CLT is oriented upwards is feasible. The membrane facing up can potentially mask any areas where the remaining portion of the GCL below has contracted.

A standard index test specifically for GCL dimensional stability would be beneficial for comparing dimensional stability between products, as dimensional stability is difficult to estimate based on current standardized tests for GCLs and geotextiles due to variation in bentonite type, adhesives used, thermal treatment procedures, scrim reinforcement, etc.

4.2.2 Permeant Type Tests

Permeant type testing was used to determine the effects on GCL dimensional stability of minerals in the water used to hydrate GCLs. GCLs hydrate in the field by drawing water from the subgrade. To test the effects of varying degrees of mineral concentration in water, tap water, deionized water, and 0.1 M CaCl_2 solution were used to permeate GCLs in cyclic wet-dry testing.

Results of this testing are presented in Figure 4.8 and Table 4.4. In both the machine and cross-machine direction for both GCL types, tap water caused the most shrinkage, followed closely by deionized water. The 0.1 M CaCl_2 solution caused the least amount of shrinkage.

Figure 4.8. Strains versus Cycle for Permeant Type Tests

Table 4.4. Permeant Test Maximum Strain Comparison

GCL Type	Tap Water	DI Water		0.1 M CaCl_2	
	Maximum Strain (%)	Maximum Strain (%)	Reduction in Strain Compared to Tap Water (%)	Maximum Strain (%)	Reduction in Strain Compared to Tap Water (%)
ST (MD)	-13.26	-10.19	24	-4.64	65
ST (XMD)	-11.38	-10.65	6	-2.65	77
CLT (MD)	-10.99	-8.95	19	-5.56	49
CLT (XMD)	-4.62	-1.59	66	-1.14	75

Cation exchange caused by the high concentration of calcium ions in the 0.1 M CaCl_2 solution disrupted swelling of the bentonite during hydration by collapsing the DDL. This resulted in low shrinkage in the subsequent shrinkage stage of the test. This lack of shrink-swell behavior is evidenced by the small amplitude of the deformation curves in Figure 4.8. The 0.1 M CaCl_2 was visually observed to prevent the individual granules of bentonite from swelling sufficiently to form one unified mass. This may be due to the granular bentonite never being allowed to undergo osmotic swelling. If dry bentonite is subjected to divalent cations, the montmorillonite will adsorb the cations and prevent osmotic swelling from ever occurring (Scalia and Benson 2011). The crystalline swelling upon rehydration of specimens with 0.1 M CaCl_2 solution had a significantly lower magnitude than the osmotic swelling occurring in the specimens hydrated to 50% gravimetric moisture content with tap water and DI water.

High cation concentration tends to lead to a flocculated clay structure in clays, as the DDL is much thinner, which restricts the particles from sliding relative to one another into an oriented arrangement (Yong and Warkentin 1975). Though no imaging was done to confirm whether the particles had a flocculated or dispersed microstructure, the bentonite in the GCL likely held a flocculated granular structure when hydrated with 0.1 M CaCl_2 . When each individual granule underwent swelling and shrinkage, this response produced little impact on the overall dimensions of the GCL specimen.

With tap water and deionized water, the bentonite clay particle orientation likely became dispersed with a thicker DDL compared to the 0.1 M CaCl_2 solution

and the individual granules of bentonite swelled together to form a unified clay mass. Once the bentonite granules bonded together, the body of clay deformed to change the overall dimensions of the GCL specimen. It is unknown how a specimen permeated with a lower concentration of CaCl_2 would have performed, as tap water, which likely has some dissolved salts in it, caused more shrinkage than permeating with deionized water. There may be a worst-case concentration of calcium between the amount in tap water and the amount in 0.1 M CaCl_2 that would cause sufficient swelling to form a dispersed, unified mass, which would lead to subsequent shrinkage, but also have a sufficient cation content to interfere with the recovery of shrinkage strains upon wetting.

Though permeation with 0.1 M CaCl_2 was favorable from a dimensional stability standpoint, eliminating the osmotic swelling in GCLs by cation exchange with divalent cations can increase the hydraulic conductivity by several orders of magnitude to 10^{-7} cm/s (Scalia and Benson 2011). This would give GCLs similar hydraulic conductivity of CCLs, but with a layer thickness 100-200 times thinner. GCLs with hydraulic conductivities this high would not be in compliance with RCRA. Therefore, using divalent cations to precondition GCLs to be more dimensionally stable once installed is not advised.

A worst case scenario would be to have GCLs be prehydrated with sufficient amounts of water to allow osmotic swelling, then drying upon placement beneath an exposed geomembrane, then rewetting with water high in divalent cations. The shrinkage following prehydration with water would be potentially significant in magnitude, as shown in Section 4.2.1, while the swelling

following rehydration with a solution rich in divalent cations would be minimal and provide less recovery of strain than rehydration with water could provide.

4.2.3 Overburden Tests

An overburden pressure applied to GCL specimens was found to significantly reduce the amount of shrinkage in specimens of all GCL types. Results of overburden testing are presented in Figure 4.9 and Table 4.5.

Figure 4.9. Strains versus Cycle for Overburden Tests

Table 4.5. Overburden Maximum Strain Comparison

GCL Type	Unconfined	6 kPa		20 kPa	
	Maximum Strain (%)	Maximum Strain (%)	Reduction in Strain Compared to Unconfined (%)	Maximum Strain (%)	Reduction in Strain Compared to Unconfined (%)
ST (MD)	-13.26	-5.12	61	-2.63	80
ST (XMD)	-11.38	-1.82	84	-1.76	85
CLT (MD)	-10.99	-0.95	91	-0.99	91
CLT (XMD)	-4.62	0.00	100	0.00	100

A 6 kPa surcharge generally restricted shrinkage as much as a 20 kPa surcharge, except in the case of ST in the machine direction. In CLT, no significant shrinkage was noted in either direction with an overburden of 6 kPa or 20 kPa. Specimens experienced a net expansion rather than shrinkage in the cross-machine direction. This expansion was likely due to the minimal contraction of specimens of this type in the cross-machine direction upon drying under no confinement in combination with the tendency of the GCL to expand due to Poisson's ratio effects from an out of plane stress.

For ST, shrinkage decreased with increasing overburden stress. However, the shrinkage was still sufficient to cause potential panel separation in the machine direction for field applications. Unconfined and confined specimens of ST had similar shrinkage behaviors in the first one to two cycles. In the second cycle, specimens with 20 kPa of confinement reached stable shrinkage behavior in both the machine and cross-machine direction. Specimens with 6 kPa of confinement continued to accumulate net shrinkage strain in the machine direction until the fourth wet-dry cycle and thus had greater shrinkage in the machine direction than specimens with 20 kPa of confinement.

Overburden confinement reduced shrinkage likely for several reasons. The first explanation for the reduction in shrinkage is that friction between the GCL and the pan was increased, which did not allow for the GCL to move relative to the pan. At the end of each stage in the wet-dry cycle, the ST specimens were observed to be adhered to the trays, even though they were detached from the trays in the previous stage. The overburden tended to hold the specimens tightly against the tray, which promoted adherence to the tray. This adhesive force would have to be overcome in order for the specimens to shrink or swell. A second explanation is that the downward load transferred through the GCL structure exerted an outward in-plane force on the bentonite. This force resisted the tendency of the GCL to shrink upon drying. A third potential explanation is that by covering the GCL upper surface with dead weight to support an overburden load, the surface area available for moisture loss was significantly reduced. Instead of taking 16 hours to dry, the GCL took approximately 88 hours to dry. A slower drying rate, even at the same temperature, may have reduced the amount of shrinkage compared to a faster drying rate. More testing on the effect of drying rate on GCL shrinkage is warranted.

Applying an overburden pressure was effective in improving GCL dimensional stability, even under intense thermal cycles. Likely in the field, any confinement would be applied by adding cover soil, which prevents the range of temperatures conducted in this test from occurring in addition to supplying a confinement pressure. Cover soil dramatically reduces heat development in the

barrier geosynthetics due to the black geomembrane no longer being directly exposed to sunlight. Temperature ranges within the top 1 m of cover soils and in the geosynthetics in final covers beneath 1 m of cover soil are generally similar to temperature ranges the air above a landfill, with some reduction in seasonal temperature amplitude. In areas with cold winters and mild summers, geosynthetic temperatures in final covers have been reported from a maximum of 22-25°C to a minimum of 2-4°C (Yesiller et al. 2008).

The reduced temperature cycling in addition to the reduction in shrinkage provided may be sufficient to prevent seam separation in all GCLs covered by at least 0.3 m of soil (approximately 6 kPa confining stress). Specimens of ST with 6 kPa of confinement still exhibited sufficient shrinkage in the laboratory to cause theoretical loss in panel overlaps in the machine direction due to the small overlap required in relation to the length of the roll. GCL overlaps at the end of rolls should be increased significantly, as a 1.3% strain was mobilized in testing at 60°C. Future tests at reduced temperatures under overburden loading should be conducted to evaluate whether panel separation under less extreme thermal cycling is possible.

4.3 Thermal Expansion Tests

Most materials, including polymers, tend to expand when heated and contract when cooled. Measuring this expansion in GCLs is difficult as heating a GCL without desiccating the bentonite and subsequently shrinking the GCL is challenging. Thermal testing was intended to keep the GCL hydrated during

heating to measure dimensional changes solely due to temperature increases. Results of these tests are presented in Figure 4.10.

Figure 4.10. Thermal Expansion of GCLs

It was expected that GCLs would stay fully hydrated while heated in sealed plastic bags, however steam developed in the bags upon heating to the higher temperatures, especially 80°C. This steam development indicated that moisture was leaving the GCL into the surrounding air within the bag and likely explains why at 80°C, ST had less thermal expansion than at 60°C. Also, measurements on the GCL had to be made quickly because the GCL began cooling as soon as it was removed from the oven, which made getting a reliable measurement difficult.

Even though completely representative measurements could not be obtained, some general conclusions can still be reached. The effect of thermal expansion within the range of temperatures likely to be encountered in the field has minimal effect on GCL dimensional stability, as the greatest thermal strain due to heating was less than 2%, and most thermal strains were less than 1%. All shrinkage strains related to cooling were less than 1%. CLT was more

susceptible to thermal expansion and contraction than ST because of the attached geomembrane component. Geomembrane thermal expansion has been well documented in literature and creates unique design considerations in landfills to prevent wrinkles in exposed geomembranes. The geomembrane component of CLT contributed to some additional thermal expansion beyond that experienced by ST. The effects of temperature alone on GCL dimensional stability can be considered negligible. In the field, temperature plays a role from the standpoint that it contributes to desiccation, but temperature that is not coupled to moisture change has little effect on GCL dimensional stability.

4.4 Subgrade Tests

GCLs placed in sealed plastic tubs on compacted subgrades in an indoor laboratory climate remained dimensionally stable in most combinations of GCL type, orientation, subgrade type, and subgrade moisture over the 20 week testing period. Though little dimensional change was observed in most specimens, nearly all specimens underwent significant moisture changes. The initial and final moisture contents are presented in Table 4.6.

Specimens placed on wet subgrades gained significant amounts of moisture. Specimens on wet sand tended to gain more moisture than specimens on wet clay. Specimens on dry sand gained moderate amounts of water; however, specimens on dry clay lost water. Most of these changes can be attributed to the unsaturated soil mechanics of the subgrade soils and the GCLs. Details of these mechanics and their significance to designing with GCLs are presented in Section 4.7.

Table 4.6. Change in GCL Moisture in Subgrade Tests

Specimen	Initial Bentonite Moisture Content (%)	Final Bentonite Moisture Content (%)	Change in Moisture Content (%)	Ratio of Final to Initial Moisture Content
ST-T-SP-D-AR	21.5	46.9	25.4	2.2
ST-T-SP-D-50	46.5	70.4	23.9	1.5
ST-B-SP-D-AR	21.8	57.5	35.7	2.6
ST-B-SP-D-50	47.7	78.4	30.7	1.6
ST-T-SP-W-AR	22.7	122.4	99.7	5.4
ST-T-SP-W-50	57.0	137.6	80.6	2.4
ST-B-SP-W-AR	23.4	153.0	129.6	6.5
ST-B-SP-W-50	49.8	164.0	114.2	3.3
ST-T-CL-D-AR	21.9	20.0	-1.9	0.9
ST-T-CL-D-50	56.5	24.5	-32.0	0.4
ST-B-CL-D-AR	22.9	21.0	-1.9	0.9
ST-B-CL-D-50	52.9	25.2	-27.6	0.5
ST-T-CL-W-AR	23.2	78.3	55.1	3.4
ST-T-CL-W-50	53.0	98.0	45.0	1.8
ST-B-CL-W-AR	25.6	122.3	96.7	4.8
ST-B-CL-W-50	58.0	125.4	67.5	2.2
CLT-T-SP-D-AR	26.1	56.3	30.2	2.2
CLT-T-SP-D-50	44.1	66.7	22.6	1.5
CLT-B-SP-D-AR	25.7	62.1	36.5	2.4
CLT-B-SP-D-50	43.6	74.0	30.4	1.7
CLT-T-SP-W-AR	28.5	68.3	39.8	2.4
CLT-T-SP-W-50	47.6	80.8	33.2	1.7
CLT-B-SP-W-AR	26.8	154.4	127.7	5.8
CLT-B-SP-W-50	42.6	164.5	121.9	3.9
CLT-T-CL-D-AR	28.5	20.1	-8.4	0.7
CLT-T-CL-D-50	43.6	22.7	-21.0	0.5
CLT-B-CL-D-AR	29.7	20.7	-9.1	0.7
CLT-B-CL-D-50	45.8	23.8	-22.0	0.5
CLT-T-CL-W-AR	29.6	64.2	34.7	2.2
CLT-T-CL-W-50	49.8	79.5	29.7	1.6
CLT-B-CL-W-AR	28.8	112.3	83.4	3.9
CLT-B-CL-W-50	49.1	118.5	69.5	2.4

In addition to subgrade conditions, moisture uptake was governed by GCL orientation. In ST, specimens oriented with the woven geotextile facing downwards tended to gain more moisture from the subgrade than specimens oriented with the woven geotextile facing upwards. This may be due to the thickness of the nonwoven geotextile in relation to the woven geotextile. With the woven geotextile being thinner, the bentonite in the GCL was located closer to the soil when oriented downwards and could thus create a more efficient suction. The nonwoven geotextile was thicker and may have had larger voids than the soils, which created a capillary break that reduced suction. Future testing which correlates the apparent opening size of bottom geotextiles to moisture uptake is warranted to confirm this estimate. In CLT, when the membrane component was oriented downwards, moisture uptake was limited to whatever water could enter the GCL from water vapor in the test container, so moisture uptake was low. When the woven geotextile was oriented downwards, moisture uptake was comparable to that in ST with the woven geotextile oriented downwards.

Typically, placement of ST on sand subgrades resulted in shrinkage or swelling of less than 2%. Results of testing ST on sand subgrades are presented in the Appendix. On clay subgrades, GCLs contracted significantly while exposed to certain conditions. Results of ST tests on clay subgrades are presented in Figure 4.11.

Figure 4.11: ST Strains on Clay Subgrade

Specimens oriented with the woven geotextile facing downward displayed the most shrinkage, while specimens with the woven geotextile facing upward displayed minimal shrinkage, no change, or significant swelling. The two specimens with the woven geotextile facing downward on dry clay contracted significantly in both the machine and cross-machine directions. Shrinkage for these specimens on dry clay was approximately 3 to 4% in the machine direction and 2 to 3% in the cross-machine direction. The two specimens oriented with the woven geotextile facing downward on wet clay contracted significantly, but to less of a degree than those on dry clay (approximately 2 to 3% in both directions).

The high shrinkage value for the ST-B-CL-D-50 specimen in the figure may have partially resulted from an anomaly, which occurred with markings on the GCL. The ink on the nonwoven fabric smeared after several measurements, and the gauge marking became oval shaped rather than round. This oval shape may have provided an artificially small machine direction measurement. Even with this anomaly, the specimen still contracted in the 3 to 4% range.

The specimens with woven up orientations tended to either exhibit little dimensional change or a small degree of swelling. Only one specimen (ST-T-CL-D-AR) displayed significant movement, which was in the form of swelling (approximately 2%).

Specimens of CLT exhibited minimal strain. Specimens of CLT tended to swell, and the swelling was generally only experienced in the machine direction. Only one test specimen of CLT displayed a significant shrinkage strain, which was approximately 2%. Results of GCL testing for CLT are presented in the Appendix.

Specimens of CLT likely displayed minor amounts of dimensional change for several reasons. The first reason is that the membrane component allows little to no interaction between the GCL and the subgrade when it is oriented downward. When the membrane component is oriented upward, the rest of GCL below may be dimensionally changing due to moisture exchange, however this change would not be expressed in measurements as only the side of the GCL facing upward is measured. The rest of the GCL beneath the geomembrane would have to exhibit significant movement with the adhesive bond at the

membrane-nonwoven interface intact for the geomembrane to be affected. Another reason for minimal amounts of dimensional change is that the relatively stiff geomembrane adhered to the rest of the GCL restrained the entire GCL from moving. This limited strain behavior was observed in the cyclic wet-dry testing until the adhesive bond between the geomembrane and the rest of the GCL was compromised.

Subgrade moisture in this experiment had little effect on GCL dimensional stability. Since the specimens were kept in a laboratory environment with approximately only a 5°C range of temperatures, there was little thermal cycling. However, in the field, subgrade moisture likely plays a role in that wet subgrades would hydrate the GCL as part of wet-dry cycling. Dry subgrades could potentially desiccate GCLs even without elevated temperatures if the GCL was at a high enough initial moisture content and the subgrade soil was sufficiently dry to have high enough suction to draw water out of the GCL.

Subgrade soil type had a marginal effect on dimensional stability. In the field, subgrade type would likely have a more pronounced role in GCL dimensional stability, as soil type greatly influences the soil water characteristic curve of the subgrade. Like subgrade moisture content, the unsaturated hydraulic behavior of the subgrade soil would have a bearing on the severity of wet-dry cycles on the GCL.

One possible cause for shrinkage in the GCL, and an explanation of why the GCLs with woven geotextile facing down exhibited more measurable shrinkage, relates to the geotextiles encapsulating the GCL. Nonwoven

geotextiles have a considerably lower modulus than woven geotextiles, meaning they can be more easily stretched (Koerner 2005). Nonwoven geotextiles also can be subjected to much greater tensile strains before failure than woven geotextiles, as the nonwoven geotextiles used in GCLs may elongate up to 50% before failure, and the woven geotextiles may only elongate 15% before failure (Athanassopoulos 2011). Due to these properties, nonwoven geotextiles may be stretched before they are connected to the woven geotextiles in order to maximize their coverage area. Over time, the nonwoven geotextile would tend to regain its original size, provided the geotextile displays elastic behavior. This return to original size would cause an observed shrinkage on the nonwoven side of the GCL, which is the side that was measured in tests on ST when the woven geotextile was oriented downward. Shrinkage of the nonwoven geotextile may cause some expansion of the woven geotextile on the other side of the GCL due to the flexural response of the entire product (analogous to the way flexure in a beam exerts compressive strains on one side of the beam and tensile strains on the other side of the beam). This flexural behavior may provide an explanation for why the GCLs with the woven side facing up were measured to have some swelling behavior.

Another explanation for why the GCLs with the woven side downward experienced greater dimensional change than those with the woven side upward is related to the relative void sizes of the two geotextile types. The thick profile of the nonwoven geotextile with relatively loose yarns in a random arrangement results in creating a thick layer of relatively large voids which separates the

bentonite from the subgrade. This layer could be thick enough to interrupt the capillary suction drawing water from the subgrade to the GCL and vice versa. The relatively thin, woven geotextile would likely not interrupt the capillary suction between the subgrade soils and the bentonite because it is thin enough that capillarity at the GCL-subgrade interface is maintained.

4.5 Mechanical Necking Tests

GCLs displayed mechanical necking under tensile loads, which is common for most materials. Specimens in the form of long GCL strips were hydrated to 50% nominal gravimetric initial moisture content. The specimens were then subjected to various increasing tensile stresses, with the longitudinal and lateral strain measured at each stress, until the GCL underwent ultimate failure. Transverse necking alone was not able to cause shrinkage greater than PST unless the GCL was subjected to tensile stresses near or equal to the ultimate failure stress of the material. The transverse (necking) strain of GCLs is presented in Figure 4.12. The data provided are taken as the average value between duplicate specimens.

The transverse strain in GCLs tended to be fairly uniform along the length of the specimen. CLT was able to withstand a greater tensile stress than ST because the attached geomembrane component in CLT provided greater reinforcement of the GCL. Both specimens of CLT failed under a tensile stress of 19.3 kN/m, while specimens of ST failed under a tensile load of 10.6 kN/m.

Figure 4.12. Transverse Strains in GCLs under Tensile Loads

For CLT specimens, a large discrepancy existed between strain on the geomembrane side of the specimen and the woven geotextile side of the specimen. The geomembrane component of the GCL underwent little dimensional change under less extreme loads. At loads in excess of the geomembrane yield stress of 7.35 kN/m (Poly-Flex 2001), the necking in the geomembrane became more significant. Final necking strain in the geomembrane component of the GCL ranged from 5.9% to 7.1%. Only one strain measurement (mid span of CLT, at 18.6 kN/m, geomembrane side of GCL) exceeded the PST in the cross-machine direction.

In contrast, on the woven side of the GCL, the GCL showed minor expansion in the upper half of the specimen rather than contraction, until stresses of at least 13.4 kN/m were applied. This behavior may have been due to wrinkles existing between the geomembrane and the rest of the GCL. When a tensile load was applied these wrinkles, if present, would pull tight causing the woven side of the GCL to expand. Final contraction of CLT on the woven side of the specimen ranged from 1.3% to 2.7%.

The stress-transverse strain behavior of ST was more linear in nature. The woven and nonwoven side of the GCL experienced approximately the same degree of shrinkage (within 1%) throughout each load stage in the test. The ultimate transverse shrinkage of ST ranged from 2.0% to 2.9%.

While nearly all of the aforementioned strains are less than the amount required to cause panel separation, it is important to note that tensile necking and wet-dry cycling can occur completely independent of each other and potentially have an additive effect. Care should be taken to consider both mechanisms when evaluating whether panel overlaps are adequate. Future research is warranted to test the interaction of thermal and moisture cycling with tensile loading of GCLs, as both temperature and moisture could affect the strength of the geotextiles and geomembranes themselves, which may lead to different necking characteristics. Testing of the effects of confinement on mechanical necking would be beneficial in the future as well.

Poisson's ratio at each stress stage was calculated to give a concise summary of the relation between longitudinal and transverse shrinkage.

Poisson's ratio is defined as the negative of the ratio of lateral strain to axial strain. The specimens tested generally had a Poisson's ratio between 0.2 and 0.5. In some instances, the GCLs displayed a negative Poisson's ratio, which is abnormal for most materials. The negative Poisson's ratio can be attributed to the expansion of the woven side of the CLT specimens expanding as wrinkles were pulled tight. Poisson's ratio tended to vary with load in specimens. The effect of loading on Poisson's ratio is presented in Figure 4.13.

Figure 4.13. Load versus Poisson's Ratio

Poisson's ratios at low axial stresses tended to be erratic and extreme. This is largely because the degree of elongation was so low that even a slight inconsistency in measurement had major implications in calculations of Poisson's

ratio. As stresses became more intense, the Poisson's ratio of the material began to trend to a constant value along the length of the specimen. This value was about 0.3 for ST, 0.5 for the geomembrane side of CLT, and about 0.2 for the woven side of CLT. Poisson's ratio increased as load increased for CLT and decrease as load increased for ST. The mechanism behind the changing Poisson's ratio of the GCLs is unclear, as GCLs are a complex composite of as many as 3 dissimilar materials all transferring a portion of the tensile load. These materials are connected in different manners as well, as the geomembrane (in the case of CLT) is somewhat weakly adhered to the nonwoven geotextile, which is securely connected to the woven geotextile by needlepunching. The transfer of load between geosynthetics is difficult to evaluate, especially due to the limited knowledge of the tensile properties of the individual geotextile.

The negative Poisson's ratio exhibited by specimens of CLT presents a unique area for future research. Currently, textiles with negative Poisson's ratios are being developed for a variety of uses (Ugbolue et al. 2007). These materials are called auxetics and would eliminate the concerns of panel shrinkage due to the necking mechanism entirely.

4.6 Field Simulation Tests

Specimens in the field simulation tests displayed similar behavior to specimens in the subgrade tests, despite being in an outdoor setting with relatively intense thermal cycling. Specimens of CLT exhibited limited changes in dimension, similar to the subgrade tests. Results of subgrade testing for CLT are presented in the Appendix. Specimens of ST exhibited greater dimensional

change and generally underwent shrinkage, especially in tests with the woven geotextile facing downward. Results of the field simulation testing on ST are presented in Figure 4.14.

Figure 4.14. ST Strain in Field Simulation Testing

Shrinkage in specimens during the field simulation tests generally ranged from 0% to 2.6%. Little difference was observed in the responses of specimens placed in the box with wet sand and those placed on the box with dry sand. In most instances, shrinkage in the machine and cross-machine direction was similar. The two factors seemingly having an influence upon shrinkage in ST were initial moisture content and GCL orientation. Specimens with 50% nominal initial moisture content experienced greater shrinkage than specimens of the same orientation with as-received initial moisture content. Specimens with the

woven geotextiles oriented downward experienced greater shrinkage than specimens of the same initial moisture content with the woven geotextiles oriented upward.

Temperatures were measured using thermocouples connected to a data logger. Measurements were taken above and below the geomembrane as well as beneath a GCL specimen. Temperature data in both the box containing wet sand and the box containing dry sand are presented in the Appendix. Temperatures in the boxes cycled diurnally and were similar between boxes with wet and dry sand. Temperatures above and below the geomembrane also were similar, as the geomembrane was thin enough for the entire panel to reach thermal equilibrium. The times that temperatures fluctuated depended on the day, but in a typical day, the temperatures were low (10 to 18°C in membrane, 12 to 20°C beneath GCL) in the morning until about sunrise. As the sun rose throughout the morning, the temperature in the boxes heated steadily. High temperatures (54 to 75°C in the membrane, 39 to 57°C beneath GCL) persisted for several hours in the mid to late afternoon and dropped steadily as the sun began to be obscured by hills northwest of the boxes. Low temperatures persisted for several hours at night until about sunrise, when the cycle repeated again. As the season changed from late summer to early autumn, diurnal cycles changed in length and intensity. The only substantial difference between the boxes with wet and dry sand was the temperature beneath the GCL. Beneath the GCL in the box with dry sand, the high temperatures ranged from 39 to 57°C, which gave an overall high of nearly 10°C more than the overall high temperature

beneath the GCL in the box with wet sand (34 to 48°C). The difference in temperature beneath GCLs in each box was likely due to the wet sand being insulated by the pore water and thus not being subject to as high of an extreme.

Throughout the day, moisture in the box changed dramatically. The mechanism proposed by Thiel and Richardson (2005), whereby water beneath the geomembrane is vaporized during the hot portion of the day, then condenses during the cooler portion and runs down the slope, was deemed to be valid. However, the conditions in the box were not perfectly representative of a field scenario, as the GCL specimens were placed approximately 150 mm apart. Therefore, the moisture evaporating in the high temperatures may have come from the subgrade because parts of the subgrade were in direct contact beneath the geomembrane, rather than from the GCL as Thiel and Richardson (2005) proposed. Each afternoon, especially in the early portion of the test program and in the box with wet sand, the underside of the geomembrane was damp from trapped vapor between the subgrade and membrane. In the following morning, the underside of the geomembrane was relatively dry, except a large quantity of water had pooled at the toe of the slope. Though the water may have come from the subgrade, unlike the GCL as Thiel and Richardson (2005) proposed, the mechanism is similar and could likely occur if the GCLs were hydrated to a sufficiently high moisture content.

Shrinkage behavior in the field simulation was much less intense than in the cyclic wet-dry laboratory tests, even though the GCLs were subjected to over 50 temperature cycles that were similar to the temperatures of cyclic wet-dry

laboratory tests. Shrinkage of specimens in the field simulation tests was similar in magnitude to shrinkage in the first 1-2 cycles of the specimens in the initial moisture content cyclic wet-dry tests. This result indicated two possible situations which are not mutually exclusive.

The temperature changes of the diurnal cycles in the field simulation test were similar to the cycling in the cyclic wet-dry tests; however the resulting moisture cycles were not the same magnitude. The GCL hydrated much more slowly when placed on a subgrade than when directly sprayed with water, and also did not have the opportunity to dry to 0% moisture because the thermal cycle was shorter in duration than in the cyclic wet-dry tests and did not have constant convection currents blowing hot air over the specimen. The effects of using a decreased hydration amount, as documented in Thiel et al. (2006), support this hypothesis. In those tests, increased shrinkage was observed for increased hydration moisture contents. Future research should focus on the amount of water entering and exiting a GCL specimen in a field environment on a daily basis. This would require study of the rate of moisture uptake of GCLs placed on subgrades. If this information was known, it may allow for adjusting the basic laboratory procedure for cyclic wet-dry test programs to better match field conditions and allow for laboratory test programs to accurately predict how much shrinkage will occur within a given period of time.

The second situation that may exist is that diurnal cycles have little bearing on the overall dimensional stability of GCLs and that seasonal cycles are more important. This hypothesis is supported by the fact that the GCLs exhibited

similar shrinkage after one hot season in the field simulation tests as specimens in the initial moisture content cyclic wet-dry tests experienced after one drying period. Under the assumption of seasonal moisture cycles, the GCL hydrates in the winter months when it is not subjected to heat-related drying and desiccates in summer months when it is subjected to high temperatures.

Continued testing of the field simulation specimens through the winter and spring months could confirm the seasonal effect on GCL moisture and its implications on dimensional stability. Field testing would need to be conducted over several years to compare the intensity of seasonal fluctuation with laboratory wet-dry cycles. A relationship between shrinkage strain after several seasonal cycles in the field and after the same number of cycles in the laboratory would be beneficial for making overlap guidelines based on laboratory testing. One limitation to the field simulation test is that it does not replicate changing groundwater conditions due to seasonal fluctuation. In a true field situation, ground moisture may change due to precipitation, however in the field simulation, no change is possible because the subgrade is covered by a geomembrane above and by a lined plywood box on the sides and below.

4.7 Engineering Significance

As the connection between subgrade type, subgrade moisture, GCL type, GCL moisture, and temperature cycling becomes better understood, it will become possible to forecast the degree to which shrinkage could occur and thus sequence landfill construction accordingly. Much of the connection of the above factors can potentially be determined based on the soil-water characteristic curve

(SWCC) of the subgrade and GCL. If the SWCC of both the subgrade soil and the GCL are known, it is possible to estimate the moisture content to which the GCL will equilibrate when placed on a subgrade.

An example of a SWCC curve with GCL and subgrade soil properties similar to the GCL and subgrade soils used in the testing program is presented in Figure 4.15. The curves for GCLs and sand soils were developed using the Fredlund and Xing (1994) model with parameters taken from Beddoe et al. (2011) for GCLs and Gallage and Uchimura (2010) for sands. The GCL SWCC was developed on a product that was similar to ST. No SWCCs have been reported for GCLs with a membrane component. These products would react much differently with subgrade depending upon which side of the GCL faced downward. The curves for clay soils were developed using the van Genuchten (1980) model with parameters taken from empirical relations in Tinjum et al. (1997).

Figure 4.15. Soil Water Characteristic Curves for Subgrades and GCLs

Soil-water characteristic curves follow a hysteretic pattern. When soils and GCLs hydrate, they move along the wetting curve from high suction to low suction (right to left in Figure 4.15). When soils and GCLs dry, they move along the drying curve from low suction to high suction (left to right in Figure 4.15). The wetting curves are illustrated by dashed lines in Figure 4.15, while the drying curves are represented as solid lines. The wetting curves for clay soils were not provided by Tinjum et al. (1997), and therefore were estimated according to guidelines recommended by Fredlund et al. (2011).

Estimating the soil suction precisely by using a SWCC is problematic due to the hysteretic nature of the curves. At a given soil suction, the soil may be on the wetting curve, drying curve, or somewhere between the two bounding curves along an intermediate curve called a scanning curve (Fredlund et al. 2011). For this reason, predictions for GCL moisture content based on subgrade moisture are wide ranges intended to serve as rough estimates.

As GCLs are thin in comparison to the underlying subgrade soil, a small amount of water transferred between the soil and the GCL likely has a negligible effect on the overall moisture content in the subgrade but a significant effect on the moisture content of the GCL. Under this assumption, the subgrade will move negligibly along the soil-water characteristic curve, while the GCL will move significantly. Thus, when a GCL is placed on a subgrade, moisture content of the GCL will follow the trend of either the wetting or drying curve towards the suction value associated with the subgrade, while the subgrade will exhibit negligible movement in response to giving up or taking in moisture of the GCL.

The SWCCs generally provided good predictions of the movement of water between subgrade soil and GCL, based on the data collected from the subgrade tests in Section 4.4. The prediction of the final moisture content of GCLs placed on dry sand subgrades did not agree with results of the subgrade tests, as the soil water characteristic curves indicate that a sand subgrade soil of about 2% moisture content should lead to a GCL water content of approximately 20%, indicating that the GCL will lose water to the subgrade if initially at 25 to 50% gravimetric moisture content. The opposite of this occurrence happened, with the GCL actually gaining moisture and hydrating to between 47 and 78% gravimetric moisture content. The prediction of the final moisture content of GCLs on wet sand was fairly accurate, as the SWCC predicted that GCL final moisture contents would range from 75 to 150% gravimetric moisture content. Specimens in subgrade tests ranged from 122 to 164% gravimetric moisture content. The predictions for both dry and wet clay also were accurate. On a dry clay subgrade, the SWCC predicted that GCLs will lose moisture to the subgrade when placed at 25% or higher for a final GCL moisture content of 0 to approximately 20%. In the subgrade tests, GCLs ranged from 20 to 25% final moisture content, and all GCLs desiccated under these conditions. On a wet clay subgrade, the SWCC predicted that the GCL final moisture content would reach approximately 60 to 150%. In subgrade tests, GCLs ranged from 78 to 125% gravimetric moisture content. Though the SWCCs drawn above are based on published values for similar soils, rather than tests on the specific soils and

GCLs used, they are generally good predictors of the final moisture content of a GCL and could prove useful in establishing guidelines for overlap distances.

Subgrade testing has indicated that once GCLs are covered, they are much less likely to contract beyond the PST. As most GCLs are covered within the first year or two, and evidence suggests that cycle durations are seasonal rather than diurnal, shrinkage during the initial 1-2 cycles is critical. If a wet sand or clay subgrade allows for the GCL to hydrate to high levels (i.e., greater than 100% gravimetric moisture content), before a dry season with high temperatures beneath an exposed geomembrane, there will be a high potential for panel separation.

If the subgrade beneath a GCL is sufficiently dry, especially in clay subgrades, the high suction in the subgrade will potentially cause desiccation in the GCL rather than hydration. This desiccation would potentially cause shrinkage, but provided the initial moisture content of the GCL is relatively low (less than 50% gravimetric moisture content), the shrinkage would be minimal in the first hydration cycle based on the results of the initial moisture content tests. If GCLs were prehydrated to improve hydraulic properties, they could be subject to high levels of shrinkage on dry subgrades, as the subgrade would have much greater suction than the GCL and cause severe desiccation.

If developed further, required overlap distances for a given GCL type could be estimated by a methodology combining initial moisture content testing with soil water characteristic curves. The methodology would consist of the following steps:

1. Establish soil water characteristic curves for the GCL and subgrade soil. For the methodology to be practical, soil water characteristic curves for subgrade soils would have to be highly generalized into a design chart format. The design engineer would use empirical relations between Atterberg limits, optimum moisture content, compaction water content, soil grain size, etc. to develop the curves for soils. The soil water characteristic curves for GCLs could be established and specified by the GCL manufacturer.
2. Conduct cyclic wet-dry testing using the expected moisture content from the soil water characteristic curves for as many cycles as the GCL is planned to remain beneath and exposed geomembrane. This requires determination of whether GCL wet-dry cycles are diurnal or seasonal and how intense they are.
3. Evaluate whether GCLs will be subject to tensile forces and conduct tensile necking tests accordingly.
4. Based on cyclic wet-dry testing and tensile necking results, determine the required overlap distance of panels by the expected amount of shrinkage plus an adequate safety factor. The safety factor would depend upon the variability of data from the cyclic wet-dry testing.

The above steps all require some forms of additional testing on a larger number of specimens and a larger variety of GCLs and subgrade tests to prove their validity. Most of the tests could be conducted by GCL manufacturers and be used to create design charts for a given GCL product. Such charts, once

created, could be used for as long as the specific GCL type is produced, with minor modifications from some follow-up testing. Required overlap distances in the panels would likely increase compared to current recommendations, unless time beneath exposed geomembranes was minimized or subgrade moistures were not conducive to large swings in moisture content. Because of the variability between and even within GCL rolls, safety factors would have to be relatively high to be conservative.

Another approach to ensuring separation does not occur would be to confirm the mechanism(s) that cause shrinkage and reduce or eliminate them. Heat bonding the geotextiles, as referenced in Section 2.8, is a possible solution to prevent overlaps if it is proven not to disrupt the long term strength of the geotextiles or the hydraulic performance of the GCL. Development of auxetic geotextiles (i.e. those with a negative Poisson's Ratio) that expand when subjected to tension would eliminate concerns with necking-related shrinkage. Developing a method to precondition bentonite such that it does not accumulate shrinkage strains with wetting and drying would be beneficial as it would reduce the complications associated with accounting for shrinkage in design and the extra work associated with heat bonding.

Chapter 5: Summary, Conclusions, and Recommendations

5.1 Summary and Conclusions

A systematic test program was conducted to evaluate the relative effects of cyclic wetting and drying, temperature, subgrade type and moisture, and mechanical necking on GCL dimensional stability in landfill applications. Cyclic wetting and drying was conducted with varying combinations of initial moisture content, permeant type, and overburden pressure. A field simulation test was conducted to test the coupled effects of subgrade moisture, temperature, and bentonite desiccation on GCL dimensional stability under cycle durations and intensities encountered in the field.

Testing was conducted on five different types of GCLs for the initial moisture content tests. Each of the five types of GCL fit one of three basic geosynthetic configurations: (1) nonwoven/woven, (2) nonwoven/nonwoven, and (3) woven/nonwoven with a geomembrane laminated to the surface of the nonwoven geotextile. The initial moisture content tests were a subset of cyclic wet-dry testing. Each GCL type had 10 specimens, which were divided into five pairs. Each pair was subjected to a different initial moisture content and cycled daily between dry conditions and 50% gravimetric moisture content by oven drying at 60°C and rehydrating with a spray bottle. Tests were conducted for 20 wet-dry cycles, which was determined to be a sufficient number of cycles for shrinkage equilibrium to be reached. Based on the data obtained initial moisture content testing, the following conclusions were drawn:

1. As the level of initial hydration increased, the shrinkage in the first cycle increased. The effect of initial moisture content on shrinkage became negligible as the number of wet-dry cycles increased.
2. Strain behavior stabilized in fewer cycles for specimens that were hydrated to higher initial moisture contents. The number of wet-dry cycles required to reach stable cyclic shrinkage response varied from 8 to 20 cycles.
3. GCLs with a laminated membrane component were highly anisotropic, with average maximum strains in the machine direction approximately 3 times the cross-machine direction strain. GCLs without a membrane component were slightly anisotropic, with average maximum strains in the machine direction ranging from 1.0 to 1.1 times the cross-machine direction strain.
4. Panel separation threshold (PST) in the machine direction (1.3% strain) was exceeded in the first wet-dry cycle for specimens hydrated to an initial gravimetric moisture content above 75%. In the cross-machine direction, PST was exceeded in specimens without a membrane component (3.3% strain) in the first wet-dry cycle hydrated to above 75 to 100% initial moisture content. GCL types with a laminated geomembrane did not exceed PST (6.6% strain).
5. The incremental shrinkage and swelling generally increased with cycle number until reaching stable behavior, suggesting that the bentonite fabric may have changed from flocculated orientation to dispersed

and/or the macrostructure became reformed to remove clods and cause greater movement of the entire clay mass.

6. In specimens without an attached geomembrane, mass per unit area (overall, geosynthetic only, and bentonite only) had a significant effect on the degree of shrinkage. GCL types with the lowest average mass per unit area experienced the most shrinkage (17.5% MD, 16.5% XMD), while types with the highest average mass per unit area experienced the least shrinkage (12.1% MD, 11.6% XMD).
7. In specimens with a geomembrane, shrinkage was significantly less, especially in the cross-machine direction. Shrinkage ranged from 10.4 to 11.3% in the machine direction and 3.5 to 4.3% in the cross-machine direction. Shrinkage in specimens with geomembranes was not affected by mass per unit area, but rather the strength of the adhesive bonding the nonwoven geotextile to the membrane.

Data from the initial moisture content tests were used to select two GCL types to be used in subsequent testing. Type ST was chosen because it was the most commonly specified of all the GCL types and underwent an intermediate amount of shrinkage for types without a geomembrane component. Type CLT was chosen because, of the two types with a geomembrane component, it experienced the most significant shrinkage.

Permeant type testing was conducted by subjecting GCLs to daily wet-dry cycling with deionized water, tap water, and 0.1 M CaCl_2 at 50% gravimetric moisture content by oven drying at 60°C and rehydrating with a spray bottle.

Tests were conducted for 20 wet-dry cycles, which was determined to be a sufficient number of cycles for shrinkage equilibrium to be reached. Based on the data obtained from permeant type testing, the following conclusions were drawn:

1. Specimens hydrated with deionized water and tap water responded similarly to wet-dry cycling, with tap water experiencing marginally more net shrinkage.
2. Specimens hydrated with 0.1 M CaCl_2 experienced significantly less shrinkage than specimens hydrated with water. Shrinkage in type ST was reduced by approximately 65% in the machine direction and by approximately 80% in the cross-machine direction versus hydration with tap water. Shrinkage in type CLT was reduced by approximately 50% in the machine direction and by approximately 75% in the cross-machine direction. The amount of incremental shrinkage and swelling also was much smaller.
3. Reduction in shrink-swell behavior with 0.1 M CaCl_2 may be due to lack of granule reshaping because of insufficient swelling upon wetting and/or a disruption in the transition from a flocculated clay fabric to a dispersed fabric, with the flocculated structure having less susceptibility to volume change.

Overburden tests were conducted by subjecting GCLs to wet-dry cycling with tap water at 50% gravimetric moisture content by oven drying at 60°C and rehydrating with a spray bottle under confinements of 0 kPa, 6 kPa, and 20 kPa.

Tests were conducted for 20 wet-dry cycles, which was determined to be a sufficient number of cycles for stable cyclic strain behavior to be reached. Based on the data obtained from permeant type testing, the following conclusions were drawn:

1. Overburden confinement significantly reduced the shrink-swell behavior of both GCL types.
2. GCLs with no membrane component are still susceptible to loss of panel overlap in the machine direction if subjected to long term cycling at high temperatures under confinements of 20 kPa or less.
3. There was not an appreciable difference between confinement with 6 kPa and 20 kPa, except in type ST in the machine direction. The ST specimens covered by 6 kPa of overburden underwent a significant shrinkage of nearly 5%, while covering with 20 kPa resulted in shrinkage of less than 2% in the machine direction.

Thermal expansion tests were conducted on specimens hydrated to 50% gravimetric moisture content by cooling and heating to 0, 10, 40, 60, and 80°C in plastic bags to facilitate temperature change without moisture loss. Based on the data obtained from permeant type testing, the following conclusions were drawn:

1. When moisture change is minimized, GCLs tended to expand slightly when heated and contract slightly when cooled. This expansion/contraction generally was very small (less than 1% in most cases, less than 2% in all cases).

2. Changes in temperature affected GCLs with attached geomembranes more, as the additional polymer material is more subject to thermal strains.
3. Change in temperature without moisture change had minor contribution to GCL dimensional change compared to other factors.

Subgrade tests were conducted by placing GCLs on compacted soil subgrades in a laboratory environment for 140 days in different combinations of orientation, subgrade type, subgrade moisture, GCL type and GCL initial moisture. Based on the data obtained from subgrade tests, the following conclusions were drawn:

1. GCLs underwent significant changes in moisture as a result of being placed upon compacted subgrades. All GCL specimens started at a gravimetric moisture content of 20 to 60%. GCLs gained moisture on sandy subgrades, with moisture contents ranging from as low as 47% on dry sand to as high as 165% on wet sand. On dry clay subgrades, GCLs lost moisture, with moisture contents ranging from 20 to 25%. On wet clay subgrades, GCLs gained moisture, with moisture contents ranging from 64 to 125%.
2. GCLs with attached geomembranes underwent minimal dimensional change.
3. GCLs without attached geomembranes placed on sand subgrades generally experienced shrinkage or swelling strains of less than or equal to 2%.

4. GCLs without attached geomembranes placed on dry clay subgrades tended to experience significant shrinkage when the woven geotextile was oriented downward. Maximum shrinkage was about 3 to 4% in the machine direction and about 2 to 3% in the cross-machine direction.
5. GCLs without attached geomembranes placed on wet clay subgrades contracted marginally, but to less of a degree than those on dry clay.
6. GCLs without geomembranes placed in the woven up orientation experienced little dimensional change or moderate swelling.

Tensile necking tests were conducted by hanging weights from 150 by 1500 mm specimens and measuring the cross-machine contraction with each load increment. Based on the data obtained from tensile necking tests, the following conclusions were drawn:

1. Tensile forces caused significant cross-machine shrinkage, however shrinkage strains were less than PST at stresses less than within 95% of ultimate failure.
2. Specimens with a geomembrane component displayed different shrinkage characteristics on different sides of the GCL. In CLT, strains were as high as 7.1% on the geomembrane side and only up to 2.7% on the woven geotextile side. In ST, shrinkage strains were comparable on both sides and ranged from 2.0 to 2.9% before failure.
3. Poisson's ratio changed with increasing load stages. In specimens with a geomembrane component, Poisson's ratio was negative at low

stresses at certain locations on the specimen. Poisson's ratio tended to asymptotically reach a value of about 0.3 for ST, 0.5 for the geomembrane side of CLT, and 0.2 for the woven side of CLT. The non-constant Poisson's ratio was attributed to changes in load path throughout the GCL as the different textiles and membranes deformed non-uniformly.

Field simulation tests were conducted by placing specimens with different combinations of GCL type, orientation, initial moisture content, and subgrade moisture content on compacted sand slopes. The specimens were placed beneath a south-facing exposed geomembrane in late summer through early fall. Based on the data obtained from field simulation tests, the following conclusions were drawn:

1. Specimens with geomembrane components exhibited minimal dimensional change. Specimens without geomembrane components experienced 0 to 2.6% shrinkage strain.
2. Specimens hydrated to 50% nominal initial moisture content experienced greater shrinkage than specimens of the same orientation and as-received initial moisture content.
3. Specimens with woven geotextiles oriented downward experienced greater shrinkage than specimens of the same initial moisture content with woven geotextiles oriented upward.
4. Temperatures in the membrane above the GCL varied from low temperatures of 10 to 18°C to high temperatures of 54 to 75°C on a

daily basis, however shrinkage strain in specimens after over 50 days in the field simulation was comparable to strains experienced in one wet-dry cycle in the laboratory, suggesting that moisture cycles in the field are seasonal rather than daily and/or that daily moisture cycles in the field are less intense than in the laboratory, even if more extreme temperature swings in the field are realized.

5.2 Recommendations

Based on results of the test program, several opportunities are available for future research. In addition, general recommendations related to mitigating issues related to GCL dimensional stability are provided.

As a result of initial moisture content tests, there was evidence to suggest that accumulated shrinkage strain in GCLs involved a transition from a flocculated clay microstructure in the bentonite to a dispersed clay structure. If proven valid, knowledge of the clay microstructure could allow for beneficial preconditioning of bentonite to reduce shrinkage accumulation. Future tests should be conducted to verify changes in microstructure and prove whether transition from flocculated to dispersed microstructure is a mechanism for shrinkage.

As a result of permeant type tests, it was concluded that permeation with 0.1 M CaCl_2 reduced the shrinkage and swelling potential when compared to water. In addition, it was concluded that permeation with tap water resulted in greater shrinkage and swelling potential than deionized water. These results suggest that there may be a worst-case concentration of ions between 0.1 M

CaCl₂ and pure water that results in the greatest possible shrinkage. More tests on permeant types with a lower concentration of cations should be conducted to determine whether there is a worst-case concentration of divalent cations that will result in the greatest shrinkage.

Future tests should be conducted with GCLs placed on subgrades to determine hydration rates of GCLs. This would allow for better prediction of wet-dry cycle durations and allow for more detailed guidelines related to how long GCLs may be left beneath exposed geomembranes. In addition, more tests should be conducted to confirm the validity of using GCL and subgrade SWCCs to predict the amount of water a GCL may uptake from surrounding soils.

As GCL properties have proven to be variable both within a roll and between rolls, tests should be conducted to determine the variability of GCL shrinkage among nominally the same products. Improved manufacturing procedures to reduce the variability in GCL properties would increase the reliability of GCLs and allow for more absolute guidelines as to the period for which GCLs may be left beneath exposed geomembranes.

In general, it was determined that overburden pressure greatly reduces GCL shrinkage, so GCLs should be overlain by at least 300 mm of cover soil in as timely a manner as possible to prevent shrinkage. Guidelines for the minimum overlap of GCL panels in the machine direction also should be revised and the minimum overlap should be increased. A shrinkage strain of greater than 1.3% in the machine direction was observed in early stages of many of the tests performed. Doubling the required overlap would prevent many cases in

which the GCL shrinkage exceeded PST or ensure that PST was exceeded much later. Incorporating a laminated geomembrane component into GCLs also reduced shrinkage appreciably. If GCLs must be left beneath an exposed geomembrane for extended periods of time, GCLs with a laminated membrane component should be considered.

Prehydration of GCLs is not recommended if the GCL is to be placed beneath an exposed geomembrane during the summer months. High initial moisture contents in GCLs led to shrinkage beyond the PST within one wet-dry cycle. If prehydration is absolutely necessary, overlaps should be increased significantly such that if drying occurs, adequate overlap will remain.

Finally, a methodology for more site-specific overlap criteria based on index testing should be adopted. Current overlap criteria are unconservative in certain cases and have led to inadequate composite liners in some field scenarios. The test procedures and analysis methods used in this thesis could serve as a basis for establishing more site-specific overlap criteria.

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Appendix

Figure A.1. Incremental Strains for 200R

Figure A.2. Incremental Strains for ST

Figure A.3. Incremental Strains for DN

Figure A.4. Incremental Strains for CL

Figure A.5. Incremental Strains for CLT

Figure A.6. Histograms of MD/XMD Ratios in Initial Moisture Content Tests

Figure A.7. Results of Subgrade Tests on ST

Figure A.8. Results of Subgrade Tests on CLT

Figure A.9. Results of Field Simulation Tests

Figure A.10. Temperatures in Field Simulation Tests (Dry Sand)

Figure A.11. Temperatures in Field Simulation Tests (Wet Sand)

Table A.1. Raw Measurements for 200R Initial Moisture Content Tests (MD)

Cycle # →	1		2		3		4		5		6		7		8		9		10		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
200R-AR-A	96.48	96.21	94.67	95.59	90.89	94.34	90.00	93.82	87.47	92.77	87.88	92.28	86.12	91.85	84.88	91.69	84.12	90.97	84.00	90.44	83.53
200R-AR-B	97.15	96.68	95.09	96.39	89.31	94.63	86.44	94.40	87.83	92.90	86.27	92.23	84.38	91.25	83.32	90.05	81.24	90.53	81.40	89.21	81.53
200R-50-A	95.22	95.21	92.99	95.13	89.80	93.47	88.92	92.59	87.89	92.61	87.00	92.28	85.58	92.60	84.71	91.44	83.47	91.64	82.28	90.06	82.46
200R-50-B	97.18	96.21	94.05	94.73	90.10	93.73	89.52	93.53	88.54	92.94	87.68	91.75	86.61	92.13	85.16	91.01	84.69	90.77	83.76	90.66	82.99
200R-75-A	96.27	96.28	90.63	94.46	86.19	91.86	85.04	92.10	85.87	92.08	83.46	91.12	83.65	90.69	83.16	90.44	82.54	90.87	82.76	89.89	82.28
200R-75-B	97.41	97.40	92.69	96.03	85.51	91.59	84.04	91.98	83.04	89.54	82.71	89.75	81.29	90.20	80.68	88.61	79.02	87.57	79.77	87.71	79.49
200R-100-A	96.40	97.71	87.91	92.75	83.98	89.61	84.96	90.79	82.93	89.13	82.90	90.16	82.85	89.54	82.56	89.71	82.92	89.63	82.58	88.90	81.39
200R-100-B	95.18	95.27	85.75	90.48	84.42	89.06	84.59	89.50	83.13	88.95	83.86	88.89	82.79	88.42	83.11	87.52	83.39	86.79	81.88	86.49	81.22
200R-125-A	95.76	95.96	84.23	90.26	84.28	89.23	83.69	89.18	83.33	90.05	83.85	89.35	82.49	89.97	82.92	89.33	82.60	88.71	82.35	88.72	82.28
200R-125-B	96.67	96.83	84.37	90.04	82.45	89.85	82.15	90.19	82.07	89.62	82.58	88.65	82.28	90.61	81.80	89.20	80.60	88.85	80.90	88.26	81.66

Cycle # →	11		12		13		14		15		16		17		18		19		20		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
200R-AR-A	90.03	82.43	89.97	83.23	90.62	82.41	89.75	81.35	89.23	83.08	89.27	82.79	89.25	82.76	89.35	82.31	88.30	82.68	88.29	82.56	90.03
200R-AR-B	88.66	80.13	90.25	82.82	89.28	79.76	87.40	78.91	87.50	80.50	87.77	80.91	87.97	80.19	86.14	80.71	87.01	80.82	86.15	81.68	88.66
200R-50-A	89.98	81.35	89.95	83.21	90.41	82.00	89.79	80.82	88.75	82.52	89.07	81.53	89.15	81.81	89.11	82.85	88.92	82.39	89.15	82.05	89.98
200R-50-B	89.24	82.25	90.51	84.65	90.17	82.96	89.54	82.25	89.59	82.81	89.61	82.53	89.21	82.37	89.02	82.96	89.18	83.02	89.22	83.10	89.24
200R-75-A	88.90	81.22	89.63	82.67	88.83	81.72	88.84	79.88	87.71	81.17	88.02	81.29	88.16	80.87	87.94	81.34	87.40	81.50	87.37	81.35	88.90
200R-75-B	86.71	76.36	86.58	76.50	86.37	78.20	85.88	75.39	84.45	77.41	84.82	76.57	84.45	76.89	84.45	76.28	83.70	76.91	83.23	76.10	86.71
200R-100-A	89.04	79.30	87.29	80.37	87.05	80.89	88.03	78.58	87.49	79.10	87.23	79.46	87.07	78.51	86.75	79.30	86.56	79.41	85.41	79.14	89.04
200R-100-B	86.75	78.85	86.86	80.55	85.80	79.48	86.10	77.92	84.45	78.21	84.71	78.87	85.69	78.65	85.55	78.80	84.78	77.87	83.86	79.00	86.75
200R-125-A	88.42	81.49	88.39	81.88	88.04	82.28	88.45	81.53	87.35	81.47	88.27	80.85	87.46	80.52	87.30	81.60	87.15	81.00	86.45	81.39	88.42
200R-125-B	88.48	78.98	88.98	80.27	87.82	80.70	88.01	79.78	86.50	79.08	87.39	79.27	87.00	79.39	86.88	79.92	87.21	79.96	86.89	79.95	88.48

Table A.2. Raw Measurements for 200R Initial Moisture Content Tests (MD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
200R-AR-A	96.48	96.21	94.67	95.59	90.89	94.34	90.00	93.82	87.47	92.77	87.88	92.28	86.12	91.85	84.88	91.69	84.12	90.97	84.00	90.44
200R-AR-B	97.15	96.68	95.09	96.39	89.31	94.63	86.44	94.40	87.83	92.90	86.27	92.23	84.38	91.25	83.32	90.05	81.24	90.53	81.40	89.21
200R-50-A	95.22	95.21	92.99	95.13	89.80	93.47	88.92	92.59	87.89	92.61	87.00	92.28	85.58	92.60	84.71	91.44	83.47	91.64	82.28	90.06
200R-50-B	97.18	96.21	94.05	94.73	90.10	93.73	89.52	93.53	88.54	92.94	87.68	91.75	86.61	92.13	85.16	91.01	84.69	90.77	83.76	90.66
200R-75-A	96.27	96.28	90.63	94.46	86.19	91.86	85.04	92.10	85.87	92.08	83.46	91.12	83.65	90.69	83.16	90.44	82.54	90.87	82.76	89.89
200R-75-B	97.41	97.40	92.69	96.03	85.51	91.59	84.04	91.98	83.04	89.54	82.71	89.75	81.29	90.20	80.68	88.61	79.02	87.57	79.77	87.71
200R-100-A	96.40	97.71	87.91	92.75	83.98	89.61	84.96	90.79	82.93	89.13	82.90	90.16	82.85	89.54	82.56	89.71	82.92	89.63	82.58	88.90
200R-100-B	95.18	95.27	85.75	90.48	84.42	89.06	84.59	89.50	83.13	88.95	83.86	88.89	82.79	88.42	83.11	87.52	83.39	86.79	81.88	86.49
200R-125-A	95.76	95.96	84.23	90.26	84.28	89.23	83.69	89.18	83.33	90.05	83.85	89.35	82.49	89.97	82.92	89.33	82.60	88.71	82.35	88.72
200R-125-B	96.67	96.83	84.37	90.04	82.45	89.85	82.15	90.19	82.07	89.62	82.58	88.65	82.28	90.61	81.80	89.20	80.60	88.85	80.90	88.26

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
200R-AR-A	90.03	82.43	89.97	83.23	90.62	82.41	89.75	81.35	89.23	83.08	89.27	82.79	89.25	82.76	89.35	82.31	88.30	82.68	88.29	82.56
200R-AR-B	88.66	80.13	90.25	82.82	89.28	79.76	87.40	78.91	87.50	80.50	87.77	80.91	87.97	80.19	86.14	80.71	87.01	80.82	86.15	81.68
200R-50-A	89.98	81.35	89.95	83.21	90.41	82.00	89.79	80.82	88.75	82.52	89.07	81.53	89.15	81.81	89.11	82.85	88.92	82.39	89.15	82.05
200R-50-B	89.24	82.25	90.51	84.65	90.17	82.96	89.54	82.25	89.59	82.81	89.61	82.53	89.21	82.37	89.02	82.96	89.18	83.02	89.22	83.10
200R-75-A	88.90	81.22	89.63	82.67	88.83	81.72	88.84	79.88	87.71	81.17	88.02	81.29	88.16	80.87	87.94	81.34	87.40	81.50	87.37	81.35
200R-75-B	86.71	76.36	86.58	76.50	86.37	78.20	85.88	75.39	84.45	77.41	84.82	76.57	84.45	76.89	84.45	76.28	83.70	76.91	83.23	76.10
200R-100-A	89.04	79.30	87.29	80.37	87.05	80.89	88.03	78.58	87.49	79.10	87.23	79.46	87.07	78.51	86.75	79.30	86.56	79.41	85.41	79.14
200R-100-B	86.75	78.85	86.86	80.55	85.80	79.48	86.10	77.92	84.45	78.21	84.71	78.87	85.69	78.65	85.55	78.80	84.78	77.87	83.86	79.00
200R-125-A	88.42	81.49	88.39	81.88	88.04	82.28	88.45	81.53	87.35	81.47	88.27	80.85	87.46	80.52	87.30	81.60	87.15	81.00	86.45	81.39
200R-125-B	88.48	78.98	88.98	80.27	87.82	80.70	88.01	79.78	86.50	79.08	87.39	79.27	87.00	79.39	86.88	79.92	87.21	79.96	86.89	79.95

Table A.3. Raw Measurements for ST Initial Moisture Content Tests (XMD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
ST-AR-A	94.69	94.05	94.42	94.42	91.84	93.83	90.07	93.28	88.75	91.25	88.60	91.30	88.27	91.26	87.21	90.39	86.19	90.76	86.51	90.05
ST-AR-B	95.87	95.98	94.93	95.73	91.47	93.01	90.29	92.03	86.90	92.03	86.55	91.41	85.94	90.60	84.82	89.96	83.50	89.60	83.65	89.35
ST-50-A	95.64	94.78	92.96	93.89	90.35	92.28	90.12	93.16	88.83	91.47	88.89	90.67	87.09	91.35	85.64	90.04	84.08	89.24	84.49	88.74
ST-50-B	96.29	95.48	94.46	95.45	89.23	92.93	90.57	92.43	89.56	92.22	88.68	91.86	87.77	91.96	87.27	90.36	85.35	90.19	86.26	90.26
ST-75-A	96.23	95.54	91.12	93.50	88.92	92.84	88.58	91.98	87.14	91.70	89.10	92.20	86.61	91.25	84.54	90.09	84.95	89.92	84.71	89.53
ST-75-B	95.56	96.10	91.94	94.46	89.22	93.23	87.54	92.34	86.47	91.39	85.95	91.37	86.57	91.15	84.83	90.19	82.96	89.34	83.11	89.46
ST-100-A	94.96	94.86	90.64	92.70	88.46	91.82	88.57	91.35	85.22	90.78	86.68	91.33	87.64	90.90	87.86	89.94	84.88	89.94	84.72	89.53
ST-100-B	95.89	96.48	89.85	93.65	89.15	92.66	87.24	92.95	87.01	90.71	87.25	91.66	85.94	92.31	86.53	91.09	84.53	90.48	84.89	90.40
ST-125-A	95.48	95.30	85.75	91.32	86.34	89.88	84.84	89.25	85.89	89.69	84.42	89.98	84.32	89.62	82.59	88.82	82.32	87.21	82.80	88.27
ST-125-B	95.64	95.02	87.96	90.56	86.73	90.74	85.44	90.04	84.46	90.31	85.00	90.23	83.92	90.60	83.72	89.98	83.41	89.40	82.86	89.85

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
ST-AR-A	94.69	89.54	83.94	89.38	84.94	89.32	83.95	88.17	82.18	87.71	82.02	87.84	82.13	87.46	81.10	86.78	82.40	86.39	82.50	86.52
ST-AR-B	95.87	88.33	81.11	89.10	83.31	88.04	79.35	86.50	80.44	87.16	80.70	87.16	81.67	86.70	80.77	86.51	80.07	86.12	80.89	85.39
ST-50-A	95.64	89.92	83.03	88.98	83.95	88.55	81.24	88.46	79.93	87.45	81.10	88.35	81.86	87.93	81.48	87.77	81.56	87.52	80.86	86.75
ST-50-B	96.29	88.58	83.39	89.34	85.17	89.13	83.23	88.58	82.41	88.85	83.06	88.79	83.19	88.50	81.51	87.73	81.73	87.92	82.54	86.86
ST-75-A	96.23	88.53	82.49	88.86	83.71	88.53	82.14	88.40	80.70	87.00	80.60	88.16	81.51	87.05	80.07	86.52	82.39	86.44	79.88	86.15
ST-75-B	95.56	88.84	80.92	88.83	80.84	87.23	80.93	87.40	78.35	86.82	78.37	86.56	78.11	87.09	77.95	85.28	78.72	85.52	77.61	83.98
ST-100-A	94.96	88.74	81.33	88.80	83.42	88.03	82.86	88.36	81.99	88.56	80.70	88.07	80.83	88.10	79.39	87.68	81.03	87.55	81.04	86.31
ST-100-B	95.89	90.22	81.70	89.25	83.18	89.48	83.44	89.33	81.24	88.52	82.44	88.01	81.73	88.59	81.23	87.87	81.69	87.94	80.74	86.70
ST-125-A	95.48	87.87	81.58	87.85	82.00	86.45	82.05	87.50	79.46	85.65	80.59	85.96	78.63	85.36	79.53	85.60	79.95	85.67	80.16	84.41
ST-125-B	95.64	88.87	81.53	88.98	82.73	88.60	81.90	89.33	82.11	87.41	80.81	88.25	81.07	87.98	80.65	87.78	81.05	87.84	81.01	87.17

Table A.4. Raw Measurements for ST Initial Moisture Content Tests (XMD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
ST-AR-A	95.48	94.99	94.68	95.23	92.81	93.96	90.44	93.78	89.25	93.06	87.23	91.87	86.73	91.29	84.78	88.81	84.96	89.46	84.62	89.40
ST-AR-B	94.44	95.12	94.44	94.39	93.09	94.70	91.76	93.84	91.19	94.05	89.66	93.34	88.88	92.76	87.96	92.62	87.25	91.92	87.08	91.47
ST-50-A	95.79	95.38	94.86	95.55	94.49	95.09	93.84	94.23	92.66	92.27	92.28	93.87	91.00	93.19	90.92	91.82	90.12	92.39	90.31	92.68
ST-50-B	94.73	94.85	94.04	94.39	93.18	93.95	92.47	93.20	92.24	93.19	89.97	92.72	89.74	91.88	87.17	91.40	87.33	90.95	87.65	90.93
ST-75-A	94.29	94.85	92.56	93.32	91.22	92.56	90.13	91.72	89.98	92.23	88.48	91.46	87.72	91.37	86.77	90.38	87.53	90.25	86.80	90.00
ST-75-B	93.26	93.48	91.61	92.67	89.76	91.05	86.20	89.31	84.69	90.05	83.83	88.53	82.26	88.56	81.80	86.35	82.48	87.89	81.26	87.34
ST-100-A	94.82	94.40	91.80	92.97	88.98	91.78	86.77	90.47	86.54	91.12	84.48	89.06	84.45	90.11	83.87	87.02	83.70	86.48	83.27	88.58
ST-100-B	94.46	94.24	90.67	92.90	88.28	90.68	86.43	91.09	84.43	89.08	84.67	88.88	84.17	88.77	83.12	87.40	83.26	88.02	83.88	88.17
ST-125-A	94.62	94.78	90.43	91.88	86.88	91.39	84.90	89.95	85.18	89.33	83.16	87.48	82.59	87.66	81.65	86.43	81.92	85.64	82.36	87.38
ST-125-B	94.52	94.52	89.92	91.67	87.95	89.92	86.40	89.91	85.80	89.36	84.21	88.22	84.11	87.98	84.57	87.38	83.43	87.63	84.44	83.66

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
ST-AR-A	95.48	89.70	84.36	89.12	83.89	89.20	83.00	89.88	83.01	89.11	82.61	89.39	82.46	87.93	83.29	88.27	81.64	88.91	82.17	88.54
ST-AR-B	94.44	91.43	85.83	91.08	84.96	91.25	84.97	90.47	84.84	90.58	83.13	89.90	83.50	88.34	82.84	89.07	81.72	88.58	83.30	88.11
ST-50-A	95.79	92.06	89.62	91.96	88.61	91.38	88.57	91.63	87.06	90.52	86.54	90.94	86.94	90.09	86.93	89.89	86.56	89.63	86.44	90.31
ST-50-B	94.73	91.29	86.19	90.80	86.34	91.06	85.81	90.56	84.49	89.98	83.43	89.43	83.28	88.07	83.75	88.64	82.59	88.31	82.42	88.33
ST-75-A	94.29	90.93	86.08	89.57	86.15	90.44	86.17	89.30	84.87	89.45	85.80	88.71	85.04	88.27	84.63	87.81	84.67	88.61	84.50	88.68
ST-75-B	93.26	87.91	81.40	86.33	81.58	88.67	81.52	87.29	80.84	87.20	80.74	86.58	80.34	85.10	80.51	85.75	79.79	85.55	80.42	85.44
ST-100-A	94.82	88.90	83.28	87.35	82.88	88.72	82.97	88.75	81.64	88.11	81.35	88.96	82.05	85.91	81.56	87.75	80.25	86.48	84.47	87.11
ST-100-B	94.46	88.95	82.61	87.58	82.07	88.39	80.70	87.62	80.14	86.16	81.23	86.96	80.68	84.09	80.68	85.29	80.08	86.20	79.82	86.27
ST-125-A	94.62	87.93	82.22	87.28	82.15	87.63	80.55	87.21	79.57	85.70	79.44	86.16	79.73	83.42	80.02	85.33	78.52	85.19	78.61	85.24
ST-125-B	94.52	87.73	82.86	87.21	83.37	87.66	81.95	87.67	81.94	86.65	80.85	87.61	81.91	83.91	79.38	85.21	80.50	86.10	80.31	86.22

Table A.5. Raw Measurements for DN Initial Moisture Content Tests (MD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
DN-AR-A	95.81	96.03	95.15	97.45	92.21	95.85	91.34	95.27	89.74	95.15	90.03	95.39	89.68	95.72	89.07	94.24	88.50	94.51	89.02	94.45
DN-AR-B	96.85	97.35	96.29	97.26	93.23	95.69	92.47	94.62	91.31	95.22	91.72	95.03	89.84	94.89	89.10	95.05	89.20	93.90	89.46	93.63
DN-50-A	95.61	95.45	93.22	95.30	91.78	94.00	91.13	93.95	90.09	93.90	89.15	93.52	89.30	94.82	88.57	92.81	88.46	92.88	87.65	92.17
DN-50-B	96.09	95.68	93.64	95.20	90.12	93.70	89.14	94.00	88.38	93.50	88.59	93.33	87.68	93.28	88.02	92.47	86.58	93.04	87.22	92.27
DN-75-A	96.47	97.45	94.87	96.85	92.66	94.46	91.12	94.37	90.36	93.68	88.91	93.37	89.48	94.04	88.23	92.97	87.79	92.55	87.23	91.84
DN-75-B	96.11	97.17	93.95	96.10	92.50	95.84	92.23	94.64	90.52	94.03	89.37	93.63	88.97	93.57	88.48	93.51	88.25	92.79	88.00	92.36
DN-100-A	95.95	96.97	91.07	94.02	88.53	91.97	87.73	92.14	85.84	91.67	85.80	92.43	86.13	92.18	86.29	92.67	84.79	90.81	84.87	91.56
DN-100-B	97.17	97.18	91.59	93.16	88.74	93.09	88.37	91.72	87.53	91.09	86.18	90.82	85.84	91.32	84.86	90.33	83.79	89.50	84.03	88.74
DN-125-A	97.06	97.68	93.61	95.49	92.50	93.66	91.71	94.11	91.32	94.20	89.98	93.68	89.71	94.11	89.13	93.53	87.97	92.53	87.00	92.65
DN-125-B	97.25	98.04	94.07	95.13	92.50	95.81	92.95	96.15	91.65	94.93	89.76	94.22	90.30	94.37	89.19	93.89	88.30	93.45	88.14	93.08

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
DN-AR-A	95.81	94.49	87.34	94.38	88.35	94.12	87.84	94.84	87.59	93.92	87.44	93.98	87.53	93.83	87.24	93.52	87.82	93.58	87.87	92.65
DN-AR-B	96.85	93.90	88.76		88.63	93.77	88.31	93.92	88.06	93.28	87.48	92.58	87.11	93.59	86.44	92.61	87.11	92.08	86.78	92.42
DN-50-A	95.61	92.88	86.69	93.10	87.03	92.29	87.45	92.79	86.39	92.50	87.15	92.70	86.88	92.93	87.06	92.90	86.85	92.48	86.51	92.19
DN-50-B	96.09	92.05	85.80	92.53	86.37	92.18	85.84	91.61	85.34	91.62	85.43	92.00	85.82	91.36	85.73	91.49	85.49	91.64	85.52	91.08
DN-75-A	96.47	92.28	86.62	92.57	86.56	92.89	86.30	91.84	86.20	92.11	86.19	91.20	85.62	91.39	85.52	90.69	84.81	89.63	83.69	88.94
DN-75-B	96.11	92.26	86.86	91.41	86.45	92.70	87.62	92.32	87.09	92.27	86.62	91.17	86.93	92.23	85.77	91.98	86.42	90.75	86.24	90.70
DN-100-A	95.95	91.92	84.02	91.90	85.09	91.75	85.00	92.10	85.32	91.48	84.65	91.49	84.54	91.26	84.37	91.77	84.75	92.00	84.80	84.60
DN-100-B	97.17	89.28	82.60	89.83	83.47	89.25	83.31	89.72	82.40	88.88	82.87	89.07	82.71	89.10	82.24	88.29	82.34	88.20	82.23	88.13
DN-125-A	97.06	93.17	87.44	92.72	86.81	91.85	87.65	92.29	86.79	92.71	86.62	92.76	85.92	92.05	86.04	91.83	85.32	91.64	85.65	91.48
DN-125-B	97.25	93.32	87.42	92.75	87.87	93.15	87.69	92.88	86.50	92.41	87.03	92.28	85.16	92.35	84.83	92.16	85.13	91.39	85.07	92.38

Table A.6. Raw Measurements for DN Initial Moisture Content Tests (XMD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
DN-AR-A	94.85	95.60	94.14	95.27	91.82	93.17	90.29	93.41	90.93	93.35	88.79	94.12	89.48	94.39	88.50	93.01	88.11	91.61	88.03	93.01
DN-AR-B	95.41	95.45	93.21	95.00	92.01	93.60	90.31	92.24	89.41	92.56	88.16	92.30	88.27	93.30	88.30	92.47	87.13	91.12	86.47	91.09
DN-50-A	94.76	94.62	93.26	93.47	90.83	93.04	89.39	92.34	88.50	91.40	86.95	91.93	88.51	92.35	87.01	92.42	86.88	92.50	87.20	91.26
DN-50-B	97.28	97.62	96.35	98.04	91.89	95.39	90.34	95.87	90.14	94.77	89.49	95.13	89.54	95.36	88.72	93.68	87.66	94.44	87.57	93.04
DN-75-A	95.80	95.27	94.11	94.85	92.27	93.85	90.66	94.00	90.51	93.20	89.51	93.06	89.73	93.39	88.54	92.47	88.72	92.02	87.56	92.20
DN-75-B	95.55	95.51	93.14	95.25	92.89	94.48	91.30	94.23	89.66	93.20	89.47	93.21	89.87	93.24	88.89	92.80	88.19	92.14	87.25	92.25
DN-100-A	95.24	95.49	90.38	93.18	89.45	92.10	87.19	90.98	86.85	90.37	86.84	90.88	85.62	90.91	85.00	89.81	84.76	89.28	84.49	90.11
DN-100-B	95.82	95.10	88.80	91.49	87.90	90.14	84.96	88.99	83.67	87.57	84.18	89.39	84.82	90.09	84.52	88.79	82.59	87.44	82.79	87.04
DN-125-A	95.33	96.20	92.77	94.96	91.96	93.33	90.29	93.99	89.77	93.19	89.38	93.14	90.00	93.44	89.39	93.43	89.02	92.16	89.52	92.63
DN-125-B	96.78	96.82	93.37	94.46	93.91	94.38	90.85	93.85	90.16	94.60	89.93	93.65	89.63	93.93	88.95	93.35	89.62	92.71	88.73	92.16

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
DN-AR-A	94.85	92.60	86.13	92.94	87.48	92.13	86.77	92.29	86.58	91.90	86.30	92.18	85.84	92.19	85.20	91.70	85.88	91.66	85.98	90.66
DN-AR-B	95.41	91.49	84.98	91.32	86.13	90.67	85.32	91.08	84.96	91.50	84.50	91.34	84.49	90.80	84.94	91.24	84.59	90.53	85.19	90.71
DN-50-A	94.76	90.67	84.84	90.95	85.58	90.62	86.40	91.40	85.69	90.69	85.03	91.77	85.26	90.85	85.14	91.13	85.38	90.70	86.44	90.20
DN-50-B	97.28	93.58	85.56	93.22	87.38	93.57	86.29	93.12	85.33	91.19	86.02	92.64	85.53	92.56	85.31	92.04	85.38	92.46	85.05	91.06
DN-75-A	95.80	92.25	87.12	92.54	86.76	91.87	87.64	93.06	87.40	92.43	87.60	92.34	87.16	91.92	86.68	92.76	87.17	92.20	87.32	91.50
DN-75-B	95.55	92.18	86.25	92.49	87.47	92.49	87.12	92.31	87.00	92.01	87.05	91.59	86.12	91.82	85.63	91.32	86.61	91.49	86.18	90.48
DN-100-A	95.24	89.69	83.34	90.13	84.21	89.21	84.62	90.08	84.46	88.16	84.12	89.96	84.79	89.54	83.93	89.79	84.21	89.82	84.69	83.93
DN-100-B	95.82	86.86	81.31	88.14	82.07	87.39	82.42	87.66	82.46	86.70	81.76	87.11	81.66	87.20	80.32	86.81	80.92	86.52	80.68	85.05
DN-125-A	95.33	92.32	87.61	92.69	88.05	91.37	87.58	92.45	87.18	92.14	86.73	92.07	87.19	92.03	85.88	91.64	86.39	92.03	86.85	90.80
DN-125-B	96.78	93.17	87.95	92.05	88.48	92.52	87.32	92.58	87.49	92.20	87.44	92.56	87.34	92.37	86.22	91.62	86.52	91.18	86.43	91.48

Table A.7. Raw Measurements for CL Initial Moisture Content Tests (MD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CL-AR-A	97.33	97.36	96.67	96.44	95.44	96.67	95.55	96.33	95.45	96.46	94.70	96.81	94.39	96.30	91.75	95.95	91.22	95.98	90.96	95.49
CL-AR-B	94.64	95.19	94.68	94.85	93.07	94.54	93.84	94.50	93.13	95.03	92.46	93.96	92.18	94.15	88.18	93.37	87.90	93.77	88.80	93.58
CL-50-A	96.85	97.52	96.57	96.74	95.51	95.98	95.51	95.66	94.89	96.11	94.70	96.14	94.78	95.74	91.76	95.24	92.41	95.64	92.21	95.68
CL-50-B	95.61	95.92	95.18	95.19	94.01	94.90	94.34	94.62	93.54	94.86	92.60	94.48	92.10	93.97	88.89	93.45	89.18	93.70	88.29	94.89
CL-75-A	97.88	97.63	96.14	97.09	94.14	96.62	94.63	96.72	94.33	97.03	93.23	97.27	93.18	96.84	89.52	95.98	90.16	96.76	90.27	96.04
CL-75-B	96.00	95.79	94.19	94.75	92.34	94.74	91.86	94.79	90.74	94.82	89.56	94.19	88.76	94.10	85.42	93.16	86.57	93.64	86.64	93.46
CL-100-A	95.19	95.09	92.94	94.13	91.86	94.10	91.49	94.02	89.81	93.81	87.68	93.79	87.31	92.84	84.06	92.19	85.27	92.67	85.37	92.99
CL-100-B	96.60	96.76	95.42	96.19	94.51	95.73	93.71	95.17	92.27	95.16	90.75	95.22	89.11	94.60	87.58	94.19	88.42	93.96	86.87	94.02
CL-125-A	94.19	94.28	92.87	93.19	91.52	92.86	91.05	93.13	89.69	92.88	87.86	92.94	87.46	92.20	85.46	92.08	85.66	92.34	85.52	91.84
CL-125-B	94.11	93.98	91.63	92.69	90.80	92.82	90.40	92.60	89.36	92.50	87.22	92.55	86.53	91.93	84.08	91.65	85.44	91.69	84.97	91.59

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CL-AR-A	97.33	94.70	89.60	94.85	89.12	94.34	89.29	95.77	87.32	95.02	88.11	94.85	89.56	94.93	88.78	95.19	87.94	95.09	89.29	95.77
CL-AR-B	94.64	93.21	86.34	93.14	87.65	92.73	87.20	93.24	87.27	93.44	86.42	93.50	86.82	93.33	87.15	93.21	86.54	94.31	87.49	94.06
CL-50-A	96.85	95.74	91.00	95.04	90.32	96.00	90.31	95.09	90.97	95.80	90.43	95.87	89.98	95.91	89.85	95.89	89.48	96.72	90.35	96.38
CL-50-B	95.61	92.59	87.13	93.03	86.68	93.41	87.16	93.22	86.46	93.17	85.91	93.67	85.71	93.03	85.45	92.78	86.65	93.35	85.77	93.10
CL-75-A	97.88	95.23	89.07	95.39	89.14	95.42	88.10	95.38	88.33	95.69	88.96	96.08	89.11	95.66	88.68	95.59	89.26	96.26	88.41	95.50
CL-75-B	96.00	93.87	86.78	93.25	86.36	93.84	85.97	93.87	86.30	93.40	86.54	94.25	86.51	93.61	86.34	93.55	86.14	93.86	85.94	93.79
CL-100-A	95.19	92.30	84.62	93.23	85.04	92.57	86.06	92.72	84.96	92.40	84.55	93.18	85.36	93.56	85.62	93.30	86.03	93.22	86.06	92.51
CL-100-B	96.60	94.53	86.25	94.04	86.28	94.21	86.10	94.34	86.09	93.79	85.22	94.16	85.97	93.57	85.64	93.89	86.26	93.38	85.40	93.29
CL-125-A	94.19	92.28	84.63	91.91	85.02	92.31	84.17	91.91	84.37	91.81	84.25	92.41	85.02	92.59	83.85	91.87	85.01	92.05	84.05	91.79
CL-125-B	94.11	91.38	84.24	90.98	85.02	91.76	84.23	91.14	84.75	91.47	84.22	91.31	83.99	91.17	84.52	91.17	84.05	91.07	84.21	91.47

Table A.8. Raw Measurements for CL Initial Moisture Content Tests (XMD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CL-AR-A	95.27	95.44	95.07	95.20	94.96	95.12	95.23	95.41	95.10	94.88	94.60	95.36	94.61	95.27	94.22	95.08	94.11	94.86	94.24	93.78
CL-AR-B	95.54	95.76	95.68	96.00	95.73	96.24	95.80	95.73	95.82	95.89	95.52	96.24	95.48	95.92	94.85	95.81	94.64	95.62	95.10	95.18
CL-50-A	97.16	97.41	96.90	96.80	96.39	96.99	97.07	97.15	96.66	96.88	96.46	97.02	96.91	97.45	96.31	97.36	96.08	96.55	96.76	95.98
CL-50-B	95.69	95.65	95.55	95.33	95.44	95.46	95.30	95.30	95.15	95.37	95.09	95.58	94.64	95.08	93.99	95.03	94.46	94.91	93.87	93.17
CL-75-A	93.14	93.20	92.58	92.55	92.20	92.71	92.45	92.04	92.25	92.30	92.03	92.22	91.68	92.04	91.14	92.30	91.23	92.31	91.68	91.06
CL-75-B	99.10	98.61	98.30	98.35	97.98	98.35	97.90	98.30	97.50	98.20	97.03	98.03	96.01	98.21	95.53	97.36	95.79	97.91	96.18	96.23
CL-100-A	96.72	95.99	95.78	95.78	95.67	96.08	95.45	95.62	95.46	95.86	95.24	96.20	95.02	95.96	93.95	95.65	93.94	95.24	94.35	93.82
CL-100-B	94.86	94.30	94.07	94.29	93.36	94.05	93.00	93.80	92.86	94.19	92.24	93.83	91.69	93.59	90.78	94.86	90.94	94.14	90.66	90.49
CL-125-A	95.95	96.72	96.30	95.67	96.42	96.30	96.22	96.19	95.47	96.31	95.51	96.59	94.84	96.32	93.57	96.15	94.33	96.55	94.30	93.43
CL-125-B	96.78	97.56	96.86	97.39	96.93	97.61	96.88	97.56	95.78	97.54	95.84	97.50	96.09	97.35	94.56	97.49	94.46	97.58	95.83	95.07

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CL-AR-A	95.27	95.32	94.01	94.80	93.34	94.58	94.30	95.17	93.56	94.74	93.36	95.26	93.79	94.83	92.56	94.80	93.30	94.84	93.04	93.07
CL-AR-B	95.54	95.55	93.84	95.54	94.98	95.75	94.62	95.60	94.77	95.80	94.16	95.84	94.31	95.72	94.12	95.93	93.80	95.96	94.72	94.70
CL-50-A	97.16	97.25	96.30	97.33	96.68	97.28	96.49	97.63	96.99	97.51	95.97	97.51	96.67	96.87	96.17	97.09	96.07	97.45	96.20	97.06
CL-50-B	95.69	95.20	93.59	94.96	92.96	95.01	93.13	94.96	93.14	94.88	93.64	94.80	93.52	95.14	93.51	94.27	93.27	95.02	93.28	93.21
CL-75-A	93.14	91.81	91.03	91.88	90.63	91.79	91.08	91.86	90.39	91.98	90.00	92.27	90.32	91.91	90.39	91.91	90.10	92.43	89.76	91.96
CL-75-B	99.10	98.26	96.48	98.63	96.00	98.46	95.91	97.56	95.37	97.92	95.68	98.32	95.35	98.14	95.51	97.95	94.95	98.15	94.88	95.87
CL-100-A	96.72	95.89	93.10	95.49	93.12	95.50	92.62	96.34	93.19	95.64	92.55	96.38	93.17	95.75	92.61	95.77	92.93	95.76	92.61	92.02
CL-100-B	94.86	93.19	89.98	93.19	89.87	93.16	89.40	93.44	88.94	93.27	88.18	93.55	88.63	93.30	88.47	93.33	88.27	93.49	88.06	88.52
CL-125-A	95.95	96.52	93.26	96.25	92.85	96.31	92.53	96.72	91.74	96.43	92.01	96.77	92.15	96.49	91.81	96.78	91.96	96.60	92.00	91.88
CL-125-B	96.78	97.44	94.77	97.75	95.30	98.33	95.60	98.30	95.05	98.34	94.77	98.72	94.56	98.68	94.77	98.31	94.61	98.21	94.47	94.50

Table A.9. Raw Measurements for CLT Initial Moisture Content Tests (MD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CLT-AR-A	95.45	95.55	94.88	95.32	93.51	94.81	91.99	95.07	89.80	94.29	88.64	94.21	88.42	93.78	85.84	93.19	86.85	93.39	87.40	92.83
CLT-AR-B	94.19	94.27	93.84	94.26	93.84	93.84	91.62	93.65	89.75	93.44	87.73	93.52	87.37	92.61	84.75	92.08	86.33	92.19	86.23	91.97
CLT-50-A	95.39	95.00	94.17	94.19	92.31	93.65	90.81	93.84	88.63	93.98	86.79	93.59	86.74	92.49	84.67	91.98	85.95	92.17	86.58	92.88
CLT-50-B	94.55	94.52	93.27	94.13	92.61	93.50	89.69	93.55	89.46	93.13	87.00	92.94	86.59	92.53	84.40	92.42	85.74	92.22	85.63	92.60
CLT-75-A	95.64	95.62	93.25	94.44	92.10	93.88	90.02	93.73	87.44	93.08	86.21	93.68	86.16	92.49	84.75	92.51	85.77	91.99	85.58	92.07
CLT-75-B	94.43	94.66	92.80	93.84	92.19	93.67	90.36	93.48	87.90	92.90	86.13	92.70	85.18	91.92	83.41	91.49	84.62	91.20	84.93	91.86
CLT-100-A	94.18	93.20	92.46	93.50	90.87	92.43	88.25	92.82	87.36	92.09	84.82	91.85	85.26	91.19	83.09	90.59	83.71	90.84	84.22	91.02
CLT-100-B	95.92	95.79	93.26	94.37	91.89	94.54	90.07	94.58	89.42	94.49	87.32	93.55	85.89	92.99	84.56	91.76	86.19	91.82	84.92	92.36
CLT-125-A	95.59	95.50	93.89	94.80	93.01	94.79	92.01	94.84	90.08	93.93	87.93	93.68	85.95	92.77	85.33	92.08	85.95	92.63	85.82	91.97
CLT-125-B	94.24	94.50	91.95	93.23	90.28	92.59	88.79	93.42	87.47	92.55	85.75	92.56	84.83	91.43	83.84	91.51	84.68	90.99	85.39	91.45

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CLT-AR-A	95.45	92.83	86.94	93.00	87.09	93.17	86.39	92.76	85.63	93.14	86.03	93.09	85.93	92.61	85.45	93.15	84.99	92.26	85.74	92.71
CLT-AR-B	94.19	91.91	86.81	91.79	86.38	91.33	86.48	91.60	86.38	92.84	85.96	92.65	85.65	92.56	86.41	92.17	86.53	92.11	86.22	92.20
CLT-50-A	95.39	92.17	85.89	91.75	87.69	92.34	87.08	91.63	86.23	91.96	86.30	92.29	85.19	91.98	85.25	91.48	85.54	91.62	86.05	91.43
CLT-50-B	94.55	93.13	86.52	93.77	86.90	92.82	85.50	93.48	86.59	93.49	86.51	93.38	87.04	93.23	86.33	93.34	86.85	93.76	86.82	93.35
CLT-75-A	95.64	92.70	85.58	93.72	85.87	92.85	85.37	92.92	84.45	92.73	84.51	92.75	85.60	92.20	84.69	92.31	85.40	92.54	84.88	92.02
CLT-75-B	94.43	90.95	84.07	91.53	84.20	91.34	84.28	91.03	84.27	91.51	83.51	90.74	83.47	90.77	83.16	90.15	84.76	90.71	83.60	90.62
CLT-100-A	94.18	90.98	83.81	91.24	84.63	91.02	84.40	91.22	83.99	90.79	84.10	91.05	83.91	91.17	84.78	91.63	85.46	90.91	83.27	90.91
CLT-100-B	95.92	92.62	86.34	92.71	85.67	92.93	84.62	92.91	84.94	92.31	85.72	92.88	84.50	92.44	84.87	92.01	85.78	92.30	85.47	92.48
CLT-125-A	95.59	92.21	85.56	91.89	85.41	91.88	84.40	92.02	84.44	92.14	84.79	92.79	84.31	91.87	85.02	92.02	85.59	92.00	84.96	92.03
CLT-125-B	94.24	91.08	84.59	90.90	85.42	91.59	84.94	91.82	84.99	92.86	86.79	93.69	87.03	93.31	86.44	93.10	87.38	93.75	86.56	93.35

Table A.10. Raw Measurements for CLT Initial Moisture Content Tests (XMD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CLT-AR-A	96.38	96.67	96.32	96.22	96.95	96.75	96.66	95.93	95.89	96.30	95.39	96.42	94.76	96.26	94.22	95.66	93.76	96.12	94.67	96.74
CLT-AR-B	97.82	98.00	97.81	98.02	97.86	97.54	97.34	97.21	96.47	97.23	95.63	97.22	95.09	97.08	94.14	96.85	94.73	97.08	95.73	96.61
CLT-50-A	94.45	94.38	94.66	95.05	94.76	95.12	94.28	95.14	93.70	94.80	93.23	94.80	92.39	93.75	91.66	93.82	91.04	93.61	91.91	93.97
CLT-50-B	95.98	95.37	95.61	95.33	95.84	95.35	95.19	95.18	94.51	95.67	94.63	95.71	93.92	95.25	92.33	95.55	93.57	95.83	94.00	96.03
CLT-75-A	95.78	95.70	94.51	95.25	94.44	95.02	94.37	94.81	93.08	94.53	93.11	94.79	92.53	94.60	92.96	95.02	93.29	94.86	94.50	93.96
CLT-75-B	97.47	97.43	96.96	97.64	97.23	97.20	96.67	96.50	95.92	96.98	95.03	97.07	95.08	96.43	94.12	95.89	94.76	96.59	94.29	96.16
CLT-100-A	97.23	97.09	97.36	97.23	97.87	97.40	96.84	96.99	96.47	96.62	95.45	96.73	94.83	96.51	94.12	95.39	94.39	96.33	94.49	96.11
CLT-100-B	95.32	94.92	95.42	95.40	95.25	95.47	94.74	95.05	93.94	95.30	93.97	94.86	92.88	94.62	92.85	94.27	92.31	95.09	92.91	94.79
CLT-125-A	95.24	95.33	95.68	95.51	95.03	96.06	94.53	95.91	94.45	94.82	95.17	94.59	94.02	94.02	93.06	93.58	92.98	93.81	92.19	93.81
CLT-125-B	95.72	95.57	95.34	95.87	95.61	95.33	94.92	95.57	94.76	95.25	94.39	95.18	94.20	95.28	92.58	94.80	93.92	94.75	93.43	94.25

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)
CLT-AR-A	96.38	95.55	94.39	96.38	94.73	96.34	94.62	96.02	93.99	96.76	93.96	96.69	93.66	96.43	93.64	95.99	93.81	96.30	93.57	96.10
CLT-AR-B	97.82	95.92	93.81	96.59	94.27	96.42	94.48	96.51	93.37	96.14	93.45	95.79	92.64	95.96	93.18	95.56	93.20	95.50	92.26	95.98
CLT-50-A	94.45	93.51	90.53	93.03	91.62	93.76	90.77	93.53	89.91	94.08	90.69	93.57	90.07	93.56	89.08	93.19	90.08	93.40	91.04	93.40
CLT-50-B	95.98	95.83	93.12	96.13	94.00	95.24	91.94	95.07	92.51	95.85	92.76	95.43	92.66	95.54	92.56	95.37	93.06	95.59	92.34	95.01
CLT-75-A	95.78	93.30	92.42	94.70	92.35	94.25	92.27	95.47	92.84	95.35	93.20	95.16	92.83	95.73	93.25	95.06	93.22	95.73	93.12	95.28
CLT-75-B	97.47	96.09	93.84	96.59	94.60	96.77	94.25	96.45	94.90	96.83	94.15	96.81	94.31	96.18	94.17	96.21	94.28	96.20	93.87	96.68
CLT-100-A	97.23	96.04	94.10	95.65	94.62	95.96	94.12	96.64	94.58	96.93	94.11	96.28	93.73	95.94	93.63	95.55	94.52	96.33	93.39	95.87
CLT-100-B	95.32	94.98	92.27	94.42	93.07	94.82	92.30	94.59	91.69	94.71	91.18	94.53	91.82	94.34	92.73	94.90	92.31	95.25	92.55	94.35
CLT-125-A	95.24	93.35	91.81	93.35	91.85	93.90	91.19	93.84	91.30	93.68	91.19	93.65	90.16	93.62	91.34	93.54	91.88	93.86	90.98	93.77
CLT-125-B	95.72	94.10	93.06	93.64	92.95	93.40	92.77	93.58	92.69	94.67	92.66	94.27	92.81	94.32	92.85	93.54	92.97	94.07	92.64	94.34

Table A.11. Raw Measurements for Permeant Type Tests (MD)

Cycle # →	1		2		3		4		5		6		7		8		9		10		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
ST-TW-A	96.75	97.19	96.71	97.06	95.32	97.41	92.88	94.99	92.21	95.27	90.60	94.51	88.74	93.66	87.71	91.48	87.80	92.05	88.51	92.14	87.00
ST-TW-B	96.25	96.59	95.31	96.14	93.44	95.95	91.85	94.09	91.33	95.04	88.65	94.06	87.70	93.13	86.00	91.31	86.54	91.64	87.21	91.66	85.97
ST-DI-A	94.75	95.05	94.30	95.13	91.89	93.91	91.31	93.90	89.89	93.66	89.45	93.23	87.93	91.85	87.44	92.63	87.33	92.18	86.85	92.60	87.41
ST-DI-B	96.21	96.18	94.76	97.17	91.87	95.94	90.58	95.39	89.64	95.01	88.72	94.43	87.70	94.26	87.61	93.57	87.73	93.96	87.60	94.12	87.49
ST-Ca-A	93.97	93.69	92.72	93.81	91.36	91.87	90.83	91.68	91.38	91.11	90.56	90.81	91.03	90.97	90.61	91.76	91.09	91.74	90.55	91.83	91.26
ST-Ca-B	94.61	94.17	93.31	93.29	92.31	92.13	91.83	92.46	92.06	92.35	92.25	91.55	91.58	91.77	92.30	92.11	91.54	91.72	91.75	92.68	92.09
CLT-TW-A	95.39	95.00	94.17	94.19	92.31	93.65	90.81	93.84	88.63	93.98	86.79	93.59	86.74	92.49	84.67	91.98	85.95	92.17	86.58	92.88	86.26
CLT-TW-B	94.55	94.52	93.27	94.13	92.61	93.50	89.69	93.55	89.46	93.13	87.00	92.94	86.59	92.53	84.40	92.42	85.74	92.22	85.63	92.60	87.04
CLT-DI-A	93.17	93.44	92.46	92.46	92.28	92.72	91.68	92.55	91.61	92.81	90.86	92.56	89.86	92.35	88.93	92.23	88.52	91.91	88.10	92.57	87.14
CLT-DI-B	91.03	90.83	89.80	89.20	88.39	88.88	88.05	88.80	86.71	89.50	87.58	90.42	84.67	88.20	84.32	88.40	84.45	88.28	84.70	88.78	83.29
CLT-Ca-A	94.25	92.84	91.61	91.53	89.37	91.51	89.58	90.70	89.03	90.48	91.61	90.34	88.93	91.35	88.41	90.39	88.07	90.69	89.04	90.65	89.26
CLT-Ca-B	93.12	92.25	90.85	91.52	89.85	90.49	90.31	90.68	89.75	90.56	89.80	90.90	89.66	90.74	89.87	91.39	89.48	90.53	89.90	91.18	90.20

Cycle # →	11		12		13		14		15		16		17		18		19		20		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
ST-TW-A	96.75	92.54	86.65	92.39	87.33	91.96	86.19	92.03	85.40	91.95	85.79	90.76	85.82	88.74	85.30	89.41	84.25	89.58	84.63	90.26	84.52
ST-TW-B	96.25	91.52	86.34	91.19	86.15	92.02	86.37	92.14	85.29	91.82	84.81	91.00	84.79	89.93	83.53	89.41	83.16	89.43	83.82	89.54	84.34
ST-DI-A	94.75	92.60	87.41	90.93	86.80	90.81	86.31	90.57	86.10	90.35	86.14	90.57	86.40	90.54	85.87	90.36	86.28	90.43	85.93	88.62	85.53
ST-DI-B	96.21	94.12	87.49	92.88	86.78	93.06	86.65	92.51	86.63	93.54	87.16	91.92	86.48	93.00	86.86	92.64	86.72	92.10	86.26	91.59	86.19
ST-Ca-A	93.97	91.83	91.26	91.53	91.14	90.76	90.49	91.05	90.54	91.16	90.59	90.82	89.99	90.36	90.56	91.46	90.31	92.24	89.42	90.11	89.52
ST-Ca-B	94.61	92.68	92.09	93.12	91.66	91.81	91.16	91.51	91.53	91.45	91.27	91.61	91.49	91.21	91.41	91.69	91.17	91.11	90.82	90.49	90.56
CLT-TW-A	95.39	92.17	85.89	91.75	87.69	92.34	87.08	91.63	86.23	91.96	86.30	92.29	85.19	91.98	85.25	91.48	85.54	91.62	86.05	91.43	86.06
CLT-TW-B	94.55	93.13	86.52	93.77	86.90	92.82	85.50	93.48	86.59	93.49	86.51	93.38	87.04	93.23	86.33	93.34	86.85	93.76	86.82	93.35	87.48
CLT-DI-A	93.17	92.57	87.14	91.81	87.30	91.50	86.70	91.50	87.06	91.88	86.57	91.20	86.79	91.85	86.40	92.07	86.22	91.44	85.82	91.52	86.27
CLT-DI-B	91.03	88.78	83.29	88.60	83.67	88.06	83.11	88.34	84.01	88.72	83.89	88.43	83.74	88.27	83.52	88.10	82.29	88.56	82.80	87.42	81.92
CLT-Ca-A	94.25	90.65	89.26	91.89	90.73	91.01	90.78	91.51	89.38	92.41	89.63	91.48	91.15	92.01	90.88	93.06	90.46	92.13	89.78	92.78	90.29
CLT-Ca-B	93.12	91.18	90.20	90.92	90.26	91.03	88.88	92.27	91.23	91.38	89.85	91.36	90.81	92.08	91.82	92.33	90.68	92.53	91.64	91.15	92.07

Table A.12. Raw Measurements for Permeant Type Tests (XMD)

Cycle # →	1		2		3		4		5		6		7		8		9		10		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
ST-TW-A	95.79	95.38	94.86	95.55	94.49	95.09	93.84	94.23	92.66	92.27	92.28	93.87	91.00	93.19	90.92	91.82	90.12	92.39	90.31	92.68	90.66
ST-TW-B	94.73	94.85	94.04	94.39	93.18	93.95	92.47	93.20	92.24	93.19	89.97	92.72	89.74	91.88	87.17	91.40	87.33	90.95	87.65	90.93	86.77
ST-DI-A	94.75	95.05	94.30	95.13	91.89	93.91	91.31	93.90	89.89	93.66	89.45	93.23	87.93	91.85	87.44	92.63	87.33	92.18	86.85	92.60	87.41
ST-DI-B	96.21	96.18	94.76	97.17	91.87	95.94	90.58	95.39	89.64	95.01	88.72	94.43	87.70	94.26	87.61	93.57	87.73	93.96	87.60	94.12	87.49
ST-Ca-A	93.97	93.69	92.72	93.81	91.36	91.87	90.83	91.68	91.38	91.11	90.56	90.81	91.03	90.97	90.61	91.76	91.09	91.74	90.55	91.83	91.26
ST-Ca-B	94.61	94.17	93.31	93.29	92.31	92.13	91.83	92.46	92.06	92.35	92.25	91.55	91.58	91.77	92.30	92.11	91.54	91.72	91.75	92.68	92.09
CLT-TW-A	94.45	94.38	94.66	95.05	94.76	95.12	94.28	95.14	93.70	94.80	93.23	94.80	92.39	93.75	91.66	93.82	91.04	93.61	91.91	93.97	91.70
CLT-TW-B	95.98	95.37	95.61	95.33	95.84	95.35	95.19	95.18	94.51	95.67	94.63	95.71	93.92	95.25	92.33	95.55	93.57	95.83	94.00	96.03	93.98
CLT-DI-A	93.17	93.44	92.46	92.46	92.28	92.72	91.68	92.55	91.61	92.81	90.86	92.56	89.86	92.35	88.93	92.23	88.52	91.91	88.10	92.57	87.14
CLT-DI-B	91.03	90.83	89.80	89.20	88.39	88.88	88.05	88.80	86.71	89.50	87.58	90.42	84.67	88.20	84.32	88.40	84.45	88.28	84.70	88.78	83.29
CLT-Ca-A	94.25	92.84	91.61	91.53	89.37	91.51	89.58	90.70	89.03	90.48	91.61	90.34	88.93	91.35	88.41	90.39	88.07	90.69	89.04	90.65	89.26
CLT-Ca-B	93.12	92.25	90.85	91.52	89.85	90.49	90.31	90.68	89.75	90.56	89.80	90.90	89.66	90.74	89.87	91.39	89.48	90.53	89.90	91.18	90.20

Cycle # →	11		12		13		14		15		16		17		18		19		20		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
ST-TW-A	95.79	92.06	89.62	91.96	88.61	91.38	88.57	91.63	87.06	90.52	86.54	90.94	86.94	90.09	86.93	89.89	86.56	89.63	86.44	90.31	87.09
ST-TW-B	94.73	91.29	86.19	90.80	86.34	91.06	85.81	90.56	84.49	89.98	83.43	89.43	83.28	88.07	83.75	88.64	82.59	88.31	82.42	88.33	82.55
ST-DI-A	94.75	90.93	86.80	90.81	86.31	90.57	86.10	90.35	86.14	90.57	86.40	90.54	85.87	90.36	86.28	90.43	85.93	88.62	85.53	89.75	85.30
ST-DI-B	96.21	92.88	86.78	93.06	86.65	92.51	86.63	93.54	87.16	91.92	86.48	93.00	86.86	92.64	86.72	92.10	86.26	91.59	86.19	92.02	86.45
ST-Ca-A	93.97	91.53	91.14	90.76	90.49	91.05	90.54	91.16	90.59	90.82	89.99	90.36	90.56	91.46	90.31	92.24	89.42	90.11	89.52	91.14	89.47
ST-Ca-B	94.61	93.12	91.66	91.81	91.16	91.51	91.53	91.45	91.27	91.61	91.49	91.21	91.41	91.69	91.17	91.11	90.82	90.49	90.56	91.18	90.41
CLT-TW-A	94.45	93.51	90.53	93.03	91.62	93.76	90.77	93.53	89.91	94.08	90.69	93.57	90.07	93.56	89.08	93.19	90.08	93.40	91.04	93.40	91.12
CLT-TW-B	95.98	95.83	93.12	96.13	94.00	95.24	91.94	95.07	92.51	95.85	92.76	95.43	92.66	95.54	92.56	95.37	93.06	95.59	92.34	95.01	93.18
CLT-DI-A	93.17	91.81	87.30	91.50	86.70	91.50	87.06	91.88	86.57	91.20	86.79	91.85	86.40	92.07	86.22	91.44	85.82	91.52	86.27	91.65	86.32
CLT-DI-B	91.03	88.60	83.67	88.06	83.11	88.34	84.01	88.72	83.89	88.43	83.74	88.27	83.52	88.10	82.29	88.56	82.80	87.42	81.92	93.67	83.42
CLT-Ca-A	94.25	91.89	90.73	91.01	90.78	91.51	89.38	92.41	89.63	91.48	91.15	92.01	90.88	93.06	90.46	92.13	89.78	92.78	90.29	92.84	92.11
CLT-Ca-B	93.12	90.92	90.26	91.03	88.88	92.27	91.23	91.38	89.85	91.36	90.81	92.08	91.82	92.33	90.68	92.53	91.64	91.15	92.07	93.43	91.74

Table A.13. Raw Measurements for Overburden Tests (MD)

Cycle # →	1		2		3		4		5		6		7		8		9		10	
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)
ST-UC-A	96.75	97.19	96.71	97.06	95.32	97.41	92.88	94.99	92.21	95.27	90.60	94.51	88.74	93.66	87.71	91.48	87.80	92.05	88.51	92.14
ST-UC-B	96.25	96.59	95.31	96.14	93.44	95.95	91.85	94.09	91.33	95.04	88.65	94.06	87.70	93.13	86.00	91.31	86.54	91.64	87.21	91.66
ST-6-A	71.06	72.35	70.33	71.45	70.17	70.85	69.71	71.04	69.36	70.58	69.00	70.39	69.46	70.64	69.26	70.16	69.14	70.52	68.91	70.01
ST-6-B	70.93	72.66	70.35	70.23	69.16	70.38	68.58	69.50	67.36	69.60	68.92	69.95	67.67	68.97	67.20	68.35	68.26	69.34	67.88	69.18
ST-20-A	71.45	72.50	70.57	71.10	70.72	71.18	70.83	71.64	69.75	71.12	70.41	70.51	70.69	71.28	70.57	70.95	70.26	70.80	70.25	71.32
ST-20-B	72.22	72.31	70.57	72.14	70.89	71.59	71.36	71.89	70.94	71.83	70.94	71.01	70.88	71.57	70.59	71.55	70.14	71.04	70.57	71.35
CLT-UC-A	95.39	95.00	94.17	94.19	92.31	93.65	90.81	93.84	88.63	93.98	86.79	93.59	86.74	92.49	84.67	91.98	85.95	92.17	86.58	92.88
CLT-UC-B	94.55	94.52	93.27	94.13	92.61	93.50	89.69	93.55	89.46	93.13	87.00	92.94	86.59	92.53	84.40	92.42	85.74	92.22	85.63	92.60
CLT-6-A	73.02	73.25	72.97	72.77	72.46	72.60	72.30	72.87	71.91	72.98	72.22	72.72	72.53	72.63	72.62	73.13	72.34	72.51	71.85	72.70
CLT-6-B	71.27	72.17	71.90	72.07	71.38	71.75	71.35	72.12	71.25	72.03	71.29	71.24	71.32	72.11	71.46	72.19	71.33	71.77	71.32	72.12
CLT-20-A	70.88	73.37	72.36	72.67	71.04	71.10	71.09	71.23	71.07	71.98	71.02	70.98	70.56	71.33	70.45	70.97	70.93	70.81	70.61	70.47
CLT-20-B	72.71	73.82	72.73	72.60	72.54	72.69	71.94	73.20	72.47	73.09	71.96	72.37	72.72	73.22	72.20	73.44	72.62	72.50	72.43	72.57

Cycle # →	11		12		13		14		15		16		17		18		19		20	
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)
ST-UC-A	96.75	92.54	86.65	92.39	87.33	91.96	86.19	92.03	85.40	91.95	85.79	90.76	85.82	88.74	85.30	89.41	84.25	89.58	84.63	90.26
ST-UC-B	96.25	91.52	86.34	91.19	86.15	92.02	86.37	92.14	85.29	91.82	84.81	91.00	84.79	89.93	83.53	89.41	83.16	89.43	83.82	89.54
ST-6-A	71.06	70.04	68.13	69.99	68.67	70.35	68.91	70.30	69.08	70.43	69.31	70.42	69.13	70.35	69.52	70.72	69.52	70.15	69.66	70.76
ST-6-B	70.93	69.09	67.58	68.48	66.89	68.51	66.99	68.78	66.59	68.55	67.02	68.67	67.33	68.86	67.77	68.90	66.77	69.17	66.83	68.95
ST-20-A	71.45	70.94	69.88	70.91	70.20	71.33	70.32	71.07	70.70	71.14	70.58	71.32	70.88	71.34	70.85	71.47	70.58	71.12	70.27	71.12
ST-20-B	72.22	71.14	70.25	70.83	70.86	71.19	70.38	70.86	70.89	70.93	70.59	71.05	70.88	71.33	70.61	71.57	70.58	71.48	70.73	71.23
CLT-UC-A	95.39	92.17	85.89	91.75	87.69	92.34	87.08	91.63	86.23	91.96	86.30	92.29	85.19	91.98	85.25	91.48	85.54	91.62	86.05	91.43
CLT-UC-B	94.55	93.13	86.52	93.77	86.90	92.82	85.50	93.48	86.59	93.49	86.51	93.38	87.04	93.23	86.33	93.34	86.85	93.76	86.82	93.35
CLT-6-A	73.02	72.51	71.91	72.93	72.24	73.28	72.57	73.07	73.19	73.64	72.91	73.40	72.62	73.50	72.92	73.96	73.81	73.28	73.09	73.43
CLT-6-B	71.27	71.40	71.06	72.20	71.20	71.87	72.16	72.47	72.06	72.43	72.08	72.47	71.99	73.04	72.35	72.71	72.01	72.14	71.70	72.20
CLT-20-A	70.88	70.23	70.84	71.21	70.67	72.11	72.10	72.09	71.22	71.76	71.46	71.91	71.51	71.77	71.45	71.81	71.28	71.56	71.39	71.74
CLT-20-B	72.71	72.14	72.41	73.49	72.56	72.98	73.07	73.05	73.21	73.43	73.00	73.77	73.46	73.47	73.24	72.94	73.18	72.38	73.07	73.09

Table A.14. Raw Measurements for Overburden Tests (XMD)

Cycle # →	1		2		3		4		5		6		7		8		9		10		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
ST-UC-A	95.79	95.38	94.86	95.55	94.49	95.09	93.84	94.23	92.66	92.27	92.28	93.87	91.00	93.19	90.92	91.82	90.12	92.39	90.31	92.68	90.66
ST-UC-B	94.73	94.85	94.04	94.39	93.18	93.95	92.47	93.20	92.24	93.19	89.97	92.72	89.74	91.88	87.17	91.40	87.33	90.95	87.65	90.93	86.77
ST-6-A	73.29	73.73	72.04	72.44	72.80	73.02	72.07	72.55	72.48	72.68	72.53	72.52	72.08	72.89	72.56	72.73	72.49	72.69	72.52	72.99	72.41
ST-6-B	72.20	73.28	71.78	72.61	71.54	72.46	71.89	72.69	71.61	72.55	71.89	71.82	71.23	72.16	71.65	72.10	72.04	72.14	71.42	72.13	71.67
ST-20-A	73.20	73.48	73.00	73.30	72.65	72.70	72.73	73.03	72.32	72.91	72.55	72.65	71.72	72.40	72.23	72.46	72.25	72.76	72.23	72.48	72.19
ST-20-B	72.40	72.96	71.67	72.36	71.77	71.92	72.02	71.95	71.51	72.23	71.83	71.86	71.56	72.19	71.80	72.43	71.51	71.81	71.77	71.59	71.41
CLT-UC-A	94.45	94.38	94.66	95.05	94.76	95.12	94.28	95.14	93.70	94.80	93.23	94.80	92.39	93.75	91.66	93.82	91.04	93.61	91.91	93.97	91.70
CLT-UC-B	95.98	95.37	95.61	95.33	95.84	95.35	95.19	95.18	94.51	95.67	94.63	95.71	93.92	95.25	92.33	95.55	93.57	95.83	94.00	96.03	93.98
CLT-6-A	70.62	71.50	71.51	71.80	71.66	71.90	71.67	71.94	71.76	71.83	71.36	70.82	71.35	71.65	71.33	71.83	70.70	71.22	71.08	71.66	71.57
CLT-6-B	69.87	71.70	71.34	71.88	71.20	71.89	71.81	71.62	71.45	71.84	71.00	71.37	71.32	71.40	70.80	71.61	71.31	71.53	70.69	71.38	71.09
CLT-20-A	68.73	70.72	70.72	71.09	70.32	70.06	69.92	70.84	69.99	70.70	69.94	70.12	71.50	70.95	69.93	71.18	70.36	70.25	70.24	69.98	70.27
CLT-20-B	69.41	70.20	70.65	70.53	69.57	69.86	69.85	69.93	69.70	69.93	69.71	69.68	70.06	70.57	70.00	70.47	69.87	69.95	69.75	70.14	69.80

Cycle # →	11		12		13		14		15		16		17		18		19		20		
	Initial Length (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	After Wetting (mm)	After Drying (mm)	
ST-UC-A	95.79	92.06	89.62	91.96	88.61	91.38	88.57	91.63	87.06	90.52	86.54	90.94	86.94	90.09	86.93	89.89	86.56	89.63	86.44	90.31	87.09
ST-UC-B	94.73	91.29	86.19	90.80	86.34	91.06	85.81	90.56	84.49	89.98	83.43	89.43	83.28	88.07	83.75	88.64	82.59	88.31	82.42	88.33	82.55
ST-6-A	73.29	73.00	72.46	72.48	72.49	72.58	72.40	72.76	72.56	73.21	73.00	72.92	72.95	73.18	72.75	73.34	72.94	73.07	73.09	73.44	72.63
ST-6-B	72.20	72.12	71.57	72.41	70.81	72.31	70.93	72.08	71.39	71.76	71.09	72.16	71.42	71.70	71.64	72.00	70.95	71.94	70.86	72.40	71.43
ST-20-A	73.20	72.07	72.15	72.26	72.12	72.82	72.05	72.70	72.36	72.68	72.35	72.56	72.43	72.90	72.37	72.64	72.12	72.62	72.28	72.78	72.62
ST-20-B	72.40	71.69	71.31	71.91	71.48	71.74	71.66	72.04	72.14	72.44	71.89	72.40	72.05	72.35	72.33	72.50	72.53	72.34	72.04	72.11	72.17
CLT-UC-A	94.45	93.51	90.53	93.03	91.62	93.76	90.77	93.53	89.91	94.08	90.69	93.57	90.07	93.56	89.08	93.19	90.08	93.40	91.04	93.40	91.12
CLT-UC-B	95.98	95.83	93.12	96.13	94.00	95.24	91.94	95.07	92.51	95.85	92.76	95.43	92.66	95.54	92.56	95.37	93.06	95.59	92.34	95.01	93.18
CLT-6-A	70.62	71.44	71.33	71.96	71.63	71.99	71.51	71.76	71.90	72.24	72.02	72.09	71.68	71.95	72.09	72.30	72.13	71.82	72.18	72.10	71.12
CLT-6-B	69.87	71.35	71.12	71.84	71.37	71.83	71.20	71.64	71.78	71.60	71.88	71.58	71.63	71.68	71.43	71.77	71.81	71.50	72.01	71.92	71.43
CLT-20-A	68.73	70.06	70.51	70.89	70.69	70.77	70.44	70.81	70.77	71.05	70.95	71.15	71.03	70.96	70.80	71.07	71.01	71.37	70.94	71.37	70.40
CLT-20-B	69.41	69.69	70.16	70.75	70.05	70.71	70.21	70.86	70.27	70.80	70.31	70.80	70.95	70.95	70.91	70.92	70.00	70.48	70.44	70.45	70.26