This is to certify that the
thesis entitled

HYDRAULIC CONDUCTIVITY OF GEOSYNTHETIC CLAY LINERS PERMEATED AT ELEVATED TEMPERATURES

presented by

NIMISHA H. PATEL

has been accepted towards fulfillment
of the requirements for the

M.S. degree in Environmental Engineering

Milind V. Khire
Major Professor's Signature

9/13/05
Date

MSU is an Affirmative Action/Equal Opportunity Institution

HYDRAULIC CONDUCTIVITY OF GEOSYNTHETIC CLAY LINERS PERMEATED AT ELEVATED TEMPERATURES

BY

NIMISHA H. PATEL

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Civil and Environmental Engineering

2005

ABSTRACT

HYDRAULIC CONDUCTIVITY OF GEOSYNTHETIC CLAY LINERS PERMEATED AT ELEVATED TEMPERATURES

By

Nimisha H. Patel

The environmental performance of landfill liners is primarily controlled by the fate and transport of leachate constituents from the landfill leachate. Hence, hydraulic conductivity of the liner is a key factor when selecting material for lining systems. Hydraulic conductivity is influenced not only by the properties of the porous media but also the permeant liquid. There are many studies where elevated temperatures of waste and leachate have been reported due to the aerobic decomposition of the organic fraction of waste. At elevated temperatures, soil structure and permeant viscosity change. However, there is very little experimental data on hydraulic conductivity of clays or geosynthetic clay liners (GCLs) permeated at elevated temperatures.

The primary objective of this study was to evaluate the effect of elevated permeant temperature on hydraulic conductivity of GCLs. An experimental setup was designed to meet the research objectives. The key conclusions are: (1) There is a 2 to 3 fold increase in the hydraulic conductivity of GCLs when permeated with DI water, tap water, or 0.1 M $CaCl_2$ solutions at 80 °C when compared at 21 °C; and (2) this increase in hydraulic conductivity is primarily due to decrease in the viscosity of the permeant. Hence, hydraulic conductivity of GCLs at elevated permeant temperature can be estimated by applying the viscosity correction specified in ASTM D 5084 to the hydraulic conductivity measured at a room temperature.

To my loving family

ACKNOWLEDGMENTS

At the end of my thesis I would like to thank all those individuals who made this thesis possible and an enjoyable experience for me. First of all I wish to express my sincere gratitude to Dr. Milind V. Khire, who guided this work and helped whenever I was in need. I think his presence at MSU was the best thing that could have happened to me as it allowed me to hone my skills in multi-disciplinary fields of geo-environmental engineering.

I am grateful to the members of my thesis committee, Drs. Shu-Guang Li and Tom Wolff, for their valuable time and support. I acknowledge the financial support extended to me by the Michigan State University for two semesters in the form of a Research Assistantship. I am also grateful to Mr. Saradhi Balla and Mr. Kirk Riley for giving me the opportunity to work as a Research Assistant for two semesters.

Finally, I am thankful to God to have given me my family who stood by me and will stand by my side to give me support and co-operation forever. I would like to extend my gratitude to my papa, mummy, Reshma, Falguni and Karishma. I am also thankful to my friends Ramkumar Subramanian, Rajnish Sharma, Neeraj Kohli, Vaibhav Ekbote, Monojit Bhattacharya, Gayatri Kuber, Smeeta Bhattacharya, Vandana Yadav and Swati Shah for their constant encouragement and support. Finally, I would to like to thank my professors from the Geotechnical department at the Maharaja Sayajirao University and Geotest house.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

A landfill is an engineered containment system, built to isolate waste from the surrounding environment (groundwater, surface water, and air). The key engineered components of a municipal solid waste (MSW) landfill are: 1) bottom liner system; 2) leachate collection system (LCS); 3) gas collection system; 4) capping system and; 5) surface water management system. Figure 1-1 presents the key components of an MSW landfill.

Liners are designed to create a barrier between the waste and the environment and to allow efficient drainage of leachate for collection and treatment. Lining systems are designed according to federal and state regulations. The Federal Resource Conservation and Recovery Act (RCRA), Subtitle D (1976) regulates MSW landfill design, construction, and operation under Title 40 and Part 258 of the Code of Federal Regulations According to the U.S. Federal regulations, a composite liner should consist of ≥ 60-cm-thick compacted clay having hydraulic conductivity $\leq 10^{-7}$ cm/sec overlain by ≥ 1.5-mm-thick (40 mil) flexible membrane liner (FML) for MSW landfills as shown in Figure 1-2. Michigan regulations require double composite liner system for MSW landfills. A double composite liner consists of at least 30-cm-thick sand or gravel leachate detection layer between the two composite liners. Beyond relevant environmental regulations, other key considerations for the selection of lining system include long-term performance, capital cost of construction, and ease of construction. Compatibility of lining system materials with the chemicals present in the leachate

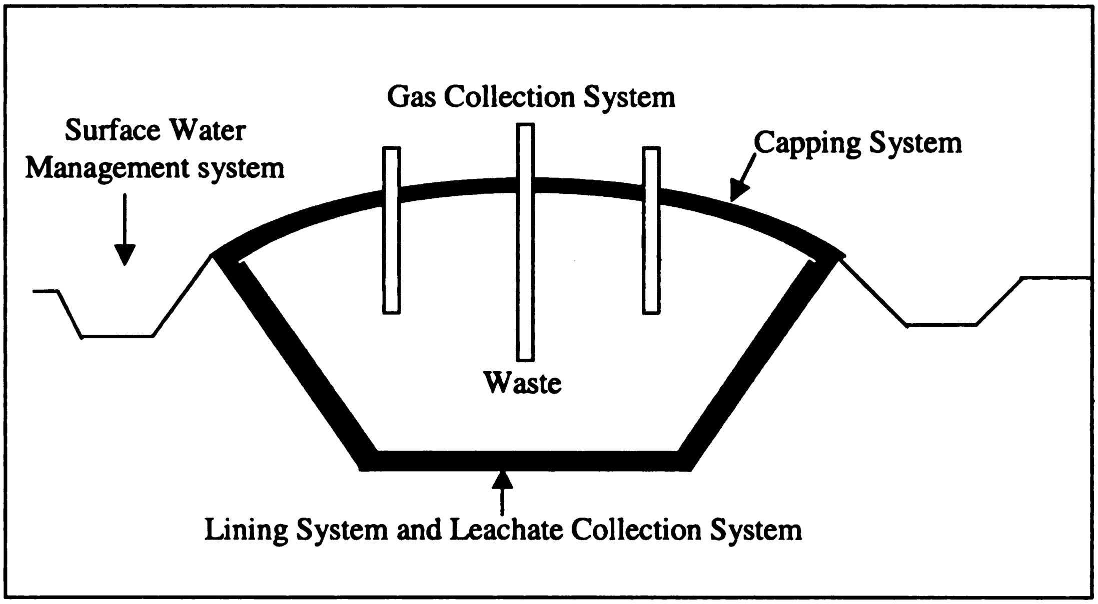

Figure 1-1: Key components of a typical MSW landfill

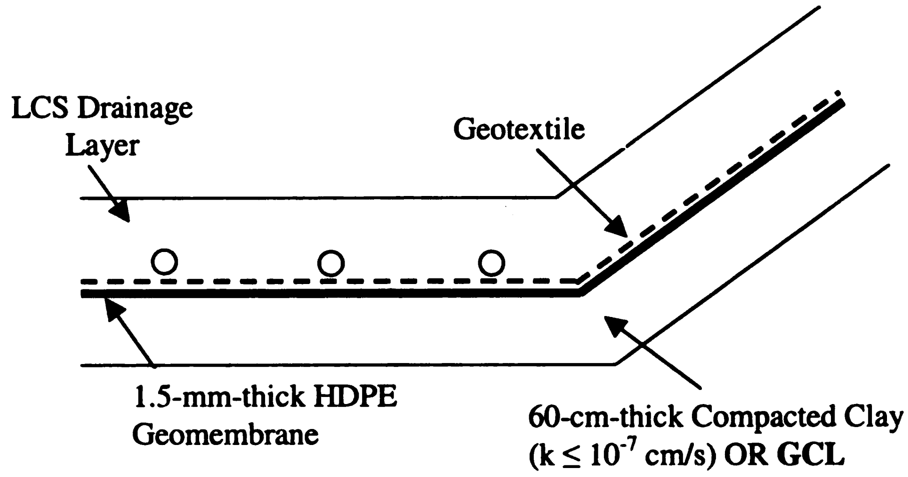

Figure 1-2: RCRA Subtitle D Liner and LCS

plays an important role in controlling the long-term performance of a lining system.

1.2 MATERIAL USED FOR LINERS

Materials commonly used for construction of liners for waste containment systems are: 1) compacted clay or clay amended with other materials (e.g., fly ash) (Ganti 2004); 2) geomembranes or flexible membrane liners (FMLs); and 3) geosynthetic clay liners (GCLs). The hydraulic conductivity of compacted clay liners (CCLs) increases in the presence of some chemicals (Alther et al. 1985; Anderson et al. 1985; Keren and Singer 1988; Gleason 1993), due to fractures when it undergoes desiccation, or due to freeze-thaw cycles (Othman and Benson 1992; Othman et al. 1994). FMLs are more resistant to the common chemicals found in MSW landfill leachate and are almost impermeable to water. High Density Polyethylene (HDPE) is the most commonly used material for liners for MSW landfills.

The environmental performance of a lining system is primarily controlled by the fate and transport of solute(s) from the landfill leachate. Advection and diffusion are the two key processes that control the fate and transport of solutes from the leachate. Advection is the migration of solutes that occurs strictly under hydraulic gradients. Diffusion is the molecular-level migration of solutes that occurs strictly under the concentration gradient. Dispersion is the mixing and spreading of the contaminant within the flow system which occurs under the combined influence of advection and diffusion. For landfill liner applications, for porous materials having relatively high ($\geq 10^{-5}$ cm/s) hydraulic conductivity, advection is the dominant process, while for porous materials having relatively low hydraulic conductivity diffusion is the dominant mode for solute transport (Quigley et al.; 1987, Rowe 1987, Shackelford 1989). Hence, hydraulic conductivity is one of the most important factors that are considered during the material selection of lining systems and to assess impacts from an existing lining system.

1.3 GEOSYNTHETIC CLAY LINERS

A GCL is a factory-manufactured material consisting of a layer of high swelling bentonite sandwiched between two geotextiles or glued to a geomembrane (Daniel and Estornell 1991; Daniel 1991, 1993; Daniel and Boardman 1993; Koerner 1994) (Figure 1-3). The bentonite content by dry mass in a typical GCL is about 5.0 kg/m^2. Extensive usage of GCLs started in 1980s. Since then, GCLs have been extensively used as a barrier material in many environmental applications including landfill liners and covers, sludge lagoon liners and covers, and secondary containment for underground storage tanks. GCLs replace or enhance performance of compacted clay layer or geomembranes in a composite liner setting. Other advantages of GCLs are ease of installation, relatively low hydraulic conductivity and a greater resistance to meteorological distress (Shan and Daniel 1991; Boardman and Daniel 1996; Kraus et al. 1997). Most often GCLs are used in places where supply of good quality natural clay is limited or site conditions are challenging for constructing a compacted clay liner with adequate construction quality control and quality assurance.

There are four types of GCLs based on how the bentonite layer is enclosed: (1) geotextile-enclosed, adhesive-bonded GCL; (2) geotextile-encased, stitch-bonded GCL; (3) geotextile-encased, needle-punched GCL; and (4) geomembrane-supported adhesive-bonded GCL.

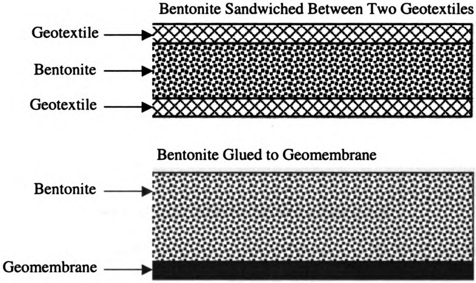

Figure 1-3: General Configuration of GCLs (Source: CETCO Lining Technologies)

Typically GCLs use powdered or granular sodium or calcium bentonite. The thickness of bentonite layer varies from 4.0 to 8.0 mm. GCLs are available in panels having a minimum width equal to 2.2 to 5.2 by 30 to 60 m length. The following points list key advantages of GCLs as compared to CCLs:

1. Hydraulic Factors: lower hydraulic conductivity compared to typical CCLs.
2. Physical/Mechanical Issues: better resistance to withstand freeze-thaw and wet-dry cycles compared to CCLs. Greater shear strength if the strength of the bond (needle-punch, adhesive, etc) is adequate. Better erosion resistance, and less potential for cracking from differential settlement.
3. Construction Issues: compared to CCLs, GCL offer superior puncture resistance, their installation is easier and relatively faster, and the quality of GCL is more consistent because it is manufactured in a controlled setting.

1.4 TEMPERATURES MEASURED IN MSW LANDFILLS

GCLs are constantly subjected to several stresses in the field including thermal stresses due to the heat generation and heat flow that occurs in natural or engineering systems such as landfills. Several studies have shown elevated temperatures at the base of landfills near the leachate collection and lining systems. Collin (1993) has reported temperatures in excess of 60 °C within landfills. Dach and Jager (1995) measured temperatures greater than 50 °C at the base of landfills in Germany. Yoshida and Rowe (2003) monitored three landfills in Japan for 12 to 30 years. They reported temperatures ranging from 20 to 50 °C near the liners. Age of waste in landfill is an important factor to consider when temperature is monitored. Hanson et al. (2005) have reported temperatures in liner system consisting of GCLs ranging from -1 °C to 35 °C for a cell located in the midwest USA and exposed for a period of more than one year after construction. Temperatures of a GCL in a landfill located in Pennsylvania over a period of 9.5 years ranged from 20 and 35 °C (Koerner 2001). Rowe (1998) reported temperatures between 10 to 30 °C and 20 to 30 °C for liners containing GCLs located in California and Florida, respectively. Gartung et al. (1999) monitored temperature variation in a German landfill and reported temperatures greater than 50 °C where the waste was 6 to 8 years old and for more than 10 years old waste the temperatures were between 20 and 40 °C.

In bioreactor landfills, moisture (leachate or other liquids) and/or air are injected into the waste to increase the decomposition rate of the waste. Decomposition results in the settlement of waste which results in an additional volume and it increases the life of the landfill. During the aerobic decomposition process, due to exothermic reactions, temperatures do increase (Mehta et al. 2001; Hater et al. 2000). Because MSW is a relatively poor conductor of heat the temperatures in landfills remain elevated until the waste has completely decomposed. Hater et al. (2000) have reported waste temperatures between 54 °C to 65 °C in an instrumented bioreactor landfill cell located in Kentucky.

Temperatures of leachate collected from recovery wells at a MSW landfill in New York have ranged from 32 °C to 58 °C (Adams and Hullings 2001). Other sites have recorded leachate temperatures as low as 21 °C. A maximum temperature of about 35 °C has been recorded in the liner of a bioreactor landfill located in California where the maximum waste temperature reached about 54 °C (Yoho County 2001). In summary, the temperatures of leachate from MSW landfills that is in contact with the LCS and liner are typically greater than the room temperature (~ 22 °C).

CHAPTER 2

FACTORS AFFECTING HYDRAULIC CONDUCTIVITY OF GCLs

The key factors that influence the hydraulic properties of GCLs are: (1) viscosity and chemistry of the hydrating and permeant liquids; (2) void ratio or dry unit weight; and (3) double layer thickness of the clay component. The change in temperature of the permeating liquid results in these changes: (1) it changes the viscosity of the permeant; (2) it causes expansion or contraction of the permeant due to change in the temperature resulting in a change in the void ratio of the clay component; and (3) it can change the double layer thickness of the clay.

The thickness of the clay double layer is influenced by the cation concentration in the solution surrounding the clay particle, the valency of the cations, and the dielectric constant of the solution. Because change in temperature can change the dielectric constant, it can change the double layer thickness. Hence, change in the temperature of the permeant can increase or decrease the hydraulic conductivity of GCLs (Rowe 1998). In addition, distribution of cations adjacent to charged clay particles which is sensitive to temperature (Mitchell 1993), can have an effect on the microstructure of the clay. These key factors affecting hydraulic properties of GCLs are presented in detail in this chapter.

2.1 VISCOSITY OF THE PERMEANT

Relationship between the hydraulic conductivity and properties of soil and permeating fluid is given by Kozeny-Carman equation (Kozeny 1927; Carman 1937; Mitchell 1993). Kozeny-Carman equation for the permeability of porous media is given by Eq. 2-1:

$$k_T = \frac{1}{k_o T^2 S_o^2}\left(\frac{e^3}{1+e}\right) = K\frac{\gamma_T}{\mu_T} \tag{2-1}$$

where,

S_o = the wetted surface per unit volume of particles;

T = tortuosity factor;

k_o = pore shape factor;

e = void ratio;

γ_T = unit weight of the permeant liquid at temperature T;

μ_T = dynamic viscosity of the permeant liquid at temperature T;

k_T = hydraulic conductivity for the permeant liquid at temperature T; and

K = intrinsic permeability of the porous medium.

The effect of permeant properties on intrinsic permeability is accounted for by the μ_T/γ_T term in Eq. 2-1. Table 2-1 presents the ratio of viscosity to unit weight for temperatures ranging from 20 to 100 °C. Table 2-1 shows that viscosity and unit weight decrease as temperature increases. The ratio of viscosity to unit weight decreases slightly as the temperature increases.

Petrov et al. (1997) permeated GCLs with ethanol and water mixtures and found that for permeants containing $\leq 50\%$ ethanol, there is a slight decrease in the hydraulic conductivity due to an increase in the viscosity of the permeate (Figure 2-1). When the concentration of ethanol in the permeant was increased to $\geq 50\%$, due to significant decrease in the dielectric constant of the permeant, the hydraulic conductivity increased. By converting the measured hydraulic conductivity into intrinsic permeability, Petrov et al. (1997) concluded that decrease in the hydraulic conductivity for permeants containing $\leq 50\%$ ethanol was due to increase in viscosity (Figure 2-2).

Table 2-1: Effect of Permeant Temperature on the Unit weight and Viscosity of DI water

Temperature **T (°C)**	**Unit Weight** **γ (kN/m^3)**	**Dynamic Viscosity** **μ (cP)**	**μ/γ** **(cP m^3/kN)**
0	9.79	1.00	0.102
40	9.73	0.65	0.066
60	9.64	0.47	0.048
80	9.53	0.36	0.037
100	9.40	0.29	0.030

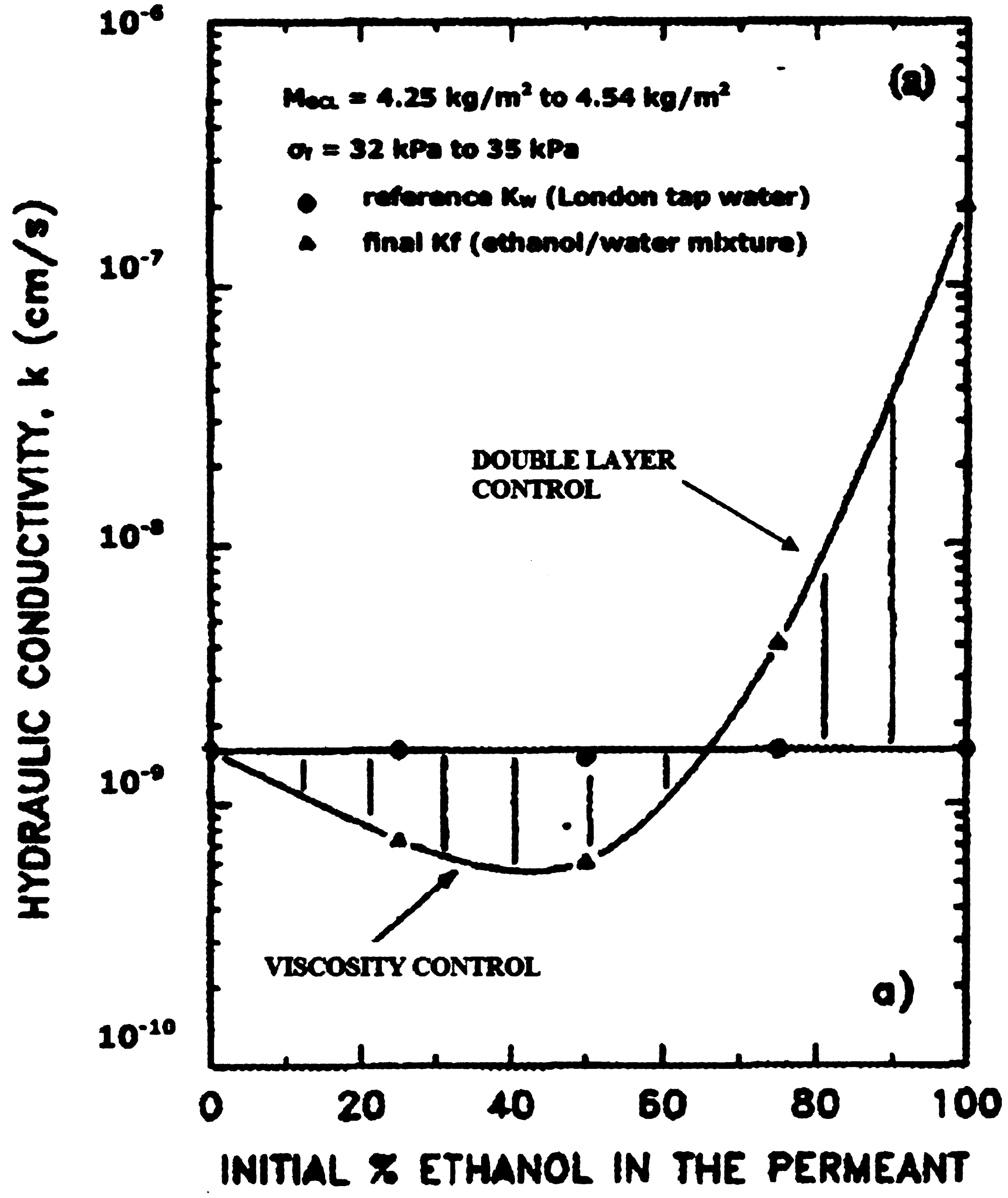

Figure 2-1: Hydraulic Conductivity of GCLs Sequentially Permeated With Tap Water and Ethanol/Water Mixtures (Mass %) (Source Petrov et al. 1997)

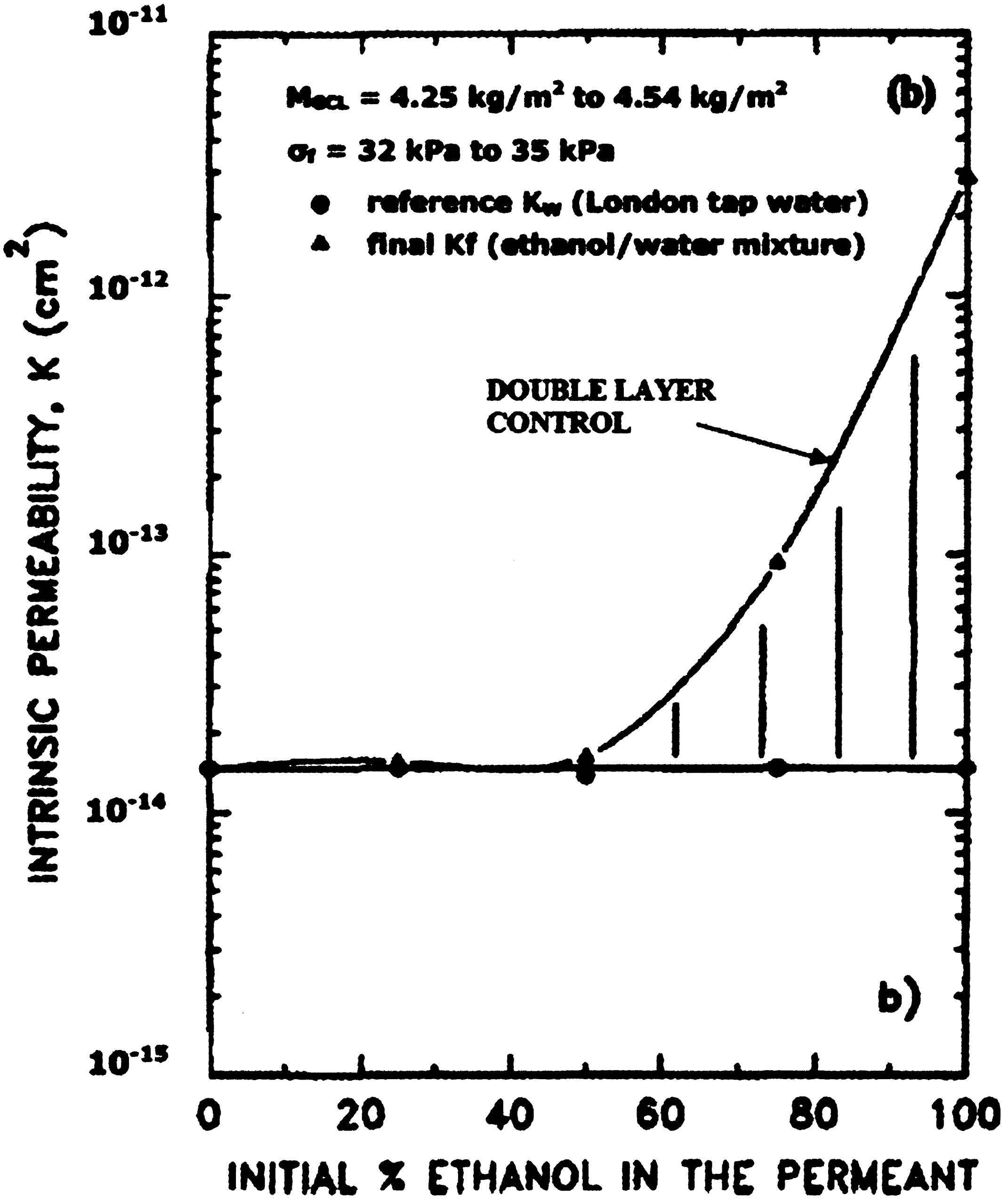

Figure 2-2: Intrinsic Permeability of GCLs Sequentially Permeated With Tap Water and Ethanol/Water Mixtures (Mass %) (Source: Petrov et al. 1997)

Because temperature of permeant also affects its viscosity, temperature change will result in a change in the hydraulic conductivity similar to measurements by Petrov et al. (1997).

2.2 DOUBLE LAYER THICKNESS

Changes in the hydraulic conductivity can be qualitatively related to the changes in the diffuse double layer that surrounds negatively charged particles of clay (Mitchell 1993).

In colloidal chemistry, the adsorbed layer (or diffuse double layer) is commonly described using the Stern-Gouy model (Gouy 1910; Mitchell 1993; Shackelford 1994; Shang et al. 1994). According to the model, a thin film called "Stern layer" consisting of oriented water dipoles and fixed hydrated cations is directly adjacent to the clay surface, while a diffuse layer of hydrated cations attracted to the clay surface resides immediately adjacent to the Stern layer. The double layer thickness (t_{dl}) is given by Shackelford et al. (2000) as follows (Eq. 2-2).

$$t_{dl} = \sqrt{\frac{\varepsilon.\varepsilon_0.R.T}{2.v^2.F^2.\eta}} \qquad (2\text{-}2)$$

where,

ε = dielectric constant of the pore water which is temperature dependent (also referred to as the relative permittivity);

ε_0 = permittivity in a vacuum;

R = Universal gas constant;

F = Faraday's constant;

T = absolute temperature (°K);

v = valence of the cation; and

η = electrolyte concentration.

According to Eq. 2-2, electrolyte concentration, cation valence, and dielectric constant affect the thickness of the diffuse double layer, which in turn affects the hydraulic conductivity of bentonite in GCL. Hydraulic conductivity reduces as the thickness of double layer increases (Mesri and Olson 1971; Shang et al. 1994; Gleanson et al. 1997; and Stern and Shackelford 1998). On the other hand, reduction in the double layer thickness results in an increase in hydraulic conductivity which is of great concern when clays and GCLs are used for environmental barrier applications. When temperature of the permeant (T) is increased, the dielectric constant of the permeant decreases and other parameters in Eq. 2-2 stay constant. Hence, when only temperature of the permeant is changed, the thickness of the double layer can represented by Eq. 2-3.

$$t_{dl} \alpha \sqrt{\varepsilon \cdot T} \tag{2-3}$$

Knowlton (1941) gave the following approximation for calculating dielectric constant from temperatures 0-100 °C.

$$\varepsilon \sim 80 - 0.4(T - 293) \tag{2-4}$$

where,

T = absolute temperature (°K).

Table 2-2 presents ε and $\sqrt{\varepsilon \cdot T}$ as a function of T for T ranging from 0 to 100 °C for DI water. Table 2-2 indicates that as T increases, there is a slight decrease in $\sqrt{\varepsilon \cdot T}$ which indicates that as the temperature of the permeant (if DI water) increases, there would a decrease in the double layer thickness which would contribute towards increase in the hydraulic conductivity of the clay.

Table 2-2: Effect of Permeant Temperature on the Dielectric Constant of DI water

Temperature T (°C)	**Temperature T (°K)**	**Dielectric Constant of DI water ε (pF.m^{-1})**	$\sqrt{\varepsilon . T}$ **(pF.m^{-1} .°K)**
0	273	88	155
20	293	80	153
22	295	79	153
40	313	72	150
60	333	64	146
80	353	56	141
100	373	48	134

2.3 MINERALOGY OF BENTONITE

The relatively low hydraulic conductivity of GCLs is due to the bentonite it contains. The mineralogy of the bentonite is an important factor as it partially controls the hydraulic conductivity. The primary mineral in bentonite clay is montmorillonite (typically about 70-90% by dry weight). Stern and Shackelford (1998) conducted experiments on three sand-clay soil mixtures permeated with distilled water. They found that when the montmorillonite fraction in clay increases, hydraulic conductivity of the sand-clay mixture permeated with distilled water decreases. Ganti (2004) evaluated the effect of bentonite content on the hydraulic conductivity of fly ash samples mixed with bentonite. Ganti (2004) found that as the bentonite content increase, the hydraulic conductivity of the sample decreases. Thus, overall montmorillonite content of bentonite is mainly responsible for the low hydraulic conductivity of GCLs (Shackelford et. al. 2000; Egloffstein 2001).Bentonite in GCLs has a relatively low hydraulic conductivity due to a relatively small particle size and a relatively thick double layer associated with montmorillonite (Mesri and Olson 1971).

At elevated temperatures, coagulation and/or the geometric re-arrangement of particles can take place. Laguros (1969) demonstrated elevated temperatures tend to change soil structure. The author found that, as temperatures increases, soil particle disperses due to an increase in the thickness of the diffuse double layer. At low temperatures, soil structure flocculates due to decrease in the diffuse double layer thickness. Dispersed clay particles yield a lower hydraulic conductivity compared to flocculated structure (Mitchell 1993).

2.4 BOUND AND FREE PORE WATER

The hydraulic conductivity of GCLs depends upon the fraction of water that is hydraulically mobile and size and tortuosity of the pathways through which the free water flows (Mesri and Olson 1971). When the volume of bound water molecules increases, the fraction of the pore space available for mobile water decreases (for a constant volume of the soil) and flow paths become smaller and more tortuous. Thus, factors that influence the fraction of bound water can impact the hydraulic conductivity of bentonite (McNeal and Coleman 1966; Egloffstein 1997; Shackelford et al. 2000; Jo et al. 2001). Likewise, volume of bound water is affected by temperature, viscosity, cation concentration and valence, and pH of the permeant solution (Mitchell 1993; McBride 1994; Egloffstein 1995; Petrov and Rowe 1997; Shackelford et al. 2000; Jo et al. 2001; Kolstad et al. 2004).

A fraction of water present in the pore spaces of bentonite is immobile and the rest is mobile for a given set of physical and chemical parameters. Mobile water is bulk pore water that is free to move under a hydraulic gradient, while immobile water is bound to the external and interlayer mineral surface by strong electrostatic forces within the diffuse double layer. For a fixed volume of clay, when the volume of bound water molecules increases, the hydraulic conductivity decreases because the volume available for fraction of freely flowing bulk water in pore spaces decreases and the cross sectional area of flow pathways becomes smaller and more tortuous.

The interlayer bound water in bentonite forms in two phases: the "crystalline" phase and the "osmotic" phase (Van Olphen 1977; McBride 1994; Prost et al. 1998). The crystalline phase occurs as montmorillonite hydrates from completely dry state. Mineral surface and cations on the surface continue to hydrate until several monolayers of water molecules are bound within the interlayer. The osmotic phase follows the crystalline phase, but occurs only when the exchange sites contain monovalent cations (Norrish and Quirk 1954; Kjellander et al. 1988; McBride 1994; Prost et al. 1998). Osmotic hydration can result in an appreciable expansion of the interlayer space, a large fraction of water getting bound in the double layer, and is responsible for a large amount of swelling and low hydraulic conductivity.

When the interlayer cations are monovalent, as is the case with Na-bentonite, both crystalline and osmotic hydration occurs, allowing the interlayer spacing to expand resulting in greater bound water and less volume for mobile water. On the other hand, when polyvalent cation (e.g., Ca^{++}) is present, a strong electrostatic attraction between montmorillonite sheets and the interlayer cations prevents osmotic swelling (McBride 1994, 1997; Quirk and Marcelja 1997). Hence, it results in less bound water and more volume of mobile water resulting in a greater hydraulic conductivity. In monovalent solutions, the volume of swelling and interlayer spacing is inversely proportional to the square root of the concentration of the solution (Norrish and Quirk 1954; McBride 1994; Zhang et al. 1995; Onikata et al. 1999).

2.5 PORE PRESSURE INCREASE DUE TO THERMAL EXPANSION

The increase in temperature of the permeant results in an increase in the pore water pressure because volumetric expansion of the pore water is greater than void space of the mineral solids (Eq. 2-2). Because of the relatively low hydraulic conductivity of the bentonite, longer time is required for this pore pressure to dissipate. In saturated soils, change in temperature generates changes in volume and/or effective stress. Thermal expansion of mineral solids and pore water is caused by temperature increases. Equation

2-5 presents the variables that control the change in pore pressure as a result of increase in temperature for soils.

$$\Delta u = \frac{n(\alpha_s - \alpha_w)\Delta T + \alpha_{ST}\Delta T}{m_v} \tag{2-5}$$

where,

Δu = change in pore water pressure;

n = porosity;

α_{ST} = physicochemical coefficient of structural volume change;

α_s = thermal expansion coefficient of cubical expansion of mineral solids;

α_w = thermal expansion coefficient of soil water;

ΔT = change in temperature; and

m_v = compressibility of the soil structure.

2.6 OTHER FACTORS

2.6.1 Chemistry of Permeant

Double layer thickness of clay particles is governed by Eq. 2-2. According to Eq. 2-2 these properties of permeant liquid can expand or shrink the double layer and hence cause can decrease or increase the hydraulic conductivity of the clay: (1) dielectric constant; and (2) concentration and valency of cations (e.g., 0.1 M versus 1 M, Na^+ versus Ca^{++}).

Jo et al. (2001) evaluated the effect of concentration and valence of cations in single-species salt solution on swelling and hydraulic conductivity of non-prehydrated GCLs. The authors found that the hydraulic conductivity of GCLs increases with: (1) the valency of the cations at a given concentration; and (2) the concentration for a given valency. In addition, the authors found that the effect of valency on the hydraulic conductivity is greatest at moderate concentrations (i.e, 0.025 – 0.1 M).

Daniel et al. (1993), Shackelford (1994), Didier and Comeaga (1997), Gleason et al. (1997), Petrov and Rowe (1997), Stern and Shackelford (1998), and Lin (1998) show that the order of permeation of bentonite has a significant effect on the final hydraulic conductivity. Hydrating bentonite with DI water before permeation with chemical solution or leachate results in a lower hydraulic conductivity than direct permeation with the chemical solution. Figure 2-3 depicts that the hydraulic conductivity of the GCL specimen prehydrated using DI water stabilized at around 7 x 10^{-9} cm/s, whereas final hydraulic conductivity of the non-prehydrated specimen remained significantly higher at around 9 x 10^{-6} cm/s.

2.6.2 Freeze-Thaw and Wet-Dry Cycles

Hewitt and Daniel (1997) proved in their experiments that GCLs can withstand at least three freeze-thaw cycles without considerable change in hydraulic conductivity. Because landfill leachate contains dissolved salts, use of salt solution as the permeant is more representatives (Lin and Benson 2000).

Lin and Benson's (2000) experiments showed an increase in hydraulic conductivity to as high as 7.6 x 10^{-6} cm/sec within 3 to 6 wetting cycles, when GCLs were permeated with 0.0125 M $CaCl_2$ solution (Figure 2-4). Erickson et al. (1994) published field performance of GCLs after one winter of freeze-thaw at a location near Milwaukee, Wisconsin. There is very little published field data of effect of freeze-thaw on hydraulic conductivity of GCLs.

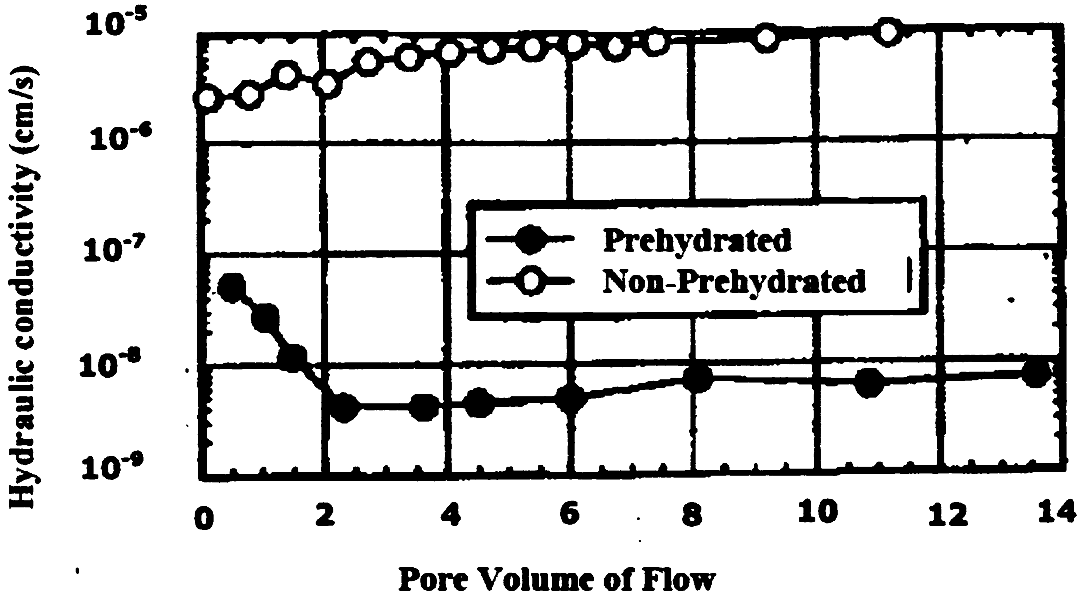

Figure 2-3: Effect of Prehydration on the Hydraulic Conductivity of a Needle-Punched GCL Permeated with a Simulated Mine Tailing Solution (Source: Shackelford et al. 2000)

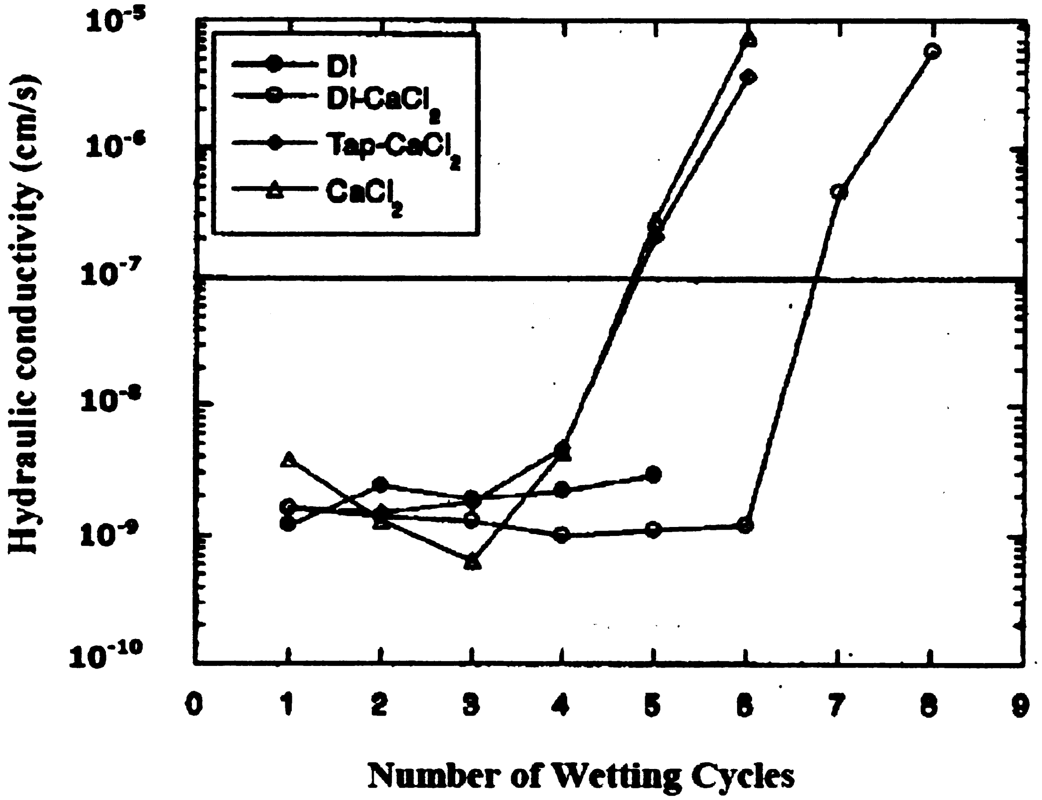

Figure 2-4: Hydraulic Conductivity as a function of Wetting Cycle and Permeant Chemistry (Source: Lin and Benson 2000)

Cullen et al. (1982) conducted research related to the effect of elevated permeant temperature on the hydraulic properties of these three clay minerals: Georgia kaolinite, Urbana illite, and bentonite. The authors used water as the permeant and the hydraulic conductivity test was conducted on a sample having dimension equal to 10.12 cm diameter and a height of 2.54 cm, constant rate of strain consolidation method was used to measure the hydraulic conductivity. Figure 2-5 presents the hydraulic conductivity of bentonite at permeant temperatures equal to 20, 90, and 160 °C. Figure 2-5 shows that there

is a slight decrease in the hydraulic conductivity at 90 °C followed by a 4-fold increase at 160 °C.

2.7 RESEARCH OBJECTIVES

All mechanical properties, hydraulic properties, and fluid transport characteristics of GCLs are typically determined at room temperature (~ 22°C) in the laboratory. However, temperature of leachate in MSW landfills where GCLs are commonly used in the lining system is rarely 20 °C. The data presented in this chapter suggests that temperature of permeant can influence the hydraulic conductivity of GCLs which will impact the rate of leakage of contaminants from landfills. Hence, the primary aim of this study is to evaluate the effect of elevated permeant temperature on the hydraulic conductivity of GCLs. Another objective of this study was to determine which property is critical to predict the change in hydraulic conductivity of GCLs when permeant temperature is increased.

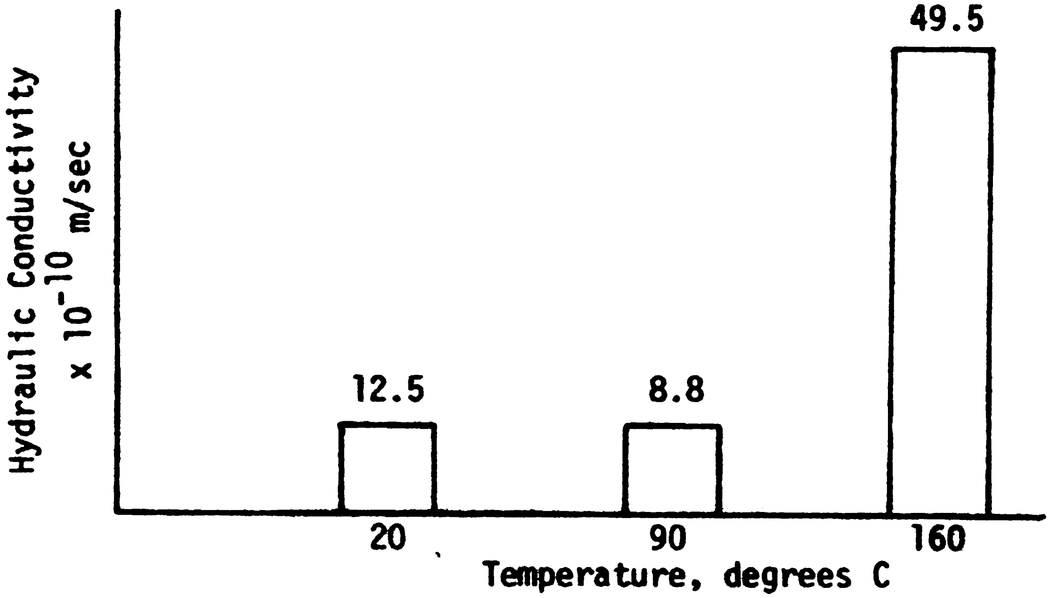

Figure 2-5: Mean hydraulic conductivity of bentonite as a function of permeant temperature (Source: Cullen et al., 1982)

CHAPTER 3

MATERIALS AND METHODS

To evaluate the hydraulic conductivity of GCLs at elevated temperatures of landfill leachate, a series of tests at temperatures ranging from the room temperature (~ 22 °C) to 80 to 100 °C were conducted.

3.1 MATERIALS

3.1.1 Geosynthetic Clay Liner

The geosynthetic clay liner (GCL) used for this study was Bentomat® DN manufactured by CETCO. The following description is based on the information provided by CETCO. This GCL contains chemically untreated sodium bentonite encapsulated between a two nonwoven geotextiles, which are needle-punched together. The maximum hydraulic conductivity reported by the manufacturer for the GCL tested in this study is 5×10^{-9} cm/sec at room temperature for DI water (Table 3-1).

3.1.2 Hydration and Permeation Liquids

The liquids used in the experiments to hydrate and permeate the GCL samples consisted of de-aired deionized water (DI water), MSU tap water, and 0.1 M calcium chloride ($CaCl_2$) solution in DI water. Electrical conductivity of these liquids is presented in Table 3-2.

Calcium chloride solutions having 0.001 M, 0.01M and 0.1 M concentrations were prepared by dissolving $CaCl_2$ (manufactured by J.T. Baker) in DI water. Measured electrical conductivity (EC) at 25 °C for 0.001 M, 0.01 M and 0.1 M concentration are given in Table 3-2. $CaCl_2$ solution of 0.1 M concentration was selected as a permeant

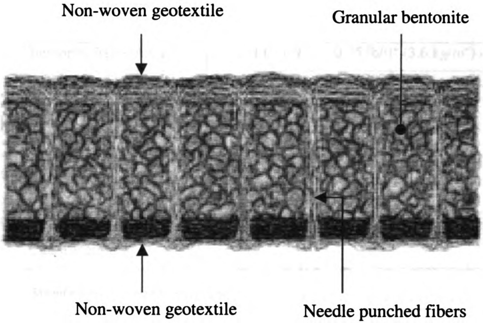

Figure 3-1: Needle-punched GCL (Bentomat® DN by CETCO)

Table 3-1: Properties of Bentomat® DN GCL

Material Property	Test Method	Required Values
Bentonite Swell Index[1]	ASTM D 5890	24 ml/2g min.
Bentonite Fluid Loss[1]	ASTM D 5891	18 ml max.
Bentonite Mass/Area[1,2]	ASTM D 5993	0.75 lb/ft^2 (3.6 kg/m^2) min.
GCL Index Flux[1,3]	ASTM D 5887	1 x 10^{-8} m^3/m^2/sec max.
GCL Hydraulic Conductivity[1,3]	ASTM D 5887	5 x 10^{-9} cm/sec max
Liquid Limit[4]	ASTM D 4318	360 %
Plastic Limit[4]	ASTM D 4318	55 %
Unified Soil Classification[4]	ASTM D 2487	CH

[1] Manufacturer provided listed properties.

[2] Bentonite mass/area reported at 0% moisture content.

[3] Index flux and permeability testing with deaired distilled/deionized water at 80 psi (551 kPa) cell pressure, 77 psi (531 kPa) headwater pressure and 75 psi (517 kPa) tailwater pressure. Reported values are equivalent to 925 gal/acre/day. This flux value is equivalent to a permeability of 5x10^{-9} cm/sec for typical GCL thickness, Actual flux values vary with field condition pressures.

[4] Test performed for current study.

Table 3-2: Electrical Conductivity of Permeant Liquids

	DI water	**Tap water**	**0.001 M $CaCl_2$**	**0.01 M $CaCl_2$**	**0.1 M $CaCl_2$**
Electrical conductivity (μS/cm)	0.6	792	225	1,640	13,800

because it closely represents the ionic strength of typical MSW landfill leachate (Schroeder et al., 2001). Table 3-2 shows that MSU tap water is relatively "hard" having equivalent salt concentration in the range of 0.001 to 0.01 M $CaCl_2$ solution.

3.2 EXPERIMENTAL SETUP

3.2.1 Permeation System

There are open and closed permeation systems that are commonly used for hydraulic conductivity testing of soils. An open system implies that the influent and/or effluent reservoirs of the system are open to the atmosphere or are connected to compressible fluid pressure sources (e.g., pressurized air). Burette systems operating with compressed or atmospheric air and flow pump systems can be classified as open system (Wang and Benson 1999). In an open system, a saturated sample can change in volume by expelling or absorbing permeant liquid from the influent and effluent burettes during permeation (Figure 3-2). A closed system uses a closed loop of liquid to permeate the soil. This is achieved by connecting the inflow and outflow drainage lines of the permeameter with a mercury capillary tube.

For this study, a 1-D consolidation permeameter manufactured by Trautwein Geotechnical Testing was used. It is a rigid wall permeameter. The permeameter was developed for measuring the hydraulic conductivity of remolded samples of soft soil, slurry backfill material, and grout. In this setup, the sidewall leakage problem during GCL testing is alleviated by using an appropriately high confining stress and a bentonite seal around the perimeter of the sample. In the 1-D consolidation permeameter, the sample undergoes consolidation along vertical direction.

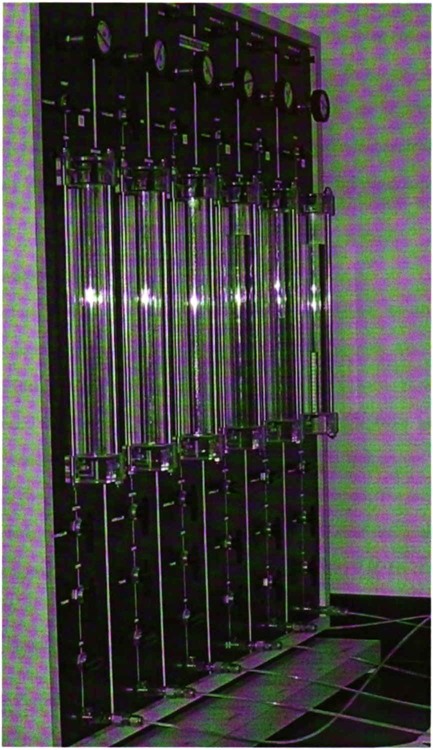

Figure 3-2: Standard Pressure Panel

In order to tolerate the elevated temperatures during testing and to maintain corrosion resistance during $CaCl_2$ permeation, the base and top plates, the sample sleeve, and valves of the permeameter were made of stainless steel. The tubes connected to the permeameter cell were made up of Nylon 6 manufactured by Dayco and was able to resist temperatures up to 105 °C. The O-rings were made up of nitrile rubber. TRAUTWEIN Standard Panel M100000 was used to apply the desired hydraulic gradient and also apply back pressure to the sample. A photograph of the panel is presented in Figure 3-2.

3.2.2 Temperature Chamber

To measure hydraulic conductivity at elevated temperatures, Model TMVH-5 temperature chamber manufactured by BMA (Bryant Manufacturing Associates) was used. This model is a low/high temperature humidity control chamber having internal dimensions equal to 2.3 m by 2.3 m by 2.9 m (Figure 3-3). It is designed to generate and control temperatures ranging from -17 °C to +200 °C. For temperature control, it incorporates a two-channel fully automatic microprocessor program. The temperature is raised by nichrome wire heaters on ceramic cores and a mechanical refrigeration system lowers the temperature. The power requirements are 208 or 220 V, 1 PH (1 Phase), 60 HZ. A photo of the 100-mm-diameter sample cell in the temperature chamber is presented in Figure 3-3.

3.2.3 Sample Preparation

The GCL samples tested were cut out form an intact roll of GCL stored in the laboratory. The sample preparation procedure presented by Daniel et al. (1997) was

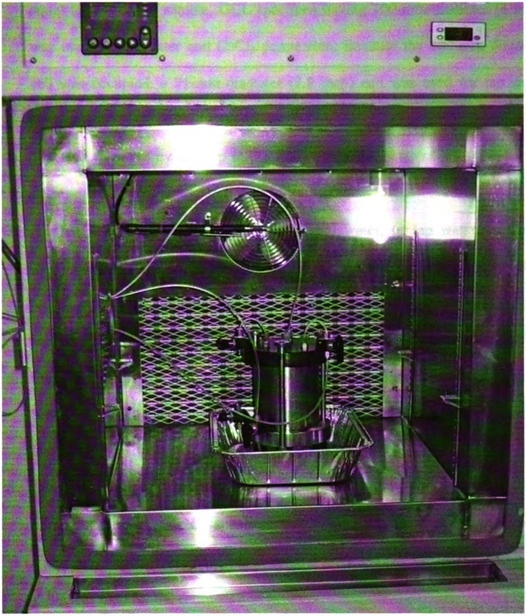

Figure 3-3: 100-mm-diameter Permeameter inside Temperature Chamber

followed. The procedure consisted of:

1. Marking the sample outline for the desired diameter of the sample to be cut from the GCL roll. It was done by placing a porous stone having the diameter equal to that of the sample. GCL specimen having 100-mm-diameter (4 inch) was used for DI water and $CaCl_2$ permeation. Because the 100-mm diameter cell was occupied, a 71-mm-diameter (2.8 inch) cell was used for tap water permeation;
2. The GCL was cut by a sharp utility knife along the outer edge of the porous stone;
3. A small quantity of the hydration liquid (DI water, or tap water, or $CaCl_2$ solution) was sprinkled on the edge of the sample with a squirt bottle to allow local hydration of the bentonite along the edge of the sample to minimize clay loss during transport of the sample to the permeameter cell;
4. Loose geotextile fibers were trimmed with a pair of sharp scissors. In case any bentonite fell out from the edges of the sample, bentonite paste (bentonite mixed with the hydration liquid) was lightly added between the geotextiles;
5. The initial weight of the GCL specimen was measured to the nearest 0.1 g. The initial thickness of the GCL specimen was measured to the nearest 0.1 mm with a vernier caliper. Total five measurements were carried out and the average value was used for the estimation of hydraulic conductivities;
6. Bentonite paste was applied along the circumference of the GCL specimen to prevent sidewall leakage when the sample was placed in the permeameter cell;

7. The lower saturated porous stone was placed in the recess in the base. The sample mould was cleaned, and the prepared GCL sample was placed;
8. Checked that the O-ring at the base is in place and free from dirt. A thin layer of vacuum grease was applied to the O-ring to avoid any possible leakage. Vacuum grease was applied at the bottom and top of the mould, the mould with sample was placed on top of the base. Greased piston was slide down to the top of the porous stone above the GCL sample. The top drain lines remain attached to the top cap;
9. The piston and top cap were placed on the sample mould. Care was taken not to crimp the top drains, when putting the top cap on the sample mould. The piston mould was twisted a little so that slots in the top place are aligned with those in the base. Clamping rods were inserted and tightened evenly with all the valves open. After tightening of clamping rods all the valves were closed;
10. A line between the "cell" burette and brass elbow fitting located on the top cap of the permeameter were connected. Similarly a line between the "tail" burette and valve located on the top cap of the permeameter were also connected (Figure 3-4). The diameter of all tubes connected to the head and tail burette were 3 mm (1/8 in). A connection between the "head" burette and one of the valves on the base of the permeameter was made;
11. Tube length to the bottom of sample was kept long enough (1 m in this case) so that the residence time of permeant liquid was ≥ 2 hrs throughout the duration of the test for hydraulic conductivities of the sample $\leq 10^{-8}$ cm/s for the hydraulic gradients applied during the tests. Hence, the permeant liquid attained

desired temperature before it permeated through GCL sample. The length of the tube carrying the permeant that has already flown through the GCL (effluent) was the approximately equal to the influent tube to cancel out the evaporation loss (a detailed discussion is presented in Chapter 4);

12. All burettes were filled with the permeant liquid. "Tail" and "Head" connection valve were opened. Confining, bottom and top pressures were applied.
13. The sample was hydrated for 48 hrs as per ASTM D 5084. During hydration of the sample no hydraulic gradient was applied on the sample. The sample was allowed to saturate under no flow condition using back pressure (prehydration is described in detail in Section 3.2.4);

    After the sample was hydrated, hydraulic conductivity tests were started on the sample by applying a hydraulic gradient at temperatures of the permeant ranging from ~ 21 °C to 100 °C. The temperature was not increased until the termination criteria specified in ASTM D 5084 was met (termination criteria are presented in detail in Section 3.2.5); and
14. After the completion of the hydraulic conductivity tests, the permeameter cell was carefully opened and the GCL specimen was retrieved for the measurement of final height, wet weight, and water content.

3.2.4 Prehydration

Prehydration allows hydration and swelling of GCL specimen prior to permeation (ASTM D 5084). For current study, the three GCL samples tested were hydrated with the liquid used for permeation (DI water, tap water or 0.1 M $CaCl_2$ solution). Prehydration was carried out by soaking the GCL specimen in the permeameter with permeant liquid

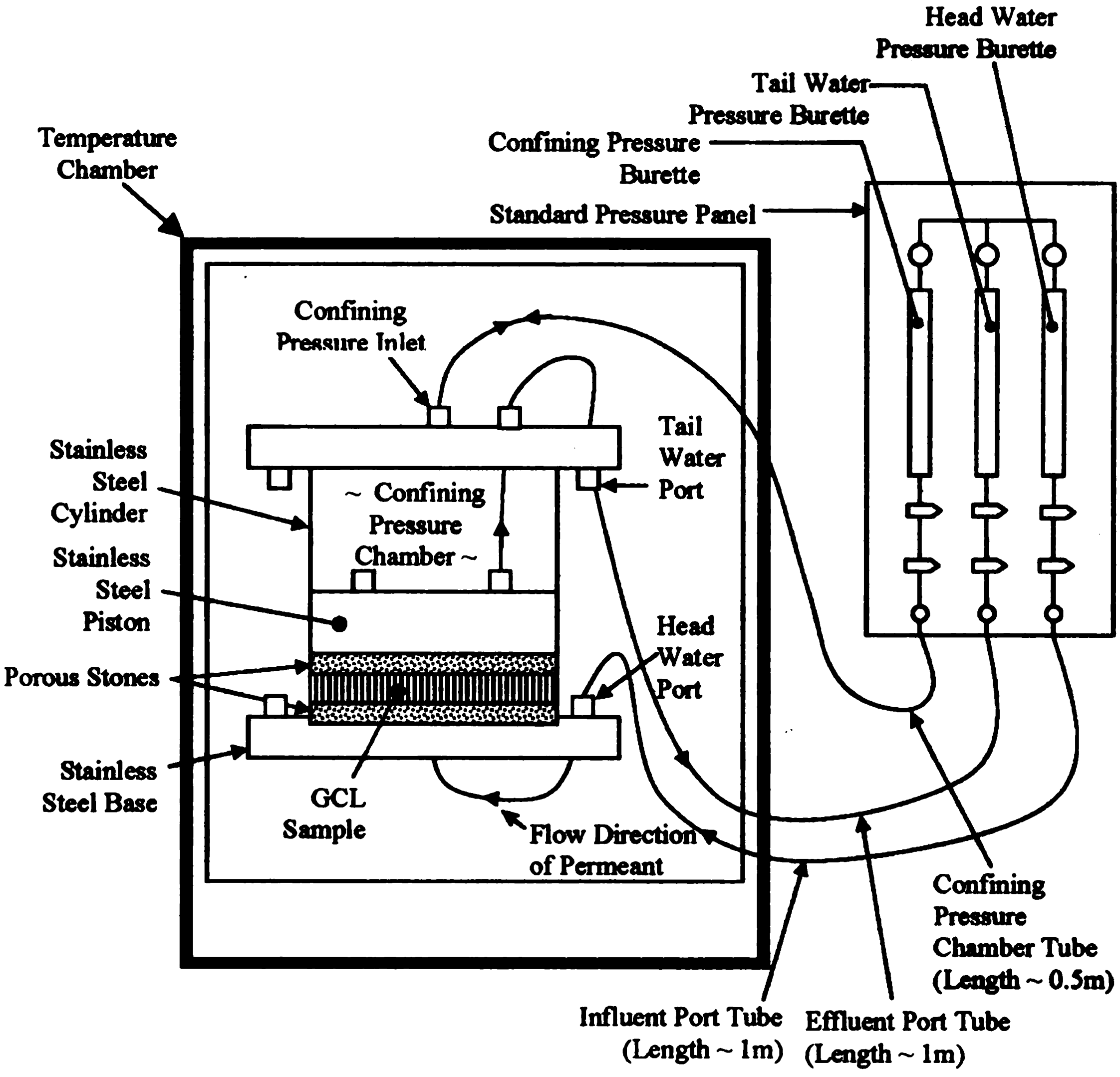

Figure 3-4: Schematic of the Experimental Set-up

for 48 hrs under no net hydraulic gradient as suggested by Ruhl and Daniel (1997). Each of GCL specimens was saturated and consolidated using a backpressure of 482.6 kPa (70.0 psi) and an effective vertical confining pressure of 69 kPa (10 psi) for a 48-hr period. After 48 hours of hydration, as per ASTM D 5084-Method C, the sample was subjected to a hydraulic gradient equal to approximately 180 to 270 to measure the hydraulic conductivity. The gradient used is in the same range as reported by Lee et. al., (2005); Ruhl and Daniel (1997) and Lin and Benson (2000). The hydraulic gradient was applied by increasing the pressure of the influent reservoir to 434 kPa (63 psi) and maintaining the backpressure at 414 kPa (60 psi). Shackelford et. al. (2000) showed that the use of higher hydraulic gradients does not significantly influence the hydraulic conductivity of GCLs.

3.2.5 Termination Criteria for Hydraulic Conductivity Testing

The termination criteria specified in ASTM D 5084 was followed. This criteria requires: (1) a minimum of four hydraulic conductivity measurements must be made; 2) the final four consecutive hydraulic conductivity measurements must all fall within 0.75 to 1.25 times the geometric mean of the four hydraulic conductivity measurements; 3) the ratio of inflow to outflow must fall between 0.75 and 1.25 for the four hydraulic conductivity measurements; and 4) no upward or downward trend should exist in the four hydraulic conductivity measurements.

3.2.6 Measurement of Hydraulic Conductivity

Hydraulic conductivity tests were conducted in accordance with ASTM D 5084-Method C. Falling head rising tail tests were carried out to measure the hydraulic conductivity. In falling head rising tail tests, readings of burettes connected to the bottom, top and confining pressure chamber of the sample were taken periodically throughout the test. Using Eq. 3-1, hydraulic conductivity values were calculated for two consecutive readings. Once termination criteria were satisfied for last four consecutive readings, the temperature was increased to 40, 60, 80 and 100°C and the test was repeated for each temperature.

ASTM D 5084 gives the following equation (Eq. 3-1) for the calculation of hydraulic conductivity, *k* for falling head rising tail test.

$$k = \frac{a_{in}.a_{out}.L}{(a_{in} + a_{out}).A.\Delta t}\ln\left(\frac{h_1}{h_2}\right) \tag{3-1}$$

where,

k = hydraulic conductivity;

a_{in} = cross-sectional area of the reservoir containing the influent;

a_{out} = cross-sectional area of the reservoir containing the effluent;

A = cross-sectional area of GCL specimen;

L = height of GCL specimen;

Δt = interval of time over which the head difference across the sample changes from h_1 to h_2;

t_1 = time at the start of the permeation trial;

t_2 = time at the end of the permeation trial;

h_1 = head loss across the specimen at t_1 in the units of height of water; and

h_2 = head loss across the specimen at t_2 in the units of height of water.

ASTM D 5084 specifies a viscosity correction for hydraulic conductivity if the test temperature was other than 20 °C. The correction converts the hydraulic conductivity to measurement at 20 °C. This correction is viscosity-based (Eq. 3-2).

$$k_{20} = \frac{\mu_T}{\mu_{20}} . k_T \tag{3-2}$$

where,

k_{20} = hydraulic conductivity corrected to 20°C;

μ_{20} = dynamic viscosity of water at 20°C;

μ_T = dynamic viscosity of water at test temperature, T; and

k_T = hydraulic conductivity at test temperature, T.

The viscosity of water depends on temperature. At 293 °K (20°C), the viscosity of water is 1.002 cP. The viscosity decreases as temperature increases. The dynamic viscosity of DI water and 0.1 M $CaCl_2$ solution at the temperatures used in this study are presented in Table 3-3.

Table 3-3: Dynamic Viscosity of DI water and $CaCl_2$ Solution at the Test Temperatures

Permeant Liquid	**Temperature** T (°C)	**Dynamic Viscosity** μ (10^{-3} N.s/m^2)
DI water[1]	20	1.004
	40	0.658
	60	0.475
	80	0.365
	100	0.294
0.1 M $CaCl_2$ Solution[2]	20	1.4
	40	1.0
	60	0.7
	80	0.5
	100	0.4

Source: [1] CRC handbook chemistry and physics

[2] Perry's Chemical Engineers Handbook

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results which consisted of the hydraulic conductivities of the GCL samples measured at temperatures ranging from the room temperature to about 100 °C for these three permeants: (1) DI water; (2) Tap water; and (3) 0.1 M $CaCl_2$ solution in DI water.

4.1 PERMEATION USING DI WATER

4.1.1 GCL

The hydraulic conductivities of the GCL specimen at 22, 40, 60, 80 and 100 °C measured during the test are plotted in Figure 4-1 along with cumulative pore volumes (PV) permeated through the sample. The geometric mean of hydraulic conductivities is presented in Table 4-1. The room temperature in the laboratory fluctuated between 21 and 22 °C.

Figure 4-1 and Table 4-1 indicate that *k* of the GCL increased as the temperature of the permeant was increased. It can be observed in Figure 4-1 that as soon as the temperature of the temperature chamber was increased, within less than 30 min, there was an increase in the *k* value followed by a smaller decrease. This initial increase in the *k* was an apparent increase due to the expansion of the tubes connecting the sample carrying the influent and effluent and the specimen cell. After the tubes were fully expanded, the permeant flow continues through the sample as it approaches steady-state when the effect of expansion of the influent and effluent tubes and the specimen cell does not influence the *k* value. As explained in Chapter 3, because the influent and effluent tubes are

Table 4-1: Geometric Mean Hydraulic Conductivities of GCL for DI water as Permeant

Temperature of the Permeant T(°C)	**Duration to Reach Termination Criteria t (d)**	**Cumulative Pore Volume PV (cm^3)**	**Geometric Mean Hydraulic Conductivity k_T (cm/s)**	**k_T / k_{22}**
22	13.7	1.2	2.6E-09 (k_{22})	1.00
40	12.0	2.0	3.0E-09	1.15
60	6.2	2.8	4.2E-09	1.60
80	6.0	3.8	5.2E-09	2.00
100	8.9	5.8	6.5E-09	2.50

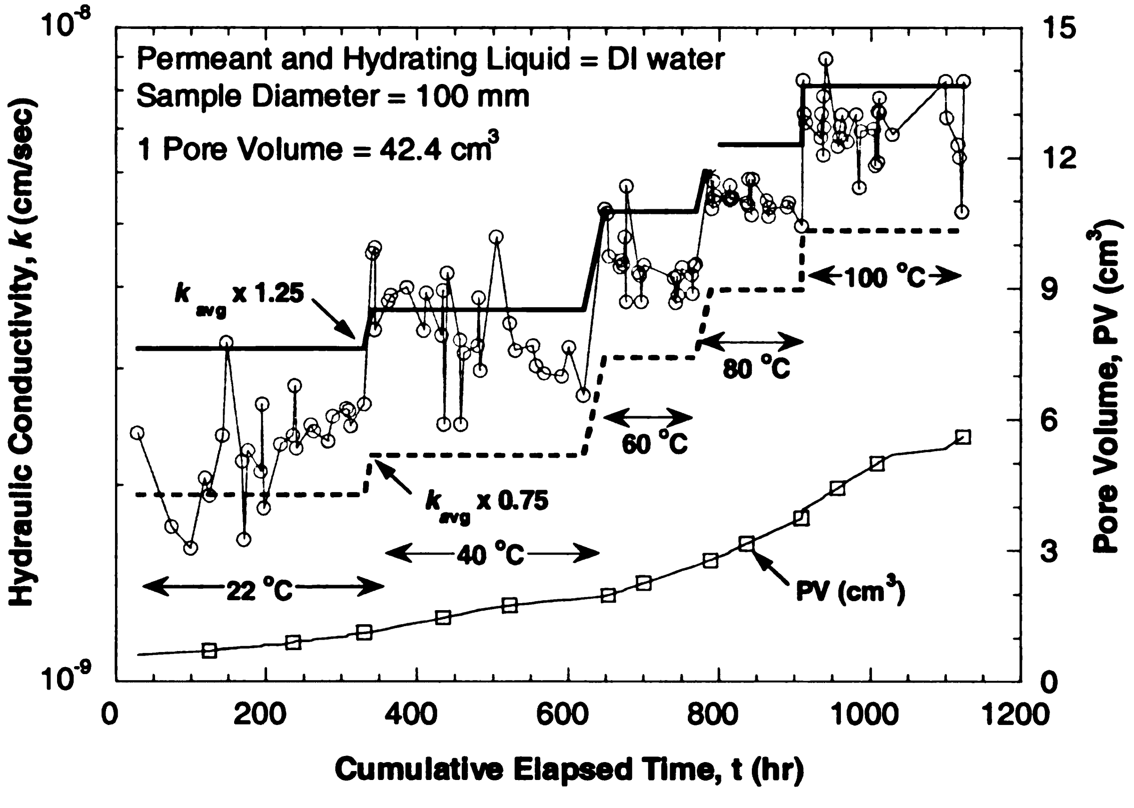

Figure 4-1: Hydraulic Conductivities of GCL for DI water as Permeant

identical in length and cross section, any evaporative or diffusive loss from the tubes cancels out and does not influence the *k* value at steady-state. Note that once the sample has met the termination criteria as per ASTM D 5084 (Method C), we have assumed that the flow has reached steady-state. The PV data plotted in Figure 4-1 and summarized in Table 4-6 indicates that the rate of flow of the permeant gradually increased as the temperature was increased. This is due to the increase in the *k* of the GCL. . Water content of the GCL sample at the end of test was 121%.

4.1.2 Bentonite Extracted from GCL

Hydraulic conductivity of bentonite extracted from the GCL was also measured using DI water as permeant to isolate the effect of needle punched fibers in the GCL and to confirm the increase in *k* values presented in Figure 4-2 due to increase in the permeant temperature. Figure 4-2 presents the *k* of the bentonite for temperatures of DI water increased from 22 to 95 °C followed by a decrease in temperature from 95 to 5 °C and increase in temperature 5 to 22 °C. Figure 4-2 shows a similar increase in hydraulic conductivity of bentonite with increase in the temperature of DI water as seen for the GCL in Figure 4-1. When temperature of the permeant was reduced, the *k* of the bentonite decreased and reached about the same value for the corresponding temperature. It was also observed that for a given temperature, the hydraulic conductivity of the bentonite (Figure 4-2) is slightly less than the GCL (Figure 4-1).

4.1.3 Temperature of Permeant

Figure 4-3 shows the change in the volume of the confining pressure burette recorded for the GCL permeated using DI water at temperatures of the permeant ranging

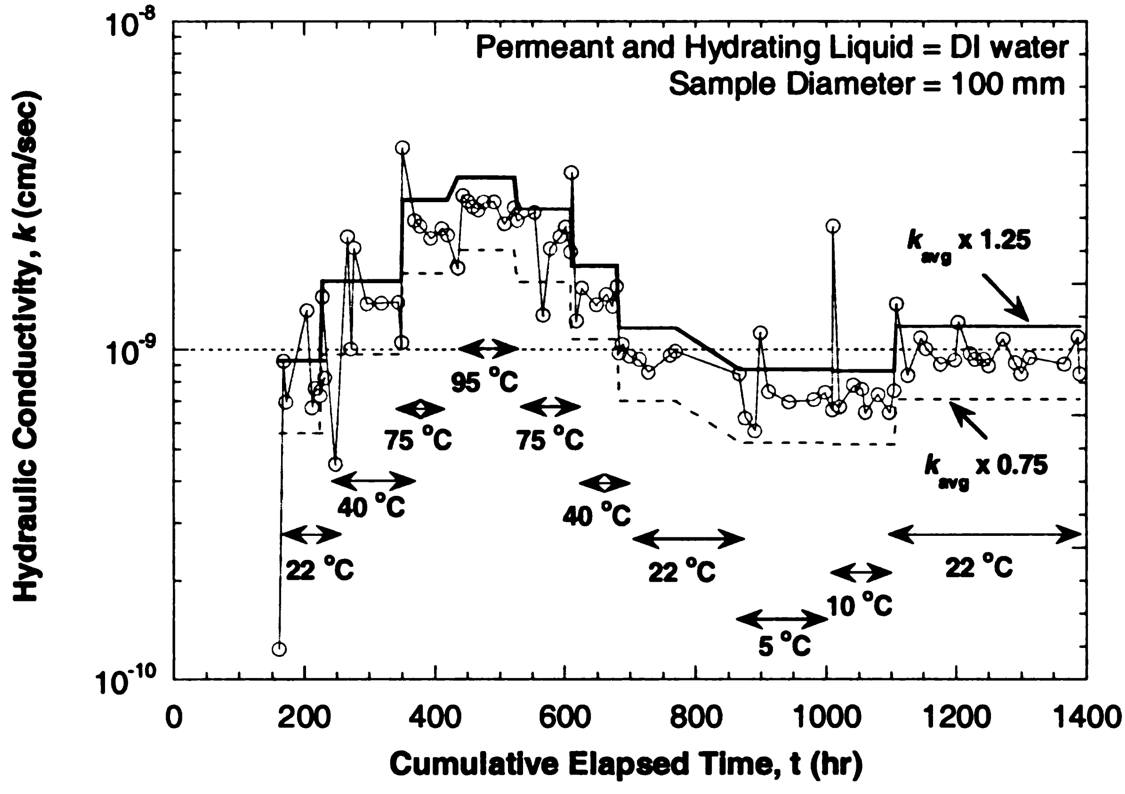

Figure 4-2: Hydraulic Conductivity of Bentonite for DI water as Permeant

from 22 °C to 100 °C. Figure 4-3 shows that as the temperature of the sample chamber is increased, the corresponding burette records increase in the volume as the permeant confined in the confining pressure chamber of the permeameter (Figure 3-4) undergoes expansion. Once the expansion is complete, the burette reading stays about the same. Figure 4-3 also shows that greater the chamber temperature, greater the volume of expansion of the permeant confined in the confining pressure chamber of the permeameter. Figure 4-3 also shows that it took about 240 minutes for the permeant in the confining pressure chamber of the permeameter to reach the temperature maintained outside the permeameter in the temperature chamber.

The minimum length of the influent and effluent tubes presented in Figure 3-4 was designed on the basis of the data presented in Figure 4-3. The length of the influent tube was equal to 1 m to allow a minimum of 240 minutes of residence time for the permeant in the influent tube to reach the temperature of the chamber maintained outside the permeameter before it enters the GCL.

4.2 PERMEATION USING TAP WATER

Because the 100-mm-diamter permeameter was occupied, for measuring *k* of the GCL using tap water as the permeant, a 71-mm-diameter permeameter was used. Tap water was used to hydrate as well as permeate the sample. Because tap water contains dissolved salts, it had a greater electrical conductivity (Table 3-2) compared to DI water.

The geometric mean of hydraulic conductivities of the GCL specimen at 22, 40, 60, and 80 °C measured during the test are summarized in Table 4-2 and plotted in Figure 4-4. Cumulative pore volumes permeated through the sample are also plotted in Figure 4-4.

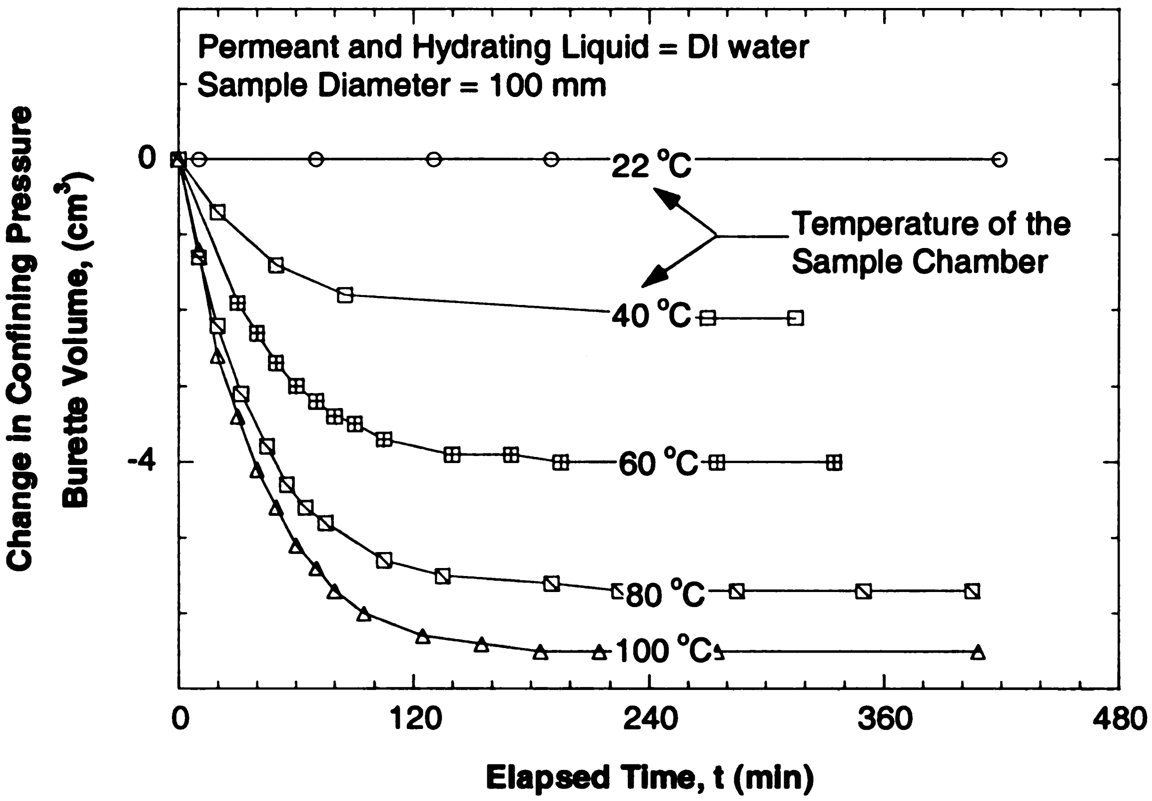

Figure 4-3: Change in Confining Pressure Burette Volume as a function of Temperature of the Sample Chamber

The geometric mean hydraulic conductivities are presented in Table 4-2. During the test at 100 °C, the specimen cell developed a leak. Hence, we were not able to measure the *k* of the GCL for tap water permeant at 100 °C. Figure 4-4 and Table 4-2 show that the *k* value of the GCL increases as the temperature of the permeant increases. The *k* values of the GCL at room temperature and the increases in the *k* values at elevated temperatures for tap water and DI water are about the same (Tables 4-1 and 4-2).

The PV data plotted in Figure 4-4 and summarized in Table 4-2 indicates that the rate of flow of the permeant gradually increased as the temperature was increased. This is due to the increase in the *k* of the GCL. Water content of the GCL sample permeated using tap water at the end of the test was 134%.

4.3 PERMEATION USING $CaCl_2$ SOLUTION

Because a MSW landfill leachate contains salts, Lin et al. (2000) and others have permeated salt solutions through GCLs to evaluate the effect on its *k*. The key findings of these studies have been: (1) appreciable increase in the *k* of the GCL if it is hydrated and permeated with salt solutions having concentration ≥ 0.1 M; and (2) greater the valency of the cations of the salt, the greater the increase in *k*. Hence, in this study, we permeated the GCL using 0.1 M solution of $CaCl_2$ and evaluated the effect at temperatures ranging from the room temperature to 80 °C. The GCL was hydrated using the $CaCl_2$ solution prior to its permeation. In order to maintain the residence time of the permeant in the influent tube at greater than 4 hrs (Figure 4-3) and allow the temperature of the permeant to reach the temperature of the surrounding chamber before it enters the GCL, the length of the influent tube was increased to 100 m. The hydraulic conductivities of the GCL specimen at 22, 40, 60, and 80 °C measured during the test are plotted in Figure 4-5 along

Table 4-2: Geometric Mean Hydraulic Conductivities of GCL for Tap water as Permeant

Temperature of the Permeant T (°C)	**Duration to Reach Termination Criteria t (d)**	**Cumulative Pore Volume PV(cm^3)**	**Geometric Mean Hydraulic Conductivity k_T (cm/s)**	**k_T/ k_{22}**
22	9.5	1.2	2.3E-09 (k_{22})	1.00
40	3.2	1.7	3.0E-09	1.30
60	9.9	3.4	3.4E-09	1.47
80	3.4	4.3	4.6E-09	2.00

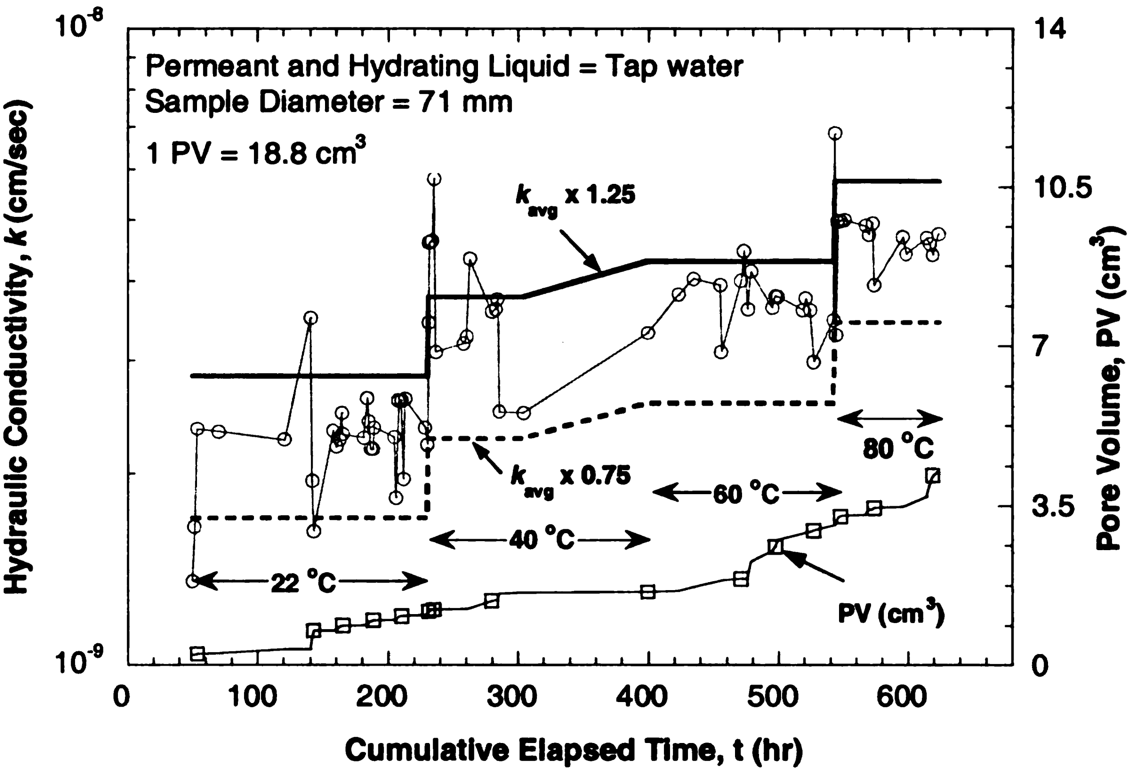

Figure 4-4: Hydraulic Conductivity of GCL for Tap water as Permeant

with cumulative PVs permeated through the sample. Geometric mean hydraulic conductivities are presented in Table 4-3. During the test at 100 °C, the influent tube severely clogged due to $CaCl_2$ precipitation. Hence, we were not able to measure the *k* of the GCL for $CaCl_2$ permeant at 100 °C. Such precipitation was relatively small at temperatures $\leq$ 80 °C.

Data presented in Figure 4-5 and Table 4-3 indicates that the *k* of GCL increased with the temperature of the permeant similar to that for when the GCL was permeated using DI and tap waters (Figures 4-1 and 4-4). However, as found by Lin et al. (2000) and others, the *k* of the GCL at a given temperature of the permeant was about 3 orders of magnitude more than the *k* values when permeated with DI and tap waters. Figure 4-5 shows that initially, at 22 °C, the *k* of the GCL fluctuated greatly. This may have occurred due to the replacement of Na^+ cations from Na-bentonite in the GCL with Ca^{++} from the permeant. Once chemical equilibrium was potentially approached, the fluctuation in the values of *k* decreased (Figure 4-5). The PV data plotted in Figure 4-5 and summarized in Table 4-3 indicates that about 190 PVs of $CaCl_2$ solution were permeated through the sample during the test lasting several days. Because *k* values of the GCL when permeated by $CaCl_2$ solution are about 3 orders of magnitude greater than the *k* values DI and tap water permeation, the PVs for $CaCl_2$ permeation were significantly more. Water content of the GCL sample permeated with $CaCl_2$ solution was 129%.

Table 4-3: Geometric Mean of Hydraulic Conductivities of GCL using $CaCl_2$ Solution as Permeant

Temperature of the Permeant T (°C)	**Duration to Reach Termination Criteria t (d)**	**Cumulative Pore Volume PV cm^3**	**Geometric Mean Hydraulic Conductivity k_T (cm/s)**	**k_T/k_{22}**
22	20	117	9.55E-07 (k_{22})	1.00
40	6.9	145	1.18E-06	1.24
60	7.55	178	1.76E-06	1.84
80	2.0	189	2.49E-06	2.61

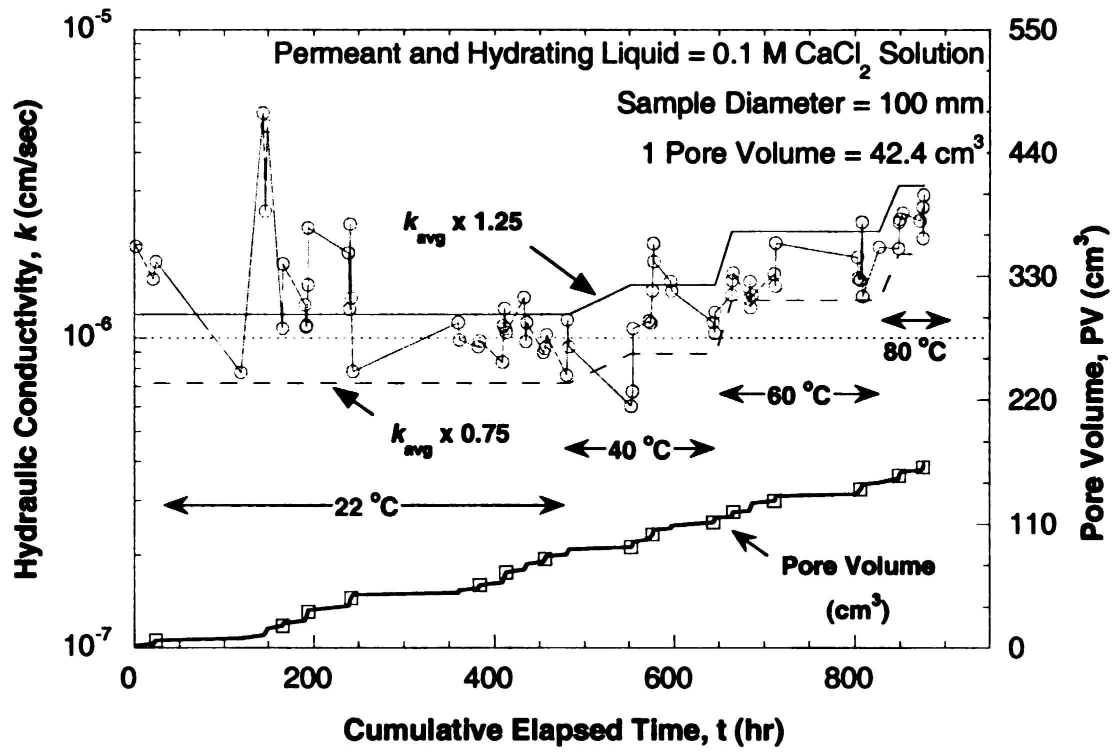

Figure 4-5: Hydraulic Conductivity of GCL for 0.1 M $CaCl_2$ Solution as Permeant

4.4 VISCOSITY CORRECTION

Petrov et al. (1997a) have demonstrated that change in viscosity of the permeant can influence the hydraulic conductivity of clays. Figure 4-6 presents the viscosity of DI water and 0.1 M $CaCl_2$ solution as a function of temperature (Perry 1984; CRC 1992).

Figure 4-6 shows that viscosity of water and the salt solution decreases as its temperature is increased. ASTM D 5084 provides an equation for viscosity correction to convert the *k* measured at a laboratory temperature to 20 °C (Eq. 3-2). In this study, we have applied this correction to all *k* values of the GCLs measured at various temperatures for the three permeants. This correction was applied to normalize the effect of the change in viscosity of the permeant due to the change in its temperature. Intrinsic permeability of GCLs was also evaluated to isolate the effect of change in viscosity and unit weight of the permeant. Intrinsic permeability was calculated using Eq. 4-1:

$$k_T = K\frac{\gamma_T}{\mu_T} \tag{4-1}$$

where,

γ_T = unit weight of the permeant liquid at temperature T;

μ_T = dynamic viscosity of the permeant liquid at temperature T;

k_T = hydraulic conductivity for the permeant liquid at temperature T; and

K = intrinsic permeability of the porous medium.

Table 4-4 and Figure 4-7 present the geometric mean *k* of the GCL measured at various temperatures for DI water as permeant, *k* corrected as per Eq. 3-2 to temperature of permeant at standard temperature of 20 °C (k_{20}), and the intrinsic permeability (*K*) of the GCL calculated using Eq. 4-1.

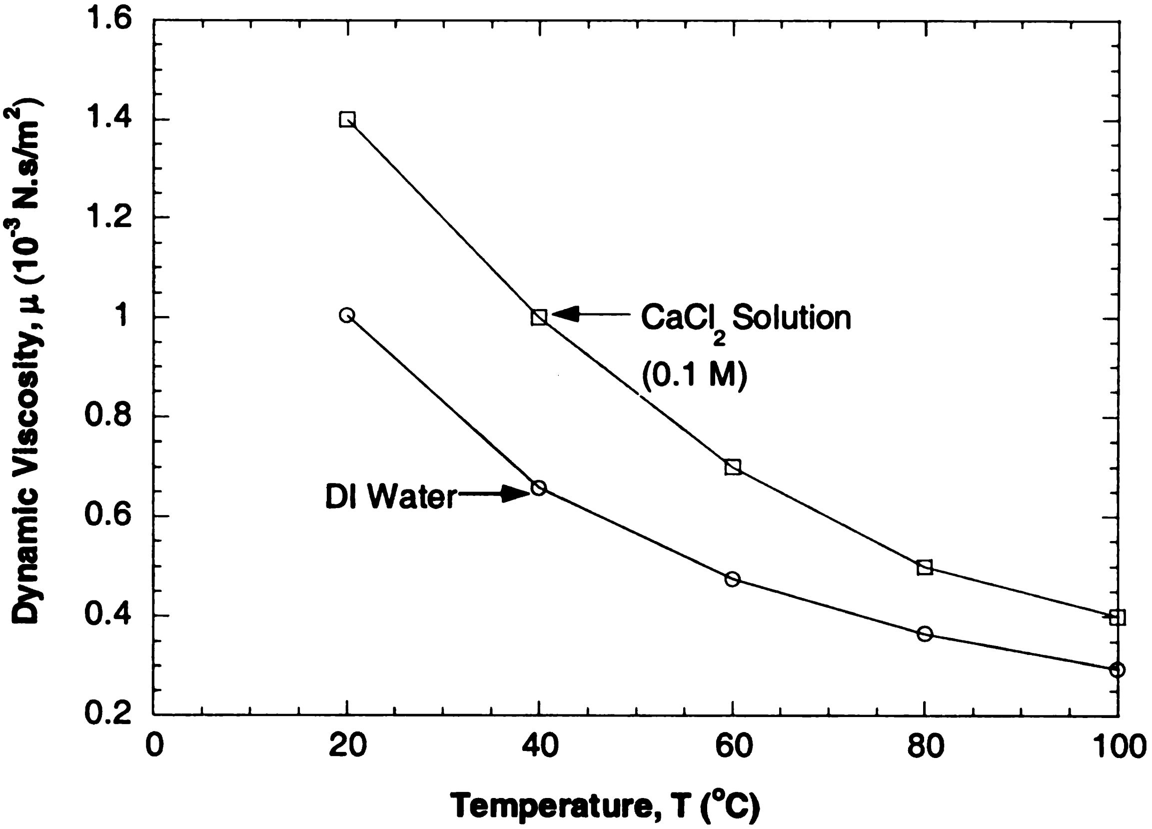

Figure 4-6: Change in Viscosity of Water and 0.1 M $CaCl_2$ Solution as a function of Temperature

An analysis of variance (ANOVA) conducted on the k_{20} and K values presented in Table 4-4 and Figure 4-7 indicates that the corrected values of *k* are equal or drawn from the populations with the same mean. Thus, the increase in *k* observed in response to the increase in the temperature of DI water used as permeant is primarily due to the decrease in the viscosity of the permeant.

A similar viscosity correction was applied to *k* values of the GCL measured for tap water and 0.1 M $CaCl_2$ solution used as permeants. The corrected values of *k* and estimated values of K are presented in: (1) Table 4-5 and plotted in Figure 4-8 for the tap water; and (2) Table 4-6 and plotted in Figure 4-9 for the $CaCl_2$ solution. An ANOVA analysis conducted on the corrected *k* and K values presented in Tables 4-5 and 4-6 also indicated that the data are equal or belong to populations having the same mean. Thus, the increase in *k* observed in response to the increase in the temperature of tap water or 0.1 M $CaCl_2$ solution used as permeants is primarily due to the decrease in the viscosity of the permeants.

It is beyond the scope of this study to quantify the effect of possible change in the double layer thickness or clay structure as suggested by Eq. 2-2 on the *k* values for the temperatures of the permeants tested. However, because corrected values of *k* and estimated K are statistically the same, the increase in *k* observed in response to the increase in the temperature of the permeants was primarily driven by decrease in the viscosity of the permeants

Table 4-4: *k* of GCL Permeated with DI water Corrected for Viscosity

Temperature of the Permeant T (°C)	**Geometric Mean of *k* values k_{avg} (cm/s)**	**Corrected *k* at 20 °C k_{20} (cm/s)**	**Intrinsic Permeability K (cm^2)**
22	2.57E-09	2.47E-09	2.53E-10
40	2.95E-09	1.93E-09	2.00E-10
60	4.17E-09	1.97E-09	2.05E-10
80	5.23E-09	1.90E-09	2.00E-10
100	6.51E-09	1.90E-09	2.03E-10

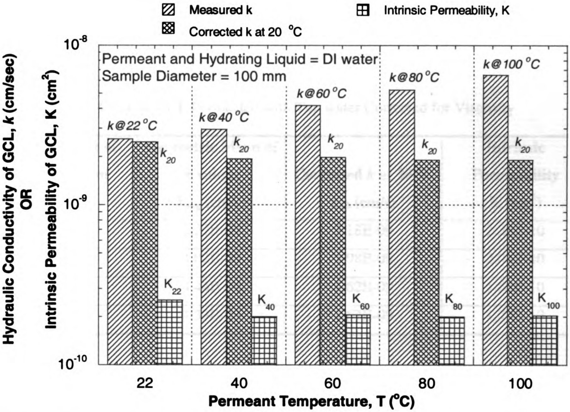

Figure 4-7: Temperature Correction for Standard Temperature due to Change in Viscosity of DI water as Permeant

Table 4-5: *k* of GCL Permeated with Tap water Corrected for Viscosity

Temperature of the Permeant T (°C)	**Geometric Mean of *k* values k_{avg} (cm/s)**	**Corrected *k* at 20 °C k_{20} (cm/s)**	**Intrinsic Permeability K (cm^2)**
22	2.27E-09	2.18E-09	2.23E-10
40	3.02E-09	1.98E-09	2.04E-10
60	3.44E-09	1.62E-09	1.69E-10
80	4.59E-09	1.67E-09	1.75E-10

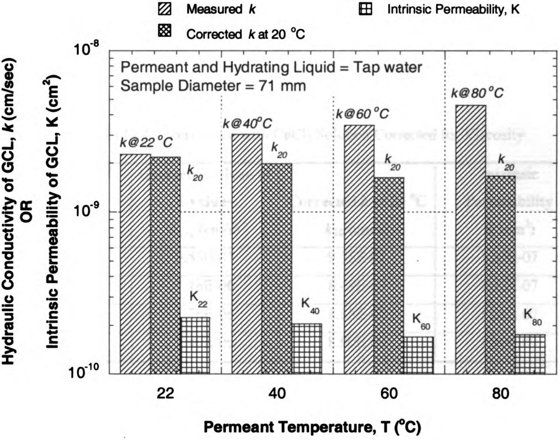

Figure 4-8: Temperature Correction for Standard Temperature due to Change in Viscosity of Tap water as Permeant

Table 4-6: *k* of GCL Permeated with $CaCl_2$ Solution Corrected for Viscosity

Temperature of the Permeant T (°C)	**Geometric Mean of *k* values k_{avg} (cm/s)**	**Corrected *k* at 20 °C k_{20} (cm/s)**	**Intrinsic Permeability K (cm^2)**
22	9.55E-07	9.55E-07	1.36E-07
40	1.18E-06	8.49E-07	1.22E-07
60	1.76E-06	8.83E-07	1.28E-07
80	2.49E-06	8.90E-07	1.30E-07

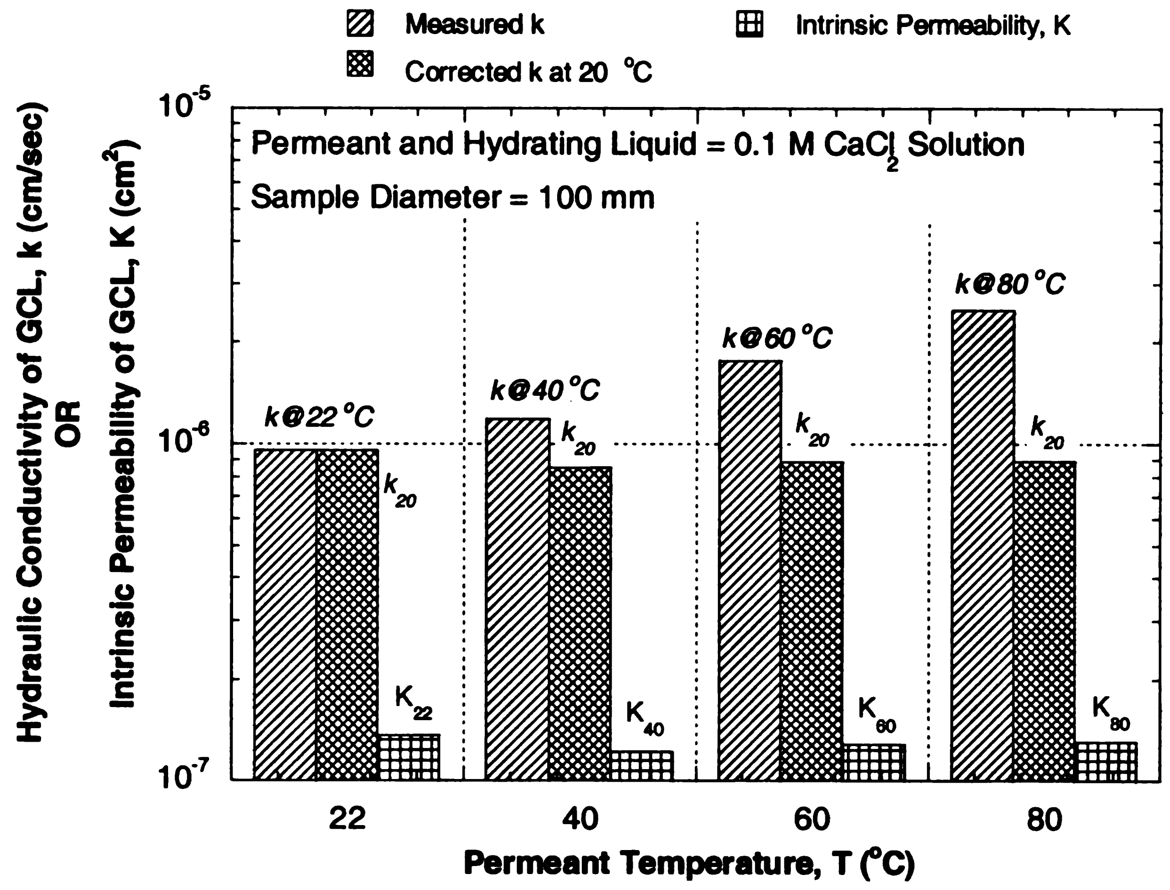

Figure 4-9: Temperature Correction for Standard Temperature due to Change in Viscosity of $CaCl_2$ Solution as Permeant

CHAPTER 5

SUMMARY AND CONCLUSIONS

In this study, the effect of elevated permeant temperature on the hydraulic conductivity of GCLs was evaluated. GCL consisting of untreated sodium bentonite sandwiched between needle-punched non-woven geotextiles was permeated with DI water, tap water, and 0.1 M $CaCl_2$ solution in three separate experiments. During each experiment, the GCL sample was hydrated using the permeating liquid for 48 hours at room temperature followed by permeation to measure hydraulic conductivity at temperatures increased in 20 °C steps starting at the room temperature (~20 to 22 °C) to 100 °C. The ASTM specified termination criteria were met before the temperature was increased during each test cycle. Based on the experimental data, the following conclusions were drawn.

1. Elevated temperature of all permeant liquids (e.g., DI water, tap water and $CaCl_2$ solution) resulted in an increase in the hydraulic conductivity of the GCL;
2. Viscosity correction applied to the hydraulic conductivities measured at various temperatures for the three permeants indicated that corrected *k* at 20 °C is about the same for all temperatures tested for a given permeant. In addition, for all three permeants, there is about three-fold increase in *k* at 80 °C when compared to *k* at 20 °C. Thus, decrease in the viscosity of the permeant when the temperature of the permeant is increase is the primary reason for the increase in the *k* of GCLs at elevated temperatures of permeant; and
3. Structural changes in the clay due to the change in the double layer properties can also influence the *k*. Because, for a given permeant, intrinsic permeabilities

calculated from the *k* values measured at various temperatures were about the same, it can be concluded that increase in permeant temperature does not result in structural changes of the clay or the changes are relatively small and hence do not influence *k*.

4. Hydraulic conductivity of GCLs at an elevated design temperature can be estimated by applying the viscosity correction specified in Eq. 3-2. The correction consists of multiplying the *k* value of the GCL measured at the room temperature by the ratio of the dynamic viscosities of the permeant at the room temperature to that at the elevated design temperature.

The key practical implication of this study is that landfill designers need to take the liner temperature into consideration when designing or investigating liners consisting of GCLs. Relatively simple viscosity correction can be used to estimate the hydraulic conductivity at the design temperature when GCL-specific hydraulic conductivity data for the design temperatures do not exist.

REFERENCES

2001, "Toward a Twenty-first Century Landfill", *Web Site*, *www.yohocounty.org/org/PPW?diwm/bioreactor.htm*.

Adams, M.A. and Hullings, D.E. (2001). "The effect of elevated bioreactor temperatures on the performance of geosynthetics." *Proceedings from the Solid Waste Association of North America, 6th Annual Landfill Symposium*, Hyatt Regency Islandia on Mission Bay, San Diego, California. SWANA: Advancing the Practice of Environmentally and Economically Sound Municipal Solid Waste Management in North America, 33-40.

Alther, G.R., Evans, J.C., Fang, H.Y. and Witmer, K. (1985). "Influence of organic permeants upon the permeability of bentonite." *Hydraulic barriers in soil and rock, ASTM STP 874*, A. I Johnson, N. J. Cavalli, and C. B. Pettersson, eds., ASTM, West Conshohocken, Pa., 64-73.

Anderson, D.C., Crawley, W., and Zabcik, J.D. (1985). "Effects of various liquids on clay soil: bentonite slurry mixtures." *Hydraulic barriers in soil and rock, ASTM STP 874*, A. I Johnson, N. J. Cavalli, and C. B. Pettersson, eds., ASTM, West Conshohocken, Pa., 93-103.

ASTM D 5084, "Standard test method for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter," *Annual Book of ASTM Standards,* Vol 04.09., ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

Boardman, B., and Daniel, D. (1996). "Hydraulic conductivity of desiccated geosynthetic clay liners." *J. Geotech. and Geoenvir. Engrg.,* ASCE, 122(3), 204-208.

Carman, P.C., (1937). Fluid flow through a granular bed: Trans. Inst. Chem. Eng. London, 15, 150–156.

Collins, H. (1993). "Impact of the Temperature inside the landfill on the behavior of barrier systems." *Proceedings of Sardinia '93, 4th International Landfill Symposium.*, S. Marghertita di Pula, Cagliari, Italy. CISA, Environmental Sanitary Engineering Center, Cagliari, 417-432.

CRC Handbook of Chemistry and Physics (1992). 73rd Ed., CRC Press, Inc.

Cullen, D.N., Moore, R.K., and Molz, F.J. (1982). "Permanent effects on elevated temperature on the hydraulic and strength properties of clay confining layers in aquifer storage of thermal energy." *WRRI Bulletin 43*, Water Resources Research Institute, Auburn University, Auburn, Alabama.

Dach, J. and Jager, J. (1995). "Prediction of gas and temperature with the disposal of pretreated residential waste." *Proceedings, Sardinia 1995, Fifth International Waste Management and Landfill Symposium,* Christensen, T.H. et. al., eds., CISA, Italy, Vol. 1., 665-677.

Daniel, D.E. (1991). "Geosynthetic clay liners." *Geotech., News,* 9(4), 28-33.

Daniel, D.E. (1993). "Clay liners." *Geotechnical practice for waste disposal,* D. E. Daniel, ed., Chapman and Hall, Ltd., London, England, 137-163.

Daniel, D.E., and Estornell, P.M. (1991). "Compilation of information on alternative barriers for liner and cover systems." *EPA/600/2-91/002,* U.S. Environmental Protection Agency, Cincinnati, Ohio.

Daniel, D.E., and Boardman, B.T. (1993). "Report of workshop on geosynthetic clay liners." *EPA/600/R-93/171,* U.S. Environmental Protection Agency, Cincinnati, Ohio.

Daniel, D., Bowders, J., and Gilbert, R. (1997). "Laboratory hydraulic conductivity tests for saturated soils." *Hydraulic conductivity and waste containment transport in soil, ASTM STP 1142,* D. Daniel and S. Trautwein, eds., ASTM, West Conshohocken, Pa., 30-78.

Didier, G., Comeaga, L., (1997). "Influence of initial hydration conditions on GCL leachate permeability." In:Well, L.W. (Ed.), Testing and Acceptance Criteria for Geosynthetic Clay Liners, ASTM STP 1308. ASTM, West Conshohocken, PA, 181-195.

Egloffstein, T. (1995). "Properties and test methods to assess bentonite used in geosynthetic clay liners." *Geosynthetic clay liners,* Balkema, Rotterdam, The Netherlands, 51-72.

Egloffstein, T., (1997). "Geosynthetic Clay Liners, Part Six: Ion Exchange." *Geotechnical Fabrics Report,* 15(5), 38-43.

Egloffstein, T. (2001). "Natural bentonites – influence of the ion exchange and partial desiccation on permeability and self-healing capacity of bentonites used in GCLs." *Geotextiles and Geomembranes,* 19, 427-444.

Erickson, A.E., Chamberlain, E.J., and Benson, C.H. (1994). "Effects of frost action on covers and liners constructed in cold environments." *Proc., 17th Madison Waste Conf.,* University of Wisconsin, Madison, Wis., 198-220.

Ganti, S. (2004) "Hydraulic conductivity and leachability of compacted bentonite amended fly ash mixtures." M.S. Project, MSU, East Lansing, MI.

Gartung, E. (1999). "Performance of compacted clay liners at the base of municipal landfills: the Bavarian experience." *Proceedings, Sardinia 1999, Seventh International Waste Management and Landfill Symposium,* Christensen, T.H. et. al., eds., CISA, Italy, Vol 3, 31-38.

Gleason, M.H. (1993). "Comparative testing of calcium and sodium smectite clays for geotechnical and environmental applications." MSc Thesis, Univ. of Texas at Austin, Austin, Tex.

Gleason, M., Daniel, D.E., and Eykholt, G.R. (1997). "Calcium and sodium bentonite for hydraulic containment applications." *J. Geotech. and Geoeniv. Engrg.,* ASCE, 123(5), 438-445.

Gouy, G. (1910). "Sur la constitution de la charge electrique a la surface d'un electrolyte." *Anniue Physique (Paris),* Serie 4, Vol. 9, 457-468.

Hanson, J.L., Yesiller, N., and Swarbrick, G.E., (2005). "Thermal analysis of GCLs at a Municipal Solid Waste landfill." *GSP 142 Waste Containment and Remediation,* 1-15.

Hater, G.R., Hamblin, G., Lane, D.T. (2000). "Full-Scale demonstration of a sequential aerobic-anaerobic landfill bioreactor." *Proceedings, Waste Tech 2000,* Orlando, Florida, Bioreactor Landfill II.

Hewitt, R.D. and Daniel, D.E. (1997). "Hydraulic conductivity of geosynthetic clay liners after freeze-thaw." *J. of Geotech. and Geoenvir. Engrg.*, ASCE, 123(4), 305-313.

Jo, H., Katsumi, T., Benson, C. and Edil, T., (2001). "Hydraulic conductivity and swelling of non-prehydrated GCLs with single-species salt solutions." *J.of Geotech. and Geoenvir. Engrg.*, 127, 557-567.

Keren, R., and Singer, M.J. (1988). "Effect of low electrolyte concentration on hydraulic conductivity of sodium/calcium-montmorillonite-sand system." *Soil Sci. Soc. of Am. J.*, 368-373.

Kjellander, R., Marcelja, S. and Quirk, J. (1988). "Attractive double-layer interactions between calcium clay particles." *J. of Colloid and Interface Science*, 126, 194-211.

Knowlton, A.E., (1941). Standard Handbook for Electrical Engineers, Seventh Edition, McGraw-Hill Book Company, NY.

Koerner, R.M. (1994). *Designing with geosynthetics*, 3rd Ed., Prentice Hall, Inc., Englewood Cliffs, N.J.

Koerner, G. (2001). "In situ temperature monitoring of geosynthetics used in a landfill." *Geotechnical Fabrics Report*, Vol. 19, No. 4, 12-13.

Kolstad, D., Benson, C., and Edil, T. (2004). "Hydraulic conductivity and swell of nonprehydrated GCLs permeated with multispecies inorganic solutions." *J. Geotech. Geoenviron. Engrg.*, 130(12), 1236-1249.

Kozeny, J., (1927). Uber kapillare Leitung des Wassers im Boden: Sitzungsber. Akad. Wiss. Wien, 136, 271–306.

Kraus, J., Benson, C., Erickson, A., and Chamberlain, E. (1997). "Freeze-thaw cycling and hydraulic conductivity of bentonite barriers." *J. Geotech. and Geoenvir. Engrg.*, ASCE, 123(3), 229-238.

Laguros, J.G. (1969). "Effects on temperature on some engineering properties of clay soils." In: Mitchell, J.K (Ed.), Proceedings of the International Conference in Effect of Temperature and Heat on Engineering Behavior of Soil, Special Report No. 103, Highway Research Board, Washington DC, 186-193.

Lee, J., Shackelford, C.D., Benson, C.H., Jo, H., Edil T.B. (2005). "Correlating index properties and hydraulic conductivity of geosynthetic clay liners." *In Press.*

Lin, L. (1998). "Effect of wet-dry cycling on swelling and hydraulic conductivity of geosynthetic clay liners." MS Thesis, University of Wisconsin-Madison.

Lin, Ling-Chu and Benson, C.H., (2000). "Effect of Wet-Dry cycling on swelling and hydraulic conductivity of GCLs." *J. of Geotech. and Geoenvir. Engrg.*, ASCE, 126(1), 40-49.

McBride, M. (1994). *Environmental chemistry of soils*, Oxford University Press, New York.

McBride, M. (1997). "A critique of diffuse double layer models applied to colloid and surface chemistry." *Clays and Clay Minerals*, 45, 598-608.

McNeal, B. and Coleman, N., (1966). "Effect of solution composition on soil hydraulic conductivity." *Soil Science Soc. of America Proceedings*, 30, 308-312.

Mehta, R., Barlaz, M.A., Yazdani, R., Augenstein, D., Bryars, M. and Sinderson, L. (2002). "Refuse decomposition in the presence and absence of leachate recirculation." *J. of Environ. Engrg.*, ASCE, 128(3), 228-236.

Mesri, G. and Olson, R., (1971). "Mechanisms controlling the permeability of clays." *Clays and Clay Minerals*, 19, 151-158.

Mitchell, J.K. (1993). *Fundamentals of soil behavior*, 2nd Ed., John Wiley & Sons, Inc., Wiley Interscience, New York, USA.

Norrish, K. and Quirk, J. (1954). "Crystalline swelling of montmorillonite, use of electrolytes to control swelling." *Nature*, 173, 255-257.

Onikata, M., Kondo, M., Hayashi, N., and Yamanaka, S. (1999). "Complex formation of cation-exchanged montmorillonites with propylene carbonate: Osmotic swelling in aqueous electrolyte solutions." *Clays and Clay Minerals*, London, 47(5), 672-677.

Othman, M.A., and Benson, C.H. (1992). "Effect of freeze-thaw on the hydraulic conductivity of three compacted clays from Wisconsin." *Transp. Res. Rec. 1369*, Transp. Res. Board, Washington, D. C., 118-125.

Othman, M.A., Benson, C.H., Chamberlain, E.J., and Zimmie, T.F. (1994). "Laboratory testing to evaluate changes in hydraulic conductivity of compacted clays caused by freeze-thaw: State-of-the-art." *Hydraulic conductivity and waste containment transport in soils, ASTM STP 1142*, D. E. Daniel and S. J. Trautwein, eds., American Society for Testing and Materials, Philadelphia, Pa., 227-254.

Perry's Chemical Engineers' Handbook (1984). 6th Ed., McGraw-Hill Book Company, 12-43-12-44.

Petrov, R.J., Rowe, R.K., Quigley, R.M. (1997). "Selected factors influencing GCL hydraulic conductivity." *J. of Geotech. and Geoenvir. Engrg.*, ASCE, Reston, VA, 123(8), 683-695.

Petrov, R., and Rowe, R. (1997). "Geosynthetic clay liner (GCL) - Chemical compatibility by hydraulic conductivity testing and factors impacting its performance." *Can. Geotech. J.*, 34, 863-885.

Prost, R., Koutit, T., Benchara, A. and Huard, E. (1998). "State and location of water adsorbed on clay minerals: consequences of the hydration and swelling-shrinkage phenomena." *Clays and Clay Minerals*, 46, 117-131.

Quigley, R.M., Yanfil, E.K. and Fernandez F. (1987). "Ion transfer by diffusion through clayey barriers." In: R.D. Woods (ed.), *Geotechnical Practice for Waste Disposal 87*, ASCE.

Quirk, J., and Marcelja, S. (1997). "Application of double-layer theories to the extensive crystalline swelling of Li-montmorillonite." *Langmuir*, 13, 6241-6248.

Rowe, R.K. (1987). "Pollutant transport through barriers." In:R. D. Woods (ed.), *Geotechnical Practice for Waste Disposal '87*. ASCE, 159-181.

Rowe, R.K. (1998). "Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste." Proceedings, *Sixth International Conference on Geosynthetics*, Rowe, R. K., ed., 25-29 March 1998, Atlanta, Georgia, 27-102.

Ruhl, J.L., and Daniel, D.E. (1997). "Geosynthetic clay liners permeated with chemical solutions and leachates." *J. Geotech. and Geoenvir. Engrg.*, ASCE, 123(4), 369-381.

Schroeder, C., Monjoie, A., Illing, P., Dosquest, D. & Thorez, J. (2001). "Testing a factory-prehydrated GCL under several conditions." *Proceedings, Sardinia 2001, 8th International Waste Management and Landfill Symposium*, CISA Environmental Sanitary Engineering Centre, Cagliari, Italy, 187-196.

Shackelford, C.D. (1989). "Diffusion of contaminants through waste containment barriers.' *Transport Res. Record*, 1219, 169-182.

Shackelford, C. (1994). "Waste-Soil Interactions That Alter Hydraulic Conductivity," *Hydraulic Conductivity and Waste Contaminant Transport in Soil*, STP 1142, ASTM, Daniel, D. and Trautwein, S., eds., 111-168.

Shackelford, C.D., Benson, C.H., Katsumi, T., Edil, T.B., and Lin, L. (2000). "Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids." *Geotextiles and Geomembranes*, Essex, England, 18(2-4), 133-162.

Shan, H., and Daniel, D. (1991). "Results of laboratory tests on a geotextile/bentonite liner material." *Proc. Geosynthetics '91,* Industrial Fabrics Association International, St. Paul, Minn., 517-535.

Shang, J., Lo, K., and Quigley, R.M. (1994). "Quantitative determination of potential distribution in Stern-Guoy double-layer model." *Can. Geotech. J.*, Ottawa, 31, 624-636.

Stern, R.T., and Shackelford, C.D. (1998). "Permeation of sand-processed clay mixtures with calcium chloride solutions." *J. Geotech. and Geoenvir. Engrg.*, ASCE, 124(3), 231-241.

Van Olphen, H. (1991). *An Introduction to Clay Colloid Chemistry*, 2nd Ed., Krieger Publishing Co., Malabar, Florida, USA.

Wang X. and Benson, C.H. (1999). "Hydraulic conductivity testing of geosynthetic clay liners (GCLs) using the constant volume method." *Geotech. Testing Journal*, GTJODJ, Vol. 22, No. 4, 227-283.

Yoshida, H. and Rowe, R.K. (2003). "Consideration of landfill liner temperature." *Proceedings, Sardinia 2003, Ninth International. Waste Management and Landfill Symposium,* Christensen, T.H. et. al., eds., CISA, Italy.

Zhang, F., Low, P., and Roth, C. (1995). "Effects of monovalent exchangeable cations and electrolytes on the relation between swelling pressure and interlayer distance in montmorillonite." *J. Colloid and Interface Sci.*, Academic Press, New York, 173, 34-41.