2010

Chemical compatibility of soil-bentonite cutoff wall backfills containing modified bentonites

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CHEMICAL COMPATIBILITY OF SOIL-BENTONITE CUTOFF WALL BACKFILLS CONTAINING MODIFIED BENTONITES

by

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A Thesis

Presented to the Faculty of
Bucknell University
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Civil Engineering

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November 2010
(Date: month and Year)

ACKNOWLEDGEMENTS

There are many people who assisted in this study in one capacity or another. First of all, I would like to thank my primary advisor, Dr. Michael Malusis, for his knowledgeable input and helpful feedback throughout every stage of my research and writing. Thanks must also be given to Dr. Jeffrey Evans and Dr. Carl Kirby, the other members of my thesis advisory committee, who provided useful input at various points along the way. Huan Luong also deserves thanks for his friendly assistance in portions of the research that required work in the Bucknell environmental engineering lab. Jim Gutelius was also a great assistance in keeping equipment running efficiently.

I would like to also thank several graduate and undergraduate students at Bucknell who provided necessary data or helped in the collection of data for my tests – E.J. Barben and SeungCheol Yeom to name a few. Richard LaFredo completed many of the initial tests in this project and deserves many thanks for his assistance. The McKenna foundation provided financial support for part of the project. Central Builders Supply (Lewisburg, PA) and others provided materials for this study. The assistance of other unnamed individuals and companies is greatly appreciated.

I would especially like to thank my parents, Sam and Cindy, for their loving support and encouragement throughout the years. Thanks for the good foundation you gave me to start out on. And of course, I owe much thanks to my beautiful wife, Gina, who showed such kindness and assistance as this study neared its completion. I love you.

Most of all, thanks be to my heavenly Father who sought me out and, though I had nothing to offer, was pleased to give me the kingdom.

TABLE OF CONTENTS

List of Tables v
List of Figures vi
Abstract viii

Chapter 1: Study Background
- **1.1 Introduction** 1.1
- **1.2 Bentonite Clay** 1.2
- **1.3 Exchangeable Cations** 1.4
- **1.4 Cation Exchange Impacts on the DDL** 1.5
- 1.4.1 Valence 1.5
- 1.4.2 Concentration 1.6
- 1.4.3 Relation to Gouy-Chapman Theory 1.7
- **1.5 Crystalline and Osmotic Swelling** 1.7
- **1.6 First Exposure** 1.9
- **1.7 Permeant Liquids** 1.12
- **1.8 Overview of Previous Studies** 1.13
- **1.9 Overview of This Study** 1.18
- **1.10 References** 1.18

Chapter 2: Creation of Acceptable Bentonite-Water Slurries and Soil-Bentonite Backfill Mixtures
- **2.1 Introduction** 2.1
- **2.2 Materials and Methods** 2.3
- 2.2.1 Materials 2.3
- 2.2.2 Slurry Preparation and Testing 2.4
- 2.2.3 Model SB Backfill Preparation and Testing 2.5
- **2.3 Results** 2.6
- 2.3.1 Bentonite-Water Slurry 2.6
- 2.3.2 Backfill Hydraulic Conductivity 2.7
- **2.4 Conclusion** 2.8
- **2.5 References** 2.9

Chapter 3: Compatibility Testing of Model SB Backfills
- **3.1 Introduction** 3.1
- 3.1.1 Significance of Soil-Bentonite Cutoff Walls 3.1
- 3.1.2 Compatibility in SB Cutoff Walls 3.2
- 3.1.3 Modified Bentonites 3.5
- 3.1.4 Objective of Study 3.5
- **3.2 Materials and Methods** 3.7
- 3.2.1 Solid Materials 3.7
- 3.2.2 Permeant Liquids 3.8

3.2.3 Index Testing of Bentonites 3.9
3.2.4 Backfill Preparation 3.10
3.2.5 Hydraulic Conductivity Testing 3.11
3.3 Results and Discussion 3.15
3.3.1 Bentonite Index Tests 3.15
3.3.2 Backfill Hydraulic Conductivity 3.17
3.3.2.1 Hydraulic Conductivity to Water 3.17
3.3.2.2 Hydraulic Conductivity to $CaCl_2$ Solutions 3.18
3.3.2.3 Influence of Bentonite 3.21
3.3.2.4 First Exposure Effects 3.26
3.3.2.5 Effect of Termination Criteria 3.29
3.4 Conclusions 3.30
3.5 References 3.32

Chapter 4: Conclusions and Recommendations
4.1 Contribution of this Study 4.1
4.2 Creation of Model SB Backfills 4.2
4.3 Evaluation of Changes in Hydraulic Conductivity 4.3
4.4 Comparison of Modified and Conventional Bentonites 4.4
4.5 Additional Conclusions and Recommendations 4.5

Appendices

Appendix A Index Test Results
Appendix B Recipes for Bentonite-Water Slurries and Soil-Bentonite Backfills
Appendix C Hydraulic Conductivity Test Results

LIST OF TABLES

Chapter 2

2.1 Properties and mineralogy of bentonites tested in study 2.12
2.2 Summary of data from hydraulic conductivity tests 2.13

Chapter 3

3.1 Properties and mineralogy of bentonites tested in study 3.41
3.2 Properties of permeant liquids used in study 3.42
3.3 Relevant properties of model soil-bentonite backfill mixtures 3.43
3.4 Results of flexible-wall hydraulic conductivity tests on consolidated SB backfill specimens (σ' = 34.5 kPa) 3.44
3.5 Pore volumes of flow (PVF) and hydraulic conductivites to $CaCl_2$ solution (k_c) corresponding to achievement of termination criteria based on ASTM D 5084 (k_{5084}), ratio of effluent to influent EC (k_{EC}), and ratio of effluent to influent Ca^{2+} concentration (k_{Ca}) in one-stage and two-stage tests. Final values of PVF and k_c (i.e., k_{fc}) are shown for comparison 3.45

LIST OF FIGURES

Chapter 2

2.1 Properties of bentonite-water slurries as a function of bentonite content: (a) Marsh viscosity; (b) density; (c) filtrate loss; and (d) *pH* 2.14
2.2 Influence of lignosulfate thinner on (a) Marsh viscosity and (b) *pH* of slurries containing 4 wt % and 5 wt % SW101 .... 2.15
2.3 Final values of hydraulic conductivity to water, k_{fw}, for model SB backfill specimens as a function of bentonite content 2.16
2.4 Hydraulic conductivity to a 50 mM $CaCl_2$ solution, k_c, versus pore volumes of flow for selected backfill specimens 2.17

Chapter 3

3.1 Swelling mechanism of MSB 3.46
3.2 Grain size distribution of sand and three bentonites used in study 3.47
3.3 Schematic of testing apparatus used 3.48
3.4 (a) Swell index and (b) liquid limit of tested clays as a function of $CaCl_2$ concentration 3.49
3.5 (a-e) Hydraulic conductivity as a function of pore volumes of flow (tap water permeant) for backfill specimens amended with 3 % or 4 % dry bentonite (total bentonite contents = 4.5-5.7 % by dry weight); (f) comparison of final values of hydraulic conductivity to tap water as a function of bentonite content 3.50
3.6 Hydraulic conductivity as a function of pore volumes of flow (tap water and $CaCl_2$ permeant) for backfill specimens containing 5.7 % NG. (Closed symbols = tap water, open symbols = $CaCl_2$ solution) 3.51
3.7 Hydraulic conductivity as a function of pore volumes of flow (tap water and $CaCl_2$ permeant) for backfill specimens containing 5.6 % MSB. (Closed circles = tap water, open circles = $CaCl_2$ solution) 3.52
3.8 Hydraulic conductivity as a function of pore volumes of flow (tap water and $CaCl_2$ permeant) for backfill specimens containing 4.6 % SW101. (Closed circles = tap water, open circles = $CaCl_2$ solution) 3.53
3.9 Summary of two-stage tests: (a) Final hydraulic conductivity of backfill specimens to $CaCl_2$ (k_{fc}), (b) ratio of k_{fc} to hydraulic conductivity to tap water (k_{fw}) at termination, and (c) ratio of final intrinsic permeability to $CaCl_2$ (K_{fc}) to final intrinsic permeability to tap water (K_{fw}) as a function of $CaCl_2$ concentration for backfill specimens 3.54
3.10 Hydraulic conductivity as a function of pore volumes of flow of $CaCl_2$ for one-stage backfill specimens containing 5.7 % NG 3.55
3.11 Hydraulic conductivity as a function of pore volumes of flow of $CaCl_2$ for one-stage backfill specimens containing 5.6 % MSB 3.56
3.12 Hydraulic conductivity as a function of pore volumes of flow of $CaCl_2$ for one-stage backfill specimens containing 4.6 % SW101 .... 3.57

3.13 Summary of one-stage tests: (a) Hydraulic conductivity of backfill specimens to $CaCl_2$ (k_{fc}), (b) ratio of k_{fc} to k_{fw} and (c) ratio of K_{fc} to K_{fw} as a function of $CaCl_2$ concentration....3.58
3.14 Summary of hydraulic conductivity testing: (a) k_{fc}, (b) k_{fc}/k_{fw} ratio, and (c) K_{fc}/K_{fw} ratio as a function of $CaCl_2$ concentration (open symbols = one-stage, closed symbols = two-stage)....3.59
3.15 Influence of bentonite content on intrinsic permeability ratio, K_{fc}/K_{fw}, for a 0.5 M $CaCl_2$ solution based on the results of the two-stage tests of this study, two granular bentonite GCL studies (GCL1: Lee and Shackelford 2005a; GCL2: Shackelford et al. 2000), and a compacted sand-attapulgite-bentonite (S-A-B) mixture containing 10 % attapulgite (A) and 10 % bentonite (B) (Stern and Shackelford 1998)....3.60
3.16 Comparison of K_{fc}/K_{fw} values from this study (two-stage tests) with those for granular bentonite GCLs (GCL1: Lee and Shackelford 2005a; GCL2: Shackelford et al. 2000) and a compacted sand-attapulgite-bentonite (S-A-B) mixture containing 10 % attapulgite (A) and 10 % bentonite (B) (Stern and Shackelford 1998) as a function of $CaCl_2$ concentration....3.61
3.17 FER for SB backfills as a function of $CaCl_2$ concentration....3.62
3.18 Comparison of first exposure ratio (FER) values for SB backfills in this study (5.7 % NG, 5.6 % MSB, and 4.6 % SW101) with those obtained for granular bentonite GCLs (data for GCL1 from Lee and Shackelford 2005a; data for GCL2 from Shackelford et al. 2000) and a compacted sand-attapulgite-bentonite (S-A-B) mixture containing 10 % attapulgite (A) and 10 % bentonite (B) (data from Stern and Shackelford 1998) as a function of $CaCl_2$ concentration....3.63
3.19 Pore volumes of flow of $CaCl_2$ solution for two-stage tests as a function of $CaCl_2$ molar concentration at various termination criteria....3.64
3.20 Comparison of final hydraulic conductivity (k_{fc}) of two-stage tests relative to hydraulic conductivities corresponding to achievement of the following termination criteria: (a) ASTM D 5084 (k_{5084}), (b) EC ratio (k_{EC}), (c) Ca^{2+} concentration (k_{Ca})....3.65
3.21 Pore volumes of flow of $CaCl_2$ solution for one-stage tests as a function of $CaCl_2$ molar concentration at various termination criteria....3.66
3.22 Comparison of final hydraulic conductivity (k_{fc}) of one-stage tests relative to hydraulic conductivities corresponding to achievement of the following termination criteria: (a) ASTM D 5084 (k_{5084}), (b) EC ratio (k_{EC}), (c) Ca^{2+} concentration (k_{Ca})....3.67

ABSTRACT

This study examined the chemical compatibility of several model soil-bentonite (SB) backfills with an inorganic salt solution ($CaCl_2$). First, bentonite-water slurry was created using a natural sodium-bentonite, as well as two modified bentonites – multiswellable bentonite (MSB) and a "salt-resistant" bentonite (SW101). Once slurries that met typical construction specifications had been created using the various bentonites, the model SB backfills were prepared for each type of bentonite. These backfills were also designed to meet conventional construction and design requirements. The SB backfills were then subjected to permeation with tap water and/or $CaCl_2$ solutions of various concentrations in order to evaluate the compatibility of the SB backfills with inorganic chemicals. The results indicate that SB backfill experiences only minor compatibility issues (i.e., no large differences between the hydraulic conductivity of the SB backfill to tap water and $CaCl_2$) compared to many other types of clay barriers. In addition, SB backfills show no major change in final hydraulic conductivity to $CaCl_2$ when permeated with tap water before $CaCl_2$ versus being permeated with $CaCl_2$ directly. These results may be due to the ability of the bentonite in the SB backfills to undergo osmotic swelling before permeation begins, and the inability of the $CaCl_2$ solutions to undo the osmotic swelling. Similar results were obtained for all three clays tested, and while MSB did show less compatibility issues than the natural bentonite and SW101, it appears that the differences in performance may generally be negligible. Overall, this study makes a significant addition to the understanding of SB cutoff wall compatibility.

CHAPTER 1

STUDY BACKGROUND

1.1 INTRODUCTION

Vertical barriers (cutoff walls) are often used to limit the flow of water (i.e., hydraulic containment) and migration of miscible contaminant plumes (i.e., geoenvironmental containment), and soil-bentonite (SB) slurry trench cutoff walls are commonly employed in the U.S. for these applications. Construction of SB cutoff walls generally involves two phases. First, a vertical trench is excavated and filled with bentonite-water slurry (typically ~5 % bentonite by weight) to maintain the stability of the trench walls. Next, the excavated soil and/or more suitable soil is mixed with slurry and dry bentonite (if needed) to create a homogeneous backfill mixture with appropriate consistency (slump), and the backfill is placed into the excavated trench to create a low permeability barrier in the subsurface (D'Appolonia and Ryan 1979; Evans 1993).

The containment performance of an SB cutoff wall depends largely on the *compatibility* of the backfill with the site groundwater, i.e., the ability of the backfill to maintain a low hydraulic conductivity (k) despite interactions between the backfill and chemical constituents in the groundwater that tend to cause an increase in k. Research has shown that various factors can negatively influence the swelling capacity and k of bentonite, including the chemical properties of permeant liquids (Alther et al. 1985; Shackelford 1994; Ruhl and Daniel 1997; Shackelford et al. 2000; Vasko et al. 2001; Jo et al. 2005; Lee and Shackelford 2005; Mitchell and Soga 2005; Shackelford 2007; Katsumi et al. 2008). Thus, incompatibility between the bentonite and the groundwater is a significant concern for SB cutoff walls in which the *k* of the backfill is governed primarily by the bentonite fraction (Evans et al. 1985). In such cases, a primary design objective is to ensure that the backfill will maintain an acceptably low *k* (i.e., typically $k \leq 10^{-9}$ m/s) upon interaction with the site groundwater.

1.2 BENTONITE CLAY

The active clay mineral in bentonite products typically used in SB cutoff walls is montmorillonite, a highly plastic and swellable smectite clay that originates largely from the weathering of igneous rocks and volcanic ash in a dry environment (Mitchell and Soga 2005). The high swelling capacity of montmorillonite is what makes bentonite such a useful component of SB cutoff walls, and plays an important role in maintaining the low *k* of the backfill. As the bentonite hydrates, the montmorillonite particles swell and close the voids between particles of more coarse material in the backfill (e.g., sand), minimizing flow through the cutoff wall. The distribution of bentonite within the voids between coarse particles is critical for establishing a low *k* (e.g. Kenney et al. 1992).

Much of the swelling behavior of bentonite is due to the adsorbed layers, or diffuse double layers (DDLs), of hydrated cations and oriented water molecules surrounding the charged surfaces of the clay platelets. When the cations in the DDLs hydrate, they overcome the van der Waals forces holding the clay platelets together, leading to expansion of the interlayer space between adjacent clay platelets (i.e., osmotic swelling) and visible swelling on the macroscopic level (van Olphen 1963; Mitchell and Soga 2005). Because the DDL exists even between the clay platelets, bentonite is able to expand its volume considerably as it hydrates (Norrish and Quirk 1954; van Olphen 1963).

As the DDL surrounding each clay platelet becomes smaller, the void spaces available for flow between the sand and the clay particles increase. Also, a stronger pull from cations between the clay platelets may pull the platelets closer together, limiting expansion of the clay (Norrish 1954). In this case, the clay is unable to fully close the larger voids, leading to a higher *k* of the backfill. The thickness of the DDLs, and thus the extent of swell exhibited by the bentonite, is affected by many factors. The factors of particular interest in this study are the valence of cations in the DDL, concentration of cations, and the first liquid to initiate hydration and swelling of the clay (Shackelford et al. 2000).

A change in the arrangement of the clay particles may also have an effect on the hydraulic conductivity of the backfill. The clay platelets may be arranged in many different configurations, two of which are discussed here. Flocculated platelets are clay platelets that are attracted together and contact either face-to-face or edge-to-face. Dispersed platelets are when clay particles are arranged in a parallel orientation (Mitchell and Soga 2005). A dispersed structure contains smaller pores and flow paths, thereby yielding a lower *k*. The effects of high cation valence and concentration can not only decrease the DDL thickness but can also cause flocculation of the clay platelets, leading to an increase in *k* due to the structural change (Frenkel et al. 1978; Spooner et al. 1985; Mitchell and Madsen 1987).

1.3 EXCHANGEABLE CATIONS

The charged surface of the clay particles that attracts cations and assists in forming the DDL is due to isomorphous substitution of some of the ions in the crystalline structure of the clay with ions of lesser charge. This process results in a net negative charge of the clay platelets, which in turn attracts positively charged cations, some of which are exchangeable. Bentonite typically exhibits a high (80-150 meq/100 g) cation exchange capacity (CEC) due to extensive isomorphous substitution in the montmorillonite, and much of this CEC is located in the interlayer regions between platelets, which may result in a long timeline for cation exchange (Mitchell and Soga 2005). Another source of CEC is broken bonds around the edges of the clay particles, which makes up approximately 20 percent of the cation exchange capacity of smectites (Mitchell and Soga 2005). However, the most exchangeable cations will be those not directly connected to the clay platelet surface, but rather those adsorbed to the DDL by the net negative charge of the clay platelet (van Olphen 1963; Mitchell and Soga 2005).

Sodium bentonite (bentonite whose exchangeable cations are mainly sodium) is commonly used in SB backfills and will readily exchange its sodium cations for calcium or other ions (Mitchell and Soga 2005). Many of the cations needed for cation exchange are found naturally in soils. Calcium ions are among the most abundant, followed by magnesium, sodium, and potassium (Mitchell and Soga 2005). In addition, there may be contaminant plumes in the subsurface that contain these and other ions, such as heavy metals (e.g., cadmium and lead). Once these cations come into contact with the backfill, cation exchange can begin with the bentonite present.

1.4 CATION EXCHANGE IMPACTS ON THE DDL

1.4.1 Valence

Because cations are an integral part of the DDL, changes to the valence of the cations (correlating to a change in the type of cations) can have a large effect on the thickness of the DDL. The exchangeable cations in the DDL can be replaced by different cations, including those with a different valence or electrical charge. For example, sodium cations in bentonite may be replaced readily by calcium and other multivalent cations, leading to a change to a higher valence (e.g., from +1 to +2). Past studies have indicated that if the cations in the DDL are of a higher valence, there may be reduced spacing between clay platelets, flocculation of the platelets, and an overall reduced swelling of the bentonite (Mitchell and Madsen 1987; Shackelford 1994; Shackelford et al. 2000; Mitchell and Soga 2005). This may be due to the fact that when multivalent cations occupy the exchange sites, the electrostatic forces attracting two clay platelets retain their strength longer and the repulsive forces are weaker (Norrish 1954).

Of concern in this study is the fact that sodium bentonite will exchange its sodium cations for calcium or other ions (Mitchell and Soga 2005). In general, multivalent cations are more likely to replace monovalent cations. This is a major concern for SB cutoff walls because, as previously mentioned, calcium and magnesium (multivalent cations) are more prevalent in soils than sodium and potassium (monovalent cations). Many heavy metals that may be of concern in geoenvironmental containment applications (e.g., lead and copper) are also multivalent cations. Because of the preferential adsorption of multivalent cations, even small concentrations of such cations can have a significant effect on the DDL of sodium bentonite (Mitchell and Soga 2005). As multivalent cations replace the sodium in the bentonite, the ability of the bentonite platelets to separate is limited, leading to shrinkage of the clay (Norrish 1954).

1.4.2 Concentration

The concentration of cations in the DDL also plays a role in the thickness of the DDL. An increase in the concentration of cations can cause a decrease in the DDL thickness and flocculation of the clay, leading to reduced swelling (D'Appolonia 1980b; Spooner et al. 1985; Mitchell and Madsen 1987; Shackelford 1994; Mitchell and Soga 2005). This is because the presence of more cations has a stronger attraction on the negatively charged clay platelets, limiting the amount of expanding the platelets can undergo (e.g. Katsumi et al. 2008). Even a higher concentration of monovalent cations alone can still lead to a decrease in the DDL thickness (Shackelford et al. 2000). A monovalent cation can replace a multivalent cation if the concentration of the monovalent cation is much higher than the concentration of the multivalent cation in solution, a phenomenon known as "mass action" (Mitchell and Soga 2005). Some have suggested that as the concentration of cations increases, there is little adsorption of water and osmotic swelling does not occur (Onikata et al. 1996). On the other hand, when the concentration is lower and cation exchange takes place on a much longer time scale, more water may stay bonded to the surface of the clay, maintaining a thicker DDL (Shackelford 2007).

Cations play an important role in the DDL, and changes in the valence and concentration of cations can impact the clay DDL, and ultimately the hydraulic conductivity of the backfill. Any liquids that collapse the thickness of the DDL ultimately increase the hydraulic conductivity. Concentration and valence both play a role in cation exchange and subsequent changes to hydraulic conductivity, as both high concentrations of monovalent cations and low concentrations of multivalent cations can both cause significant increases in hydraulic conductivity (Shackelford et al. 2000).

1.4.3 Relation to Gouy-Chapman Theory

Based on the Gouy-Chapman theory, the approximate thickness of the DDL can be calculated using the following equation (e.g., Shackelford 1994):

$$D = \sqrt{\frac{\varepsilon \kappa T}{8\pi \eta e^2 z^2}} \tag{1.1}$$

where ε is the permittivity, κ is Boltzmann's constant, T is absolute temperature, η is the cation concentration, *e* is a unit electronic charge, and *z* is the cation valence. As this equation shows, the thickness of the DDL is inversely proportional to the concentration and valence of the cations in the pore fluid. Furthermore, if the thickness of the double layer is reduced, flocculation is also more likely (Shackelford 1994). Therefore, the Gouy-Chapman theory also shows the effect of cation valence and concentration on the double layer.

1.5 CRYSTALLINE AND OSMOTIC SWELLING

The swelling of montmorillonite occurs in two phases – crystalline swelling, followed by osmotic swelling (Norrish 1954; van Olphen 1963). During crystalline swelling, water molecules enter the interlayer region of the montmorillonite to hydrate the exchangeable cations located there (Norrish 1954; Norrish and Quirk 1954). Interlayer spacings of approximately 19 Å occur as an average of three layers of water molecules are adsorbed into the interlayer (Guyonnet et al. 2005; Amorim et al. 2007). The expansion occurs in steps as successive layers of water are adsorbed and is largely dependent upon the type of cation present in the interlayer (Norrish 1954; Guyonnet et al. 2005). Upon reaching an interlayer spacing of about 19 Å, a study by Meleshyn and Bunnenberg (2005) indicates that a chainlike structure of hydrated interlayer cations locks opposite montmorillonite layers together until a critical amount of water is able to unlock the space. Instantly, the interlayer spacing then increases to around 40 Å and osmotic swelling occurs (Norrish 1954; Guyonnet et al. 2005; Meleshyn and Bunnenberg 2005).

Osmotic swelling occurs as bulk water with a low concentration of ions tries to equalize the high concentration of ions in the clay interlayer, creating osmotic pressure (van Olphen 1963). Diffuse double layers develop and the DDLs of opposite montmorillonite layers repulse each other further, resulting in large volume changes seen on the macroscale (Norrish 1954; van Olphen 1963).

However, for swelling to advance from crystalline to osmotic, the hydration energy of the interlayer cations must be able to expand the interlayer spacing to about 20 Å (Norrish 1954). Studies have shown that multivalent cations are unable to reach such large spacings (Norrish 1954; Norrish and Quirk 1954). This is potentially because the electrostatic forces attracting two montmorillonite layers together retain their strength longer in the presence of multivalent cations, as well as that the osmotic repulsive forces are weaker (Norrish 1954). Therefore, higher valence cations can limit the osmotic swell potential of bentonite.

1.6 FIRST EXPOSURE

Much of the testing that has been done on hydraulic barriers that utilize swelling clays, especially geosynthetic clay liners (GCLs), has been done in the lab. Often, samples are permeated first with water to establish a baseline hydraulic conductivity before permeation with the chemical permeant. However, in situ, clay barriers are often exposed immediately to chemicals in the subsurface that can begin cation exchange before the clay is fully hydrated. Running lab tests that hydrate the bentonite before permeation with a chemical permeant (i.e., prehydrate the clay) can therefore be very unconservative, especially for high activity clays such as bentonite that experience lower hydraulic conductivities when prehydrated with water (Shackelford 1994).

A clay that is prehydrated with water before being exposed to a permeant may have different properties than the same clay that is first exposed to the permeant and not prehydrated with water (the first exposure effect). Prehydrated clays generally exhibit lower final hydraulic conductivities in comparison to non-prehydrated clays permeated with the same chemical, and they also tend to have a higher final water content and void ratio, which correlates to a larger DDL, more swelling of the bentonite, and thus lower hydraulic conductivity (Ruhl and Daniel 1997; Shackelford et al. 2000; Lee and Shackelford 2005; Katsumi et al. 2008). For prehydrated clays, water becomes adsorbed into the DDL before permeation occurs. Once cation exchange begins to occur during permeation with a chemical solution, some of this water is forced out, although as discussed previously, if concentrations are low enough, this process occurs at a slower rate and more water is left in the DDL (Shackelford 2007). In this manner, some of the original water in the DDL remains, giving prehydrated clays more water in their post permeation end state DDL, and thus a thicker DDL, than they would have naturally adsorbed when only permeated with the chemical solution. For non-prehydrated clays, no water is adsorbed into the DDL until after permeation begins. In this manner, little or no water must be forced out of the DDL because the water is adsorbing to the DDL at the same time cation exchange and cation concentration changes are occurring. If the chemical permeant contains high valence cations or high concentrations of cations, the DDL will be thinner and not adsorb as much water compared to a prehydrated sample of the same clay. As a result, prehydrated samples have a higher final water content and void ratio, corresponding to a thicker DDL, than non-prehydrated samples despite being permeated with the same chemical permeant (Lee and Shackelford 2005).

In terms of osmotic swell, prehydrated bentonite is capable of undergoing osmotic swell, whereas non-prehydrated bentonite cannot begin to swell until subjected to permeation with the liquid of interest. In this way, prehydrated and non-prehydrated bentonite barriers begin permeation with different swell conditions. If subjected to an aggressive permeant, non-prehydrated bentonite may never reach the osmotic swell stage, whereas the prehydrated bentonite may never leave the osmotic swell stage.

The effects of prehydration are shown in the fact that prehydrated GCLs are thicker than non-prehydrated GCLs of the same type, illustrating the growth in the DDL thickness and therefore swelling of the clay due to water adsorption during prehydration.

It is also worth noting that prehydration is not the primary factor influencing the hydraulic conductivity of clays. For example, at low concentrations of $CaCl_2$ (≤ 10 to 50 mM), there is little difference between the hydraulic conductivity of prehydrated and non-prehydrated GCLs (Vasko et al. 2001; Jo et al. 2004; Lee and Shackelford 2005). As chemical concentration increases, so does the hydraulic conductivity, but no first exposure effect appears until higher $CaCl_2$ concentrations. A lack of first exposure at low cation concentrations demonstrates the importance of cation concentration in effecting hydraulic conductivity.

For non-prehydrated clays, the fact that cation exchange occurs during hydration of the clay may cause the cation composition of the clay to change before hydration is complete. Sodium bentonite exhibits more swelling than calcium or magnesium bentonite, both of which have higher valence cations than sodium bentonite (Shackelford 2007). Thus, if a non-prehydrated sodium bentonite is hydrated in a calcium solution, the bentonite may become calcium bentonite during hydration. In this example, the limited thickness of the DDL is actually a direct effect of cation valence.

Prehydration is important because bentonite is able to undergo osmotic swelling. Once the bentonite is allowed to adsorb enough water (~ 1200 mg/g), the chain of water molecules holding the bentonite interlayer space together is forced open, allowing osmotic swelling to occur (Meleshyn and Bunnenberg 2005). However, if calcium ions are able to exchange with interlayer sodium cations as swelling occurs, calcium ions are unable to adsorb as much water as sodium ions, and the amount of swelling is limited

(Amorim et al. 2007). Therefore, if cation exchange occurs before prehydration, the clay may no longer be able to exhibit osmotic swelling.

For SB backfill, the expectation is that there will be no first exposure effect at low concentrations of $CaCl_2$, and a minimal first exposure effect at higher concentrations of $CaCl_2$ due to the exposure of the bentonite to water when the backfill is mixed. The presence of water and bentonite in the backfill together allows the bentonite to hydrate to a large extent before contacting the groundwater. The final water content of backfill samples pre-permeated with water is expected to be similar to non pre-permeated samples, with pre-permeated samples having a slightly higher water content at high $CaCl_2$ concentrations. The results of studying the first exposure effect on SB backfill will aid in determining the validity of lab tests that first permeate SB backfill with water to establish a baseline hydraulic conductivity before permeation with a chemical permeant.

1.7 PERMEANT LIQUIDS

As discussed previously, SB cutoff walls are used in a wide variety of applications. As a result, SB backfill comes into contact with a wide variety of permeating liquids, from clean groundwater to large contamination plumes composed of a variety of chemicals. These permeants may contain one or many cations in varying concentrations. Because calcium is such a common cation in the soil, and because calcium has a strong cation replacing power due to its multivalence, calcium chloride ($CaCl_2$) is often used as a chemical permeant to test the compatibility of SB backfill and other hydraulic barriers that utilize swelling clays. Ruhl and Daniel (1997) concluded that a solution with a high concentration of multivalent cations such as Ca^{+2} is the most aggressive at altering the hydraulic conductivity of GCLs. Others have concluded that GCLs permeated with similar concentrations of either divalent or trivalent cations yield similar final hydraulic conductivities (Stern and Shackelford 1998; Vasko et al. 2001; Jo et al. 2005; Lee and Shackelford 2005). Also, because calcium has the same valence as many heavy metals, the use of a calcium solution is a safe way to understand how SB backfill may react with heavy metals in geoenvironmental applications. In this way, $CaCl_2$ may be taken as a representative of the multitude of possible permeants. Final hydraulic conductivities reached using $CaCl_2$ may therefore be assumed to be similar to or worse than hydraulic conductivities that would be reached using other permeants, and general conclusions can then be made concerning the behavior of the several clays to be tested.

1.8 OVERVIEW OF PREVIOUS STUDIES

Research on the compatibility of GCLs has been conducted in the past, but little has been done on the compatibility of SB cutoff walls with inorganic contaminants. This study will help to add to the body of knowledge concerning SB backfill compatibility.

Studies of GCL compatibility have examined the effects of different types and qualities of bentonites, different types and concentrations of permeant liquids, and prehydration on hydraulic conductivity. This research has also discussed and made recommendations for the termination criteria of compatibility tests in order to obtain an accurate final hydraulic conductivity, especially the need to reach chemical equilibrium between the influent and effluent (Ruhl and Daniel 1997; Shackelford et al. 2000; Vasko et al. 2001; Jo et al. 2005; Lee and Shackelford 2005; Shackelford 2007; Katsumi et al.

2008). These GCL studies have shown that the permeant's cation concentration and valence, as well as prehydration, all have an effect on the hydraulic conductivity of the GCL (Ruhl and Daniel 1997; Shackelford et al. 2000; Jo et al. 2001; Vasko et al. 2001; Jo et al. 2004; Katsumi et al. 2004; Jo et al. 2005; Katsumi and Fukagawa 2005; Lee and Shackelford 2005; Katsumi et al. 2008). They have also shown that the effect of prehydration is concentration dependent, and may have little to no effect at low (approximately less than or equal to 10 to 50 mM $CaCl_2$) permeant concentrations (Vasko et al. 2001; Jo et al. 2004; Lee and Shackelford 2005). The results of these GCL studies fit well with what is already known about how cation concentration and valence, as well as prehydration, can affect the hydraulic conductivity of clay barriers. These studies also reveal the reality that clay compatibility is an important and relevant issue that must be addressed for clay barriers.

While studies have recognized the importance of compatibility testing for cutoff walls, most research has been limited to specific compositions of the backfill or specific permeant solutions. Spooner et al. (1985) recommends more clay in the backfill for improved compatibility performance. Ryan (1985; 1987) and Day (1994) have presented case studies on compatibility testing done for various projects. Kashir and Yanful (2000) presented results of compatibility testing with representative acid mine drainage liquids. Patton et al. (2007) presented another more recent case study.

D'Appolonia and Ryan (1979) and D'Appolonia (1980a) conducted a few general, small-scale studies which utilized sodium and calcium salt solutions to study the compatibility SB backfill. Evans et al. (1995) reports the results of permeating a SB backfill specimen with a chromium solution. However, these studies were limited in scale and volume. While compatibility tests are needed for specific cases because of the many types of situations that can exist, this study plans to provide a more general look at the compatibility of SB backfill with inorganic chemicals, especially backfills utilizing modified bentonite clays that are intended to be compatible with inorganic permeant solutions.

Due to the need for compatible clay barriers in the subsurface, recent attention has been given to the development and potential use of modified bentonite clays that are resistant to shrinkage and increases in hydraulic conductivity due to incompatibility (Alther et al. 1985; Lo et al. 1994; Onikata et al. 1996; Lo et al. 1997; Ruhl and Daniel 1997; Onikata et al. 1999b; Patton et al. 2007; de Paiva et al. 2008). Many of these "contaminant-resistant" clays have been tested in GCLs and other clay liner applications. Kajita (1997) reports testing a contaminant-resistant clay with $CaCl_2$ solutions. The unnamed clay maintained low *k* values and proved resistant to chemical attack. Ruhl and Daniel (1997) also tested modified bentonites with a variety of contaminant liquids and found that they maintained lower *k* values than regular bentonite for some of the permeant liquids, but for other contaminants, the modified bentonites performed worse. This indicates that the ability of the modified bentonite to resist contaminant attack depends not only on the bentonite, but also on the type of contaminant.

Other contaminant-resistant bentonites have focused on preventing contaminant transport via sorption instead of by maintaining low *k* values. Lo et al. (1994) created a humic acid-aluminum hydroxide-clay that had a k_w value of 8×10^{-8} m/s, but which demonstrated excellent organic sorption properties. Three years later, Lo et al. (1997) reported on another organically modified clay that had a lower k_w value (7 x 10^{-11} m/s) and a large organic contaminant removal capacity. When permeated with an actual landfill leachate, the k only increased to 1.6 x 10^{-10} m/s. Although a k value of 1.1 x 10^{-9} cm/s was reached when permeated with a synthetic organic leachate, the clay still managed to delay the breakthrough of the organics in the leachate. As these studies show, certain modified clays are capable of effectively containing certain contaminants.

Polymer treatment of bentonite has also been a method used to create contaminant-resistant clays. Alther et al. (1985) tested polymerized bentonites with inorganic salts and found that, compared to non-polymerized bentonites, the polymerized bentonites experienced smaller increases in k of slurry filter cakes. "Polymer-treated" clays used in a GCL were tested by Ashmawy et al. (2002), who found that, when permeated with landfill leachates high in multivalent cations, the polymerized clays performed marginally better than the untreated clays in terms of k to the leachate.

With the variety of modified bentonites available, several have been tested for use in SB cutoff wall applications. Day (1994) reports on two modified clays considered for two different SB cutoff walls. Both experienced excessive filtrate loss when in contact with the contaminants (hazardous waste landfill leachate, brine solution), and were discarded early in the testing. Ryan (1987) reports on a SB cutoff wall application to contain BTEX and other organic contaminants that found a treated bentonite was less compatible with the contaminants than other clays in a variety of preliminary tests. More recently, Patton et al. (2007) found that SW101 (Wyo-Ben, Inc., Billings, MT), a salt-resistant bentonite, could be used to create an acceptable slurry and SB backfill for use at the Rocky Mountain Arsenal Superfund site in Colorado.

A relatively new modified bentonite of special interest to this study is "multiswellable" bentonite (MSB). MSB consists of a natural sodium-bentonite that has been complexed with propylene carbonate (PC), an organic polymer, to give the bentonite the ability to exhibit osmotic swelling in electrolyte solutions (Kondo 1996). Numerous studies have shown that MSB displays osmotic swelling in aqueous electrolyte solutions and long term resistance to chemical attack (Onikata et al. 1996; Onikata et al. 1999a; Lin et al. 2000; Shackelford et al. 2000; Katsumi et al. 2004; Katsumi and Fukagawa 2005; Katsumi et al. 2008). However, these studies have focused mainly on the use of MSB in clay liners, especially GCLs.

Many of these clays show promise in some situations against certain chemicals. This study seeks to expand the body of knowledge regarding clay compatibility in an attempt to examine the effectiveness of two of these "contaminant-resistant" bentonite products (SW101 and MSB) for providing improved compatibility in SB cutoff walls used for geoenvironmental containment. Few studies have examined the compatibility issues of SB backfill, and those that do exist lack a broad overview of the issue (e.g., D'Appolonia and Ryan 1979; D'Appolonia 1980a; Evans et al. 1995). SB cutoff walls are useful only as long as they are able to minimize the transport of contaminants in the subsurface, so a more thorough understanding of SB backfill compatibility is important for designing more efficient vertical barriers.

1.9 OVERVIEW OF THIS STUDY

The primary objectives of this study were to (1) create model SB backfill mixtures containing each type of bentonite, (2) evaluate changes in *k* of the model backfill mixtures upon permeation with $CaCl_2$ solutions encompassing a wide range of concentrations (i.e., 10 to 1000 mM), and (3) compare the results for the backfills containing the two modified bentonites with those for a backfill containing a conventional (untreated) bentonite.

The second chapter of this report will detail the creation of acceptable bentonite-water slurry and SB backfill mixtures. In order to ensure that this study is useful and practical for practitioners in the field, SB backfills that meet conventional design parameters had to be created and tested. Chapter three reviews the multitude of clay index and hydraulic conductivity tests performed to evaluate the compatibility of the three clays and their respective SB backfills. General conclusions about SB backfill compatibility are proposed. The fourth chapter reviews the general conclusions of this study and makes recommendations for further study.

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CHAPTER 2

CREATION OF ACCEPTABLE BENTONITE-WATER SLURRIES AND SOIL-BENTONITE BACKFILL MIXTURES

2.1 INTRODUCTION

Soil-bentonite (SB) slurry trench vertical barriers (cutoff walls) are commonly employed to provide *in situ* containment of contaminated groundwater. The performance of a SB barrier in these applications depends largely upon the ability of the SB backfill to maintain a low hydraulic conductivity (*k*), such that spreading of the contaminant plume is minimized while the contamination may be addressed through active or passive treatment. In many cases, the *k* of the backfill may be governed by the bentonite fraction, which typically ranges from 1-5 wt % depending upon the amount of native fines present in the backfill matrix (Sharma and Reddy 2004).

Research has shown that various factors can negatively influence the swelling capacity of bentonite, thereby causing an increase in *k* of bentonite-rich materials such as SB backfills. One such factor involves the chemical properties of liquid permeating through the barrier, most notably the concentration and valence of inorganic cations that inhibit osmotic swelling of the bentonite (e.g., Shackelford 1994). The potential for an increase in *k* of SB backfill due to interactions between bentonite and groundwater constituents, particularly divalent and/or polyvalent cations, has significant implications for SB vertical barriers used in geoenvironmental containment applications. Thus, a primary design objective in these applications is to ensure that the SB backfill and the groundwater are chemically compatible, such that interactions between the bentonite and cations in the groundwater do not result in an unacceptable increase in *k* of the backfill.

One potential approach for enhancing the chemical compatibility of SB backfill is to use modified bentonite clay designed to maintain high swelling and low *k* in the presence of electrolyte solutions (e.g., Patton et al. 2007). For example, modified bentonite clay known as *multiswellable bentonite* (MSB) has attracted considerable recent interest in the geoenvironmental engineering community due to the ability of MSB to exhibit swelling in both fresh water and electrolyte solutions (Shackelford et al. 2000; Mazzieri et al. 2005; Katsumi et al. 2008).

As described by Onikata et al. (1996), MSB is created by compounding natural bentonite with propylene carbonate (PC) that expands the clay lattice and forms a hydration shell around the interlayer cations. The resulting PC-bentonite complex exhibits osmotic swelling at NaCl concentrations higher than that in sea water (~0.6 M) (Onikata et al. 1999).

Studies have shown that MSB exhibits greater swelling and lower *k* than natural bentonite when exposed to electrolyte solutions with ionic strengths up to 1 M (Shackelford et al. 2000; Katsumi et al. 2008). Also, results of long-term *k* tests (conducted for up to seven years in some cases) illustrate that MSB offers the potential for long-term resistance against chemical attack in the presence of high concentrations of monovalent and/or divalent cations (Katsumi et al. 2008).

Based on the above considerations, MSB may be effective for SB vertical barriers in groundwater with high electrolyte concentrations. However, use of MSB in SB vertical barriers has been given little consideration to date. Therefore, the objective of this study was to perform a preliminary assessment of MSB for slurry trench barrier applications based on evaluation of slurry properties and backfill hydraulic conductivity.

2.2 MATERIALS AND METHODS

2.2.1 Materials

Three types of powdered bentonite clays were tested in this study, viz., (1) MSB (Hojun Corp., Japan), (2) a natural (untreated) sodium bentonite, or NG (NaturalGel Wyo-Ben, Inc., Billings, MT), and (3) SW101 (Wyo-Ben, Inc., Billings, MT), a "salt-resistant" bentonite developed for use in drilling and cutoff wall applications where exposure to seawater is expected. The treatment process used to create SW101 is unknown (proprietary). Nonetheless, SW101 was selected for this study based on the recent use of SW101 in an SB vertical barrier at the Rocky Mountain Arsenal Superfund site in Colorado (see Patton et al. 2007).

The physical and chemical properties and the mineralogical compositions of the three bentonites are summarized in Table 2.1. All three bentonites classify as high plasticity clays (CH; ASTM D 2487) and contain predominantly montmorillonite. The cation exchange capacity (CEC) and distilled water swell index of MSB are considerably lower than those of NG and SW101. However, MSB exhibits the highest swell index in a solution containing 50 mM NaCl or $CaCl_2$.

In addition to the bentonites, locally supplied mortar sand was used to make model SB backfills for *k* testing. The mortar sand is a poorly graded, predominantly fine sand with <5 % fines (see Malusis et al. 2009). The sand was chosen to simulate SB barrier construction in a clean sand aquifer.

2.2.2 Slurry Preparation and Testing

Construction of a SB slurry trench barrier requires the use of bentonite-water slurry (typically 4-6 wt % bentonite) to maintain stability of the excavated trench (LaGrega et al. 2001). The viscosity and density of the slurry must be sufficiently high to maintain trench stability, yet sufficiently low to be easily displaced by the backfill. The slurry also should form an adequate filter cake to minimize slurry loss from the trench during construction. Typical properties of prepared slurry include a Marsh viscosity of 32-40 s, a mud density on the order of 1.03 Mg/m^3, and a filtrate loss of <25 mL (Xanthakos 1979; Millet and Perez 1981; Evans 1993). In addition, a slurry *pH* of 6.5-10 is desirable to minimize flocculation and resulting settlement of the bentonite (Millet and Perez 1981).

In this study, slurries were prepared by blending the bentonites with tap water in a high-speed colloidal shear mixer (i.e., a Hamilton-Beach 7-speed blender at the highest speed) for 5 min. The slurries were allowed to hydrate for 24 h prior to testing for Marsh viscosity (API RP 13B), mud density, filtrate loss (ASTM D 5891), and *pH*. Mud density was measured using a mud balance (NL Baroid, Houston, TX), and *pH* was measured using an Oakton Instruments (Vernon Hills, IL) bench *pH* meter. The influence of bentonite content on these properties was investigated by testing slurries with bentonite contents ranging from 2 to 5 wt %.

2.2.3 Model SB Backfill Preparation and Testing

Model SB backfills were prepared by combining mortar sand, slurry (5 wt % bentonite), and additional dry bentonite (3 or 4 % by dry wt) in a Hobart mixer (Model #N50, Hobart Corp., Troy, OH) to ensure uniformity. The dry bentonite was added with the goal of creating backfills that exhibit a hydraulic conductivity to water, $k_w \leq 10^{-9}$ m/s, in accordance with typical requirements for geoenvironmental containment. Slurry was added incrementally until the backfills exhibited a slump (ASTM C 143-00) of 125±12.5 mm, a range consistent with typical field specifications (Evans 1993). After addition of slurry, the bentonite contents of the prepared backfills ranged from 4.5 to 5.7 % (by dry weight).

Each backfill was subjected to flexible-wall *k* testing, in accordance with ASTM D 5084-03 Method C (falling headwater-rising tailwater). Backfill specimens were prepared using the procedures described by Malusis et al. (2009) and were consolidated under an effective confining stress of 34.5 kPa prior to permeation with tap water (*pH* = 6.65, electrical conductivity, *EC* = 1.67 mS/m). A hydraulic gradient of 30 or less was maintained during permeation in all tests.

Each backfill specimen was permeated with tap water until steady-state conditions were observed and ASTM D 5084-03 termination criteria were achieved. The permeant solution then was changed from tap water to a 50 mM $CaCl_2$ solution in selected tests, and permeation continued in these tests until ASTM D 5084-03 termination criteria were re-established and the ratio of effluent *EC* to influent *EC* was within 1.00±0.05. This latter criterion has been suggested by Jo et al. (2005) as a practical criterion for ensuring that final measured *k* values are reasonably representative of long-term conditions in which chemical equilibrium has been achieved in the test specimens (i.e., chemical reactions between the permeant liquid and the bentonite are complete). This criterion is tighter than the current criterion for terminating flexible-wall *k* tests on GCLs permeated with chemical solutions (i.e., ASTM D 6766), which requires a ratio of effluent *EC* to influent *EC* of 1.0±0.1.

2.3 RESULTS

2.3.1 Bentonite-Water Slurry

Values of Marsh viscosity, density, filtrate loss, and pH for slurries prepared with MSB, NG, and SW101 are shown as a function of bentonite content in Figure 2.1. The results in Figure 2.1a illustrate that values of Marsh viscosity for the slurries containing MSB and NG were within the typical range of 32-40 s and were relatively insensitive to percentage of MSB or NG in the slurry. In contrast, the Marsh viscosity of the SW101-water slurry increased from 36 s to 200 s as the SW101 content was increased from 2 wt % to 5 wt %.

Mud densities increased with increasing bentonite content, as expected (Figure 2.1b). The mud density of MSB-water slurry was slightly lower than those of slurries containing the same percentage of NG or SW101. Slurries with a bentonite content of 5 wt % exhibited a mud density between 1.02 and 1.03 Mg/m^3, regardless of the type of bentonite. In addition, all of the slurries exhibited acceptable values of filtrate loss (Figure 2.1c) and *pH* (Figure 2.1d), regardless of bentonite content. The results in Figure 2.1 indicate that slurry containing 5 wt % MSB or NG exhibited properties generally considered acceptable for slurry trench barriers. In contrast, the viscosity of SW101 slurry may be excessively high for slurry trench barriers unless the slurry is prepared with a relatively low percentage of SW101 (i.e., 2-3 wt %), which may not be desirable. Alternatively, the viscosity of the slurry may be reduced by adding a thinning agent. For example, values of Marsh viscosity for SW101-water slurries containing 4 wt % and 5 wt % SW101 were reduced to ~40 s and ~50 s, respectively, by amending the slurries with a small amount (0.3 wt %) of chromium-free lignosulfate thinner (Spersene® CF, M-I SWACO, Houston, TX), as shown in Figure 2.2a. Although addition of thinner caused a reduction in slurry *pH*, the *pH* values were within the desirable range of 6.5-10 (Figure 2.2b). The thinner had no significant effect on slurry density or filtrate loss. Based on these results, 0.3 % thinner was added to the slurry used to prepare the model backfill containing SW101.

2.3.2 Backfill Hydraulic Conductivity

Results of the hydraulic conductivity (*k*) tests on the model SB backfills are summarized along with relevant properties of the test specimens in Table 2.2. The results show that the final hydraulic conductivity to water, k_{fw}, for the specimen containing 4.6 % SW101 (i.e., 2.5×10^{-10} m/s) was well below 10^{-9} m/s, whereas k_{fw} was only slightly below 10^{-9} m/s for the specimen containing 4.6 % NG (i.e., 8.2×10^{-10} m/s) and above 10^{-9} m/s for the specimen containing 4.5 % MSB (i.e., 7.6×10^{-9} m/s). However, k_{fw} for the MSB and NG backfills decreased with increasing bentonite content (Figure 2.3), such that values of k_{fw} for the specimens containing 5.6 % MSB, 5.7 % NG, and 4.6 % SW101 all were within the relatively narrow range of $2.2 \times 10^{-9} \leq k_{fw} \leq 2.7 \times 10^{-10}$ m/s. Given the similar k_{fw} values for these three specimens, the permeant liquid was changed from tap water to the 50 mM $CaCl_2$ solution in these three tests so that changes in k due to chemical incompatibility could be compared relative to a similar baseline k_{fw}.

Values of hydraulic conductivity to the $CaCl_2$ solution, k_c, are plotted versus pore volumes of flow (PVF) in Figure 2.4. Final values of k_c (k_{fc}) also are listed in Table 2.2 along with values of the ratio k_{fc}/k_{fw}. The tests were terminated after 2.4-2.8 PVF, once all of the aforementioned termination criteria had been achieved. The results illustrate that none of the specimens were immune to an increase in k upon permeation with the $CaCl_2$ solution. The specimen containing 4.6 % SW101 exhibited the highest k_{fc} (9.6×10^{-10} m/s) and also the highest value of k_{fc}/k_{fw} (3.8), whereas the specimen containing 5.6 % MSB exhibited the lowest k_{fc} (4.2×10^{-10} m/s) and the lowest k_{fc}/k_{fw} (1.9). The better performance of the backfill containing MSB relative to the backfill containing SW101 may have been influenced by the higher percentage of MSB (5.6 %) relative to that of SW101 (4.6 %) in the two backfills shown in Figure 2.4. Nonetheless, the results suggest that, for backfills exhibiting similar k_{fw}, backfill containing MSB may offer greater resistance to chemical attack than backfill containing NG or SW101.

2.4 CONCLUSION

Based on the results of this study, MSB appears to be viable for use in SB vertical barriers. The physical properties of MSB slurry (i.e., viscosity, density, and filtrate loss) are similar to those of slurry containing the same percentage of NG. Model SB backfills containing 5.6 % MSB, 5.7 % NG, and 4.6 % SW101 exhibited similar k to water, and all three backfills maintained acceptable k (i.e., $k \leq 10^{-9}$ m/s) when the permeant liquid was changed to a 50 mM $CaCl_2$ solution. However, the MSB backfill exhibited a lower *k* after permeation with the $CaCl_2$ solution for a sufficient number of pore volumes to achieve a ratio of influent to effluent *EC* of 1.00±0.05. The findings indicate that a more comprehensive study on the performance of MSB in SB vertical barriers is warranted.

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Table 2.1. Properties and mineralogy of bentonites tested in study.

Property	Standard	Value		
		MSB	NG	SW101
Soil classification	ASTM D 2487	CH	CH	CH
Swell Index (mL/2g)	ASTM D 5890			
Distilled water		28.5	35.0	43.0
50 mM NaCl		39.5	33.0	35.0
50 mM $CaCl_2$		19.5	12.0	18.5
Principal minerals (%)	a			
Montmorillonite		74	69	86
Cristobalite		10	14	6
Quartz		2	12	3
Plagioclase Feldspar		4	2	2
Other		10	3	3
Cation exchange capacity (meq/100 g)	b	49.8	83.4	85.7
Exchangeable metals (meq/100 g)	b			
Ca		7.7	4.9	6.1
Mg		6.1	8.8	10.2
Na		33.3	73.4	64.1
K		0.5	1.1	0.2
Sum		47.6	88.2	80.6

[a] X-ray diffraction analysis performed by Mineralogy, Inc. (Tulsa, OK)
[b] Procedures given by Shackelford and Redmond (1995), performed by Colorado State University (Fort Collins, CO)

Table 2.2. Summary of data from hydraulic conductivity tests.

Bentonite Type	Bentonite Content (dry wt %)	Water Content, w (%)	Porosity, n (---)	k_{fw} [1] (m/s)	k_{fc} [1] (m/s)	k_{fc}/k_{fw}
MSB	4.5	38.5	0.51	5.0×10^{-9}	---	---
MSB	5.6	40.0	0.54	2.2×10^{-10}	4.2×10^{-10}	1.9
NG	4.6	40.0	0.54	7.6×10^{-10}	---	---
NG	5.7	43.0	0.55	2.7×10^{-10}	6.9×10^{-10}	2.6
SW101	4.6	39.9	0.56	2.5×10^{-10}	1.1×10^{-9}	4.3

[1] k_{fw} and k_{fc} are k values to tap water and 50 mM $CaCl_2$ solution, respectively

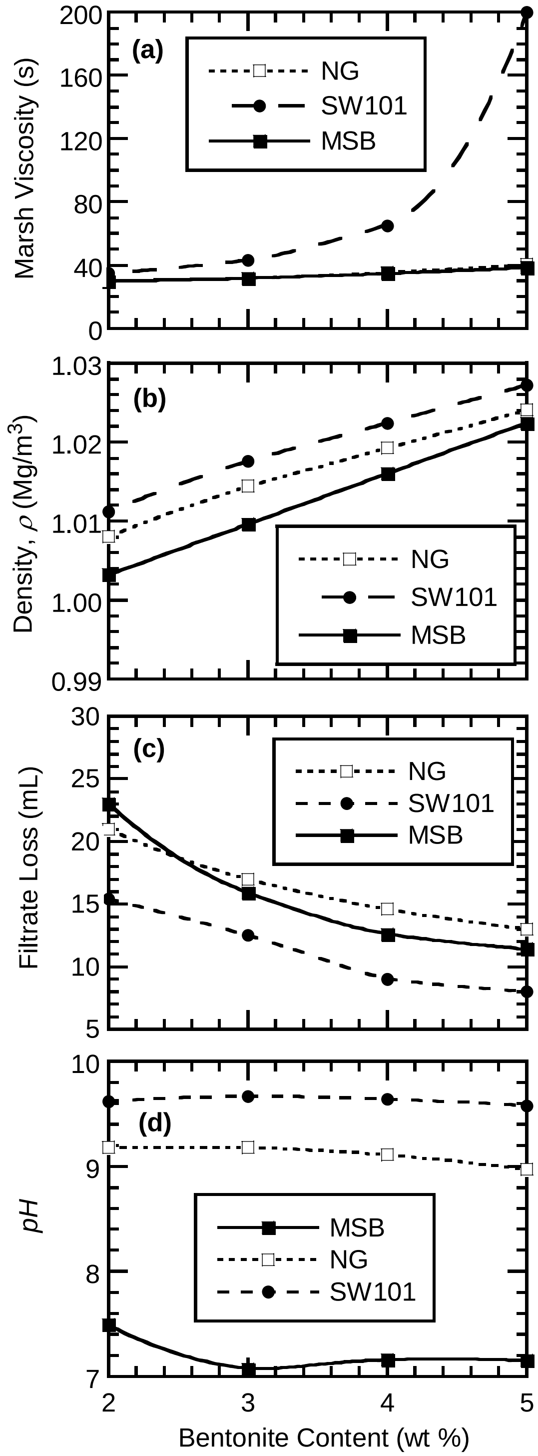

Figure 2.1. Properties of bentonite-water slurries as a function of bentonite content: (a) Marsh viscosity; (b) density; (c) filtrate loss; and (d) *pH*.

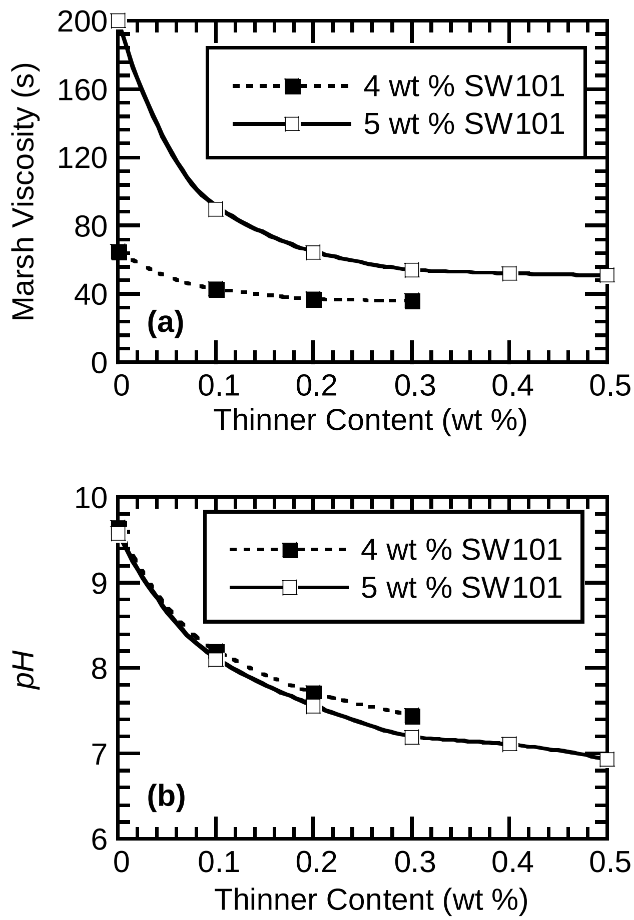

Figure 2.2. Influence of lignosulfate thinner on (a) Marsh viscosity and (b) *pH* of slurries containing 4 wt % and 5 wt % SW101.

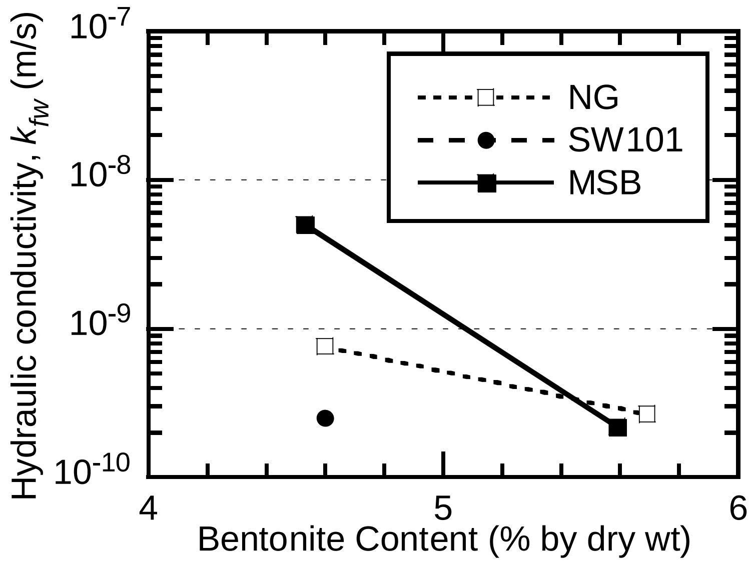

Figure 2.3. Final values of hydraulic conductivity to water, k_{fw}, for model SB backfill specimens as a function of bentonite content.

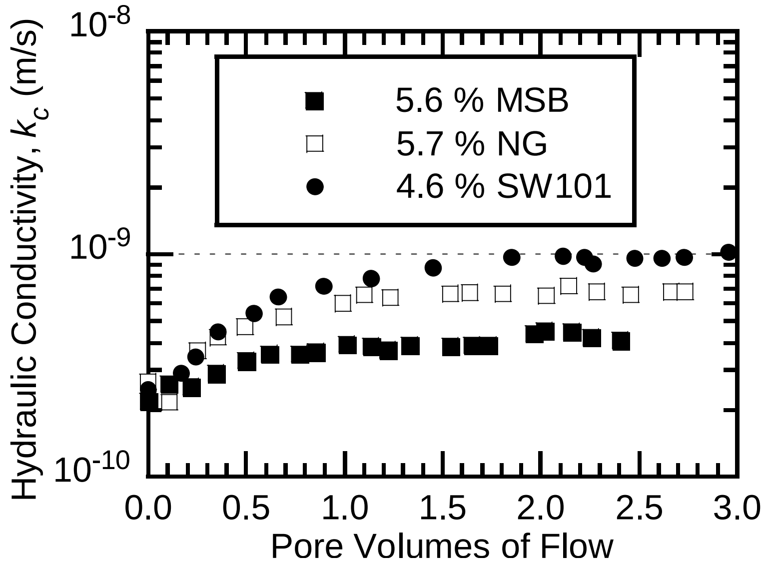

Figure 2.4. Hydraulic conductivity to a 50 mM $CaCl_2$ solution, k_c, versus pore volumes of flow for selected backfill specimens.

CHAPTER 3

COMPATIBILITY TESTING OF MODEL SB BACKFILLS

3.1 INTRODUCTION

3.1.1 Significance of Soil-Bentonite Cutoff Walls

In situations where subsurface contaminants need to be contained *in situ*, vertical barriers (i.e. cutoff walls) are commonly used until a more efficient and/or cost effective treatment technology is available (Shackelford and Jefferis 2000). In these cases, the cutoff wall is expected to contain the contaminants primarily by minimizing groundwater flow. Although a completely impervious cutoff wall is impossible to construct, cutoff walls can be designed to achieve and maintain low groundwater flow rates, thereby minimizing advective transport of subsurface pollutants at contaminated sites (Sharma and Reddy 2004).

Soil-bentonite (SB) cutoff walls are the most common vertical barriers used in the US for *in situ* containment applications. The typical construction process for SB cutoff walls involves two phases. First, a vertical trench is excavated and filled with bentonite-water slurry (typically ~5 % bentonite by weight) to maintain the stability of the trench walls. Next, the excavated soil (or more suitable soil) is mixed with slurry and dry bentonite (if needed) to create a homogeneous SB backfill, which is then placed into the excavated trench to create a barrier with a low hydraulic conductivity, k (i.e., typically $k \leq 10^{-9}$ m/s) (D'Appolonia and Ryan 1979; Evans 1993).

3.1.2 Compatibility in SB Cutoff Walls

The ability of SB cutoff walls to create and maintain a low *k* in the subsurface environment depends largely on the ability of the bentonite to swell upon hydration with water. However, research has shown that various factors can negatively influence the swelling capacity of bentonite. One such factor involves the chemical properties of liquids permeating through the barrier (Alther et al. 1985; Shackelford 1994; Ruhl and Daniel 1997; Shackelford et al. 2000; Vasko et al. 2001; Jo et al. 2005; Lee and Shackelford 2005a; Mitchell and Soga 2005; Shackelford 2007; Katsumi et al. 2008). The potential for an increase in the hydraulic conductivity of a SB cutoff wall due to interactions between the bentonite and chemical constituents in the groundwater has significant implications for SB cutoff walls used in geoenvironmental containment applications. Thus, a primary design objective in these applications is to ensure that the SB backfill and the groundwater exhibit acceptable "compatibility," such that any increase in the hydraulic conductivity of the backfill upon interaction with the groundwater results in a *k* that maintains the desired barrier performance (i.e., $k \leq 10^{-9}$ m/s).

Even during the construction of the cutoff wall, chemicals in the groundwater can have a negative influence on the ability of the slurry in the trench to keep the trench open and form a filter cake along the trench walls that prevents slurry from leaking out. The negative surface charges of clay particles enable the particles to remain dispersed in the slurry. However, if the diffuse double layer (DDL) thicknesses of the clay particles are reduced due to incompatibility with pollutants, the particles may flocculate and settle out of the slurry (Spooner et al. 1985; Ryan 1987). As a result, the ability of the slurry to form an effective filter cake can be reduced, and slurry may leak out of the trench at a greater rate than desired (Spooner et al. 1985). According to Xanthakos (1979), salt concentrations of less than one percent can cause flocculation of bentonite in the slurry.

Once the SB cutoff wall has been constructed, incompatibility between the backfill and contaminants can cause an increase in k of the cutoff wall, potentially to the extent that the wall may fail to provide effective containment. Since k of the backfill is often governed by the amount of bentonite in the backfill (Evans et al. 1985), compatibility between the groundwater and bentonite in the backfill is especially important for the cutoff wall to perform as intended.

The chemical composition of the groundwater, most notably the concentration and valence of inorganic cations, can have a large impact on the swelling ability of the bentonite and, in turn, the k of the completed cutoff wall (Shackelford 1994; Ruhl and Daniel 1997; Shackelford et al. 2000; Vasko et al. 2001; Lee and Shackelford 2005a; Mitchell and Soga 2005; Shackelford 2007; Katsumi et al. 2008). Bentonite swells many times its original volume when it comes into contact with water (Norrish and Quirk 1954; van Olphen 1963). Much of this swelling ability is a result of osmotic swelling, i.e., expansion of the interlayer regions between individual platelets as the bentonite is hydrated (Xanthakos 1979). As the bentonite swells and blocks the pore spaces between granular particles in the backfill, the k of the backfill is reduced. Therefore, if the swelling ability of the bentonite is limited, the pores will not be adequately plugged and the resulting k may be unacceptably high.

The type of cation absorbed on the exchange complex of the bentonite can have a significant influence on the properties of the bentonite. Monovalent cations, such as sodium, will allow more layers of water molecules to absorb to the clay surface than multivalent cations, such as calcium (Spooner et al. 1985). However, sodium and other monovalent cations will readily exchange with multivalent cations, and even with only about a third of the monovalent cations on the clay surfaced exchanged for multivalent ions, the bentonite will begin to exhibit less swelling (D'Appolonia 1980b; Spooner et al. 1985). Multivalent cations, because of their greater positive charge, are held more strongly by the negatively charged clay surfaces. In addition, fewer multivalent cations are required to balance the negative surface charge (e.g., one calcium ion replaces two sodium ions), resulting in less hydration water in the DDLs. Thus, exchange of monovalent cations for multivalent cations leads to a reduced DDL thickness and less macroscale swelling (Spooner et al. 1985).

The concentration of electrolytes in the pore water can also have an effect on the ability of the bentonite to swell and maintain a low *k*. Salt concentrations reduce the electrical potential between the clay platelets and the pore water, causing a reduction in double layer thickness and macroscale swelling (D'Appolonia 1980b). As the bentonite shrinks due to the loss of water from the double layer, the pores full of freely flowing water between granular particles in the backfill increase in size, allowing larger paths for fluid flow and thus a higher *k* due to the fact that *k* varies with the square of the radius of the pore (Mitchell and Madsen 1987; Jo et al. 2001). In addition to the reduced swelling, the smaller DDL allows for the repulsive forces between the clay platelets to be more easily overcome, potentially resulting in flocculation and an increase in *k* (van Olphen 1963; Spooner et al. 1985).

3.1.3 Modified Bentonites

Because of the negative effects salts can have on bentonite, various methods of countering these effects have been attempted, such as prehydrating the clay, using clays other than montmorillonite, and developing modified bentonites that are resistant to chemical attack (Millet and Perez 1981; Alther et al. 1985; Ryan 1987; Day 1994; Lo et al. 1994; Shackelford 1994; Onikata et al. 1996; Lo et al. 1997; Ruhl and Daniel 1997; Vasko et al. 2001; Jo et al. 2004; Patton et al. 2007; de Paiva et al. 2008). For example, past attempts to develop bentonites resistant to chemical attack have included various treatment techniques to modify conventional sodium bentonite using polymers, organic surfactants, acids, and other proprietary methods (Alther et al. 1985; Lo et al. 1994; Lo et al. 1997; Patton et al. 2007; de Paiva et al. 2008). However, such modified bentonites have not always shown promising results. For example, several studies have found that various "contaminant-resistant" bentonites were less suitable for geoenvironmental containment applications (i.e., higher hydraulic conductivities, excessive filtrate loss) than conventional bentonites when exposed to the same permeant (Ryan 1987; Day 1994; Ruhl and Daniel 1997).

3.1.4 Objective of Study

The primary purpose of this study was to investigate the viability of a relatively new modified bentonite, known as "multiswellable" bentonite (MSB), for use in SB cutoff walls where exposure to high electrolyte concentrations in the groundwater is expected. MSB consists of a natural sodium bentonite that has been complexed with propylene carbonate (PC) to give the bentonite the ability to exhibit osmotic swelling in electrolyte solutions (Kondo 1996).

The swelling mechanism of MSB is illustrated in Figure 3.1. The PC molecules are held to the interlayer exchange cations. When in an aqueous solution, water molecules are attracted to the cations and form a hydration shell around the cations but within the PC shell. The PC, an organic polymer, increases the basal spacing of the bentonite and promotes osmotic swelling upon hydration of the clay with electrolyte solutions. For example, MSB has been shown to exhibit osmotic swell at NaCl concentrations of 0.75 M, more than twice the concentration (0.3 M NaCl) at which natural sodium montmorillonite can exhibit osmotic swell (Onikata et al. 1999a; Onikata et al. 1999b; Mazzieri et al. 2005; Katsumi et al. 2008).

Additional studies have shown that MSB displays osmotic swelling in aqueous electrolyte solutions and exhibits long term resistance to chemical attack (Onikata et al. 1996; Onikata et al. 1999a; Lin et al. 2000; Shackelford et al. 2000; Katsumi et al. 2004; Katsumi and Fukagawa 2005; Katsumi et al. 2008). However, these studies have focused mainly on the use of MSB in clay liners, especially geosynthetic clay liners (GCLs). Katsumi et al. (2004) noted that MSB may be well suited for SB cutoff walls, and Malusis et al. (2010) showed that MSB can be used to create bentonite-water slurry and SB cutoff wall backfill that meets conventional design parameters. However, a more comprehensive study is warranted to determine whether or not MSB can perform better than natural sodium bentonite in SB cutoff walls.

3.2 MATERIALS AND METHODS

3.2.1 Solid Materials

Three types of powdered bentonite clays were used in preparing the SB cutoff wall backfills: (1) NaturalGel (NG, Wyo-Ben, Inc., Billings, MT), a natural (unaltered) sodium bentonite commonly used in cutoff walls; (2) SW101 (Wyo-Ben, Inc., Billings, MT), a modified, contaminant-resistant bentonite developed for use in drilling and cutoff wall applications where exposure to seawater is expected; and (3) MSB (Multigel 225, Hojun Corp., Japan). The NG was chosen as a control for comparison with the two modified bentonites, while SW101 was chosen due to its recent use at the Rocky Mountain Arsenal Superfund site in Colorado (Patton et al. 2007). The treatment used to create SW101 is unknown (proprietary).

The physical and chemical properties and the mineralogical compositions of the three bentonites are summarized in Table 3.1, and their grain size distributions are shown in Figure 3.2. All three bentonites classify as high plasticity clays (CH; ASTM D 2487) and contain predominantly montmorillonite. The liquid limit (to tap water) and cation exchange capacity of MSB are lower than those of NG and SW101.

In addition to the three bentonites, locally supplied sand was used to make the SB backfills (Central Builders Supply, Lewisburg, PA). The sand was a predominantly fine, poorly graded sand (SP; ASTM D 2487) with a fines content of less than 5 % (see Figure 3.2). The gravimetric water content of the sand was controlled at 9 % in order to simulate natural conditions and limit the amount of variables during the study. This sand was used in order to simulate the use of SB cutoff walls installed in a clean sand aquifer, and had a hydraulic conductivity of 1.36×10^{-2} cm/s at a void ratio similar to those of the backfill specimens ($e = 0.92$).

3.2.2 Permeant Liquids

Tap water and calcium chloride ($CaCl_2$) solutions were chosen as the permeant liquids for hydraulic conductivity testing. Their relevant properties are shown in Table 3.2. The tap water was locally sourced (Lewisburg, PA) with a *pH* of 6.6. Tap water was used to establish a baseline *k* for the various SB backfills, as well as to gage the compatibility of the various backfills by examining how the *k* of the backfill changed when exposed to $CaCl_2$ solutions. The $CaCl_2$ solutions were made using anhydrous $CaCl_2$ pellets (Fisher Scientific, Fair Lawn, NJ) dissolved in distilled water (Type II water – ASTM D 1193). Solutions containing $CaCl_2$ concentrations of 0.01, 0.05, 0.2, 0.5, and 1.0 M were used in order to assess the effect of concentration on the *k* of the SB backfills.

Calcium chloride is a chemical permeant commonly used to test the compatibility of hydraulic barriers that utilize swelling clays. For example, one study concluded that a solution with a high concentration of multivalent cations such as Ca^{+2}, compared to a variety of leachate types, is the most aggressive at altering the hydraulic conductivity of geosynthetic clay liners (GCLs), while others have found that GCLs permeated with similar concentrations of either divalent or trivalent cations (e.g., Ca^{+2}, Zn^{+2}, Cu^{+2}, La^{+3}) yield similar final hydraulic conductivities (Ruhl and Daniel 1997; Stern and Shackelford

1998; Jo et al. 2001; Vasko et al. 2001; Jo et al. 2005; Lee and Shackelford 2005a). In this way, because of the aggressiveness and similarity of $CaCl_2$ to other multivalent salts, $CaCl_2$ may be taken as representative of the multitude of multivalent cations that may come into contact with SB cutoff walls used in geoenvironmental containment, and general conclusions can be made concerning the behavior of the several clays tested.

The viscosities (μ) and unit weights (γ) given in Table 3.2 were used to calculate the intrinsic permeability (K) of the backfill specimens. Whereas changes in the hydraulic conductivity (k) of the specimens may be caused by changes in the soil structure (e.g., clay shrinkage and flocculation) as well as changes in permeant viscosity (μ) and unit weight (γ), changes in K are due to changes in the soil structure alone. By examining K, it is possible to neglect changes in permeability due to the physical properties of the liquids, and evaluate more appropriately the liquid-soil interaction effects on k. The relationship between K and k is given as follows (e.g., Shackelford 1994):

$$K = k\frac{\mu}{\gamma} \tag{3.1}$$

3.2.3 Index Testing of Bentonites

Before running hydraulic conductivity tests on the SB backfills, swell index (ASTM D 5890) and liquid limit tests (ASTM D 4318) were performed using the three bentonites to further determine their properties and to assist in predicting and explaining their reaction to the permeant solutions. The tests were used to indirectly assess the compatibility of the three different bentonite clays with the $CaCl_2$ solutions. All three clays were tested with $CaCl_2$ concentrations ranging from 0 to 1.0 M. A reduction in swell index and liquid limit indicates a potential for incompatibility, because as the DDL shrinks, the macro scale swelling of the clay is reduced (Day 1994; Shackelford et al. 2000). Lin et al. (2000) and Katsumi et al. (2008) both showed that the hydraulic conductivity of NG and MSB may be correlated with the swell index of the bentonite. Other studies have suggested that liquid limit may be better than the swell index for determining the swelling ability and hydraulic conductivity of bentonite (Evans 1994; Onikata et al. 1996; Lin et al. 2000).

For the liquid limits to $CaCl_2$ solutions, the 16 hour standing period was eliminated to save time and quickly gain an approximation of the compatibility of the bentonites with increasing $CaCl_2$ concentrations. For these samples, the liquid limit test was undertaken following all other ASTM D 4318 directions immediately after the bentonite was thoroughly mixed with the $CaCl_2$ solution (ASTM D 4318). NG was tested at 1.0 M $CaCl_2$ using this modified method as well as in accordance with ASTM D 4318. The liquid limit values given by both methods were similar (i.e., differed by only 3.5 %).

3.2.4 Backfill Preparation

Bentonite water slurry was created by mixing tap water and bentonite (5 % by weight) in a high-speed colloidal shear mixer (i.e., a Hamilton-Beach 7-speed blender at the highest speed) for 5 min. Separate slurries were made with each of the three bentonites. The slurry was then allowed to hydrate at least 24 hours before being used to create SB backfills. The properties of the slurries conformed to typical construction requirements with the addition of a chromium-free lignosulfonate thinner (Spersene® CF, M-I SWACO, Houston, TX) to the SW101 slurry (see Malusis et al. 2010).

Next, SB backfills were created by mixing the sand, slurry, and additional dry bentonite (3 or 4 % dry weight, same bentonite type as the slurry) in a Hobart mixer (Model #N50, Hobart Corp., Troy, OH). The final mix proportions are shown in Table 3.3. The slurry was added in an amount that would achieve a slump (ASTM C 143-00) of 125±12.5 mm (5±0.5 in.) in order to fulfill constructability requirements (Ryan 1976; Millet and Perez 1981; Spooner et al. 1985; Evans 1993). The addition of the dry bentonite was necessary to achieve a hydraulic conductivity to tap water (k_w) of $\leq 10^{-9}$ m/s, and to create backfill mixtures with the different bentonites that had similar k_w values. Total bentonite contents (by dry weight) in the backfills varied from 4.5 to 5.7 % (see Table 3.3). The slight differences in total bentonite content for backfills prepared using the same percentage of dry bentonite are due to the slightly different amounts of slurry added to the backfills, shown by the sight differences in gravimetric water content (w) of the backfills. After being mixed, backfill samples were allowed to sit for at least 24 hours before being placed into a flexible wall permeameter for hydraulic conductivity testing.

3.2.5 Hydraulic Conductivity Testing

The hydraulic conductivity (k) of the SB backfill samples was determined using flexible wall tests as described in ASTM D 5084, Method C (falling headwater-rising tailwater method). Test specimens were prepared by placing the loose backfill in 3 lifts within the flexible membrane, which was supported by an acrylic mold that was left in place during the test. The acrylic mold was designed so that the cell pressure could still act on the sample during the test. Measurements were taken in order to determine the initial weight-volume relationships for each speicmen. A schematic of the testing apparatus used is shown in Figure 3.3, and further detailed explanation of the specimen preparation procedures are provided by Malusis et al. (2009).

The specimens were consolidated at an effective stress (σ') of 34.5 kPa (5.0 psi), and back-pressured by increasing the cell and pore-water pressures in equal increments over several hours. Permeation was initiated after consolidation was complete. Some samples were permeated with a $CaCl_2$ solution directly (one-stage test) while other samples were permeated with tap water, then with a $CaCl_2$ solution (two-stage test). For one-stage tests, back-pressure saturation typically lasted 48 hours (and not less), although for some samples the back-pressure saturation period was extended another 48 to 72 hours to allow the sample to adequately consolidate before beginning permeation. It was desired to quickly expose these samples to $CaCl_2$, so back-pressure saturation time was kept to a minimum while still allowing for adequate consolidation. For two-stage tests, the back-pressure saturation period lasted at least 72 hours or longer.

Following saturation and consolidation, a hydraulic gradient of approximately 26 was applied across the sample, inducing the flow of the desired permeant through the SB backfill sample. For two-stage tests, permeation with water continued until the termination criteria of ASTM D 5084 were satisfied. At this point, the Skempton B-value was checked to ensure the sample had reached a saturation of at least 95 %. If so, the average of the last four *k* readings was taken as the final hydraulic conductivity to water

(k_w), and the permeant was switched to a $CaCl_2$ solution. Bladder accumulators were used to hold the influent and effluent for samples when permeated with $CaCl_2$ solutions. Permeation of the specimens with $CaCl_2$ solutions was initiated immediately after the bladder accumulators were attached.

Specimens were permeated with $CaCl_2$ solutions until several termination criteria were fulfilled. First, all ASTM D 5084 termination criteria had to be met. This necessitated that (1) the ratio of the effluent volume to the influent volume was equal to 1.0 ± 0.25, and (2) k was steady, as indicated by four or more consecutive measurements of k within ± 25 % of their mean and no significant upward or downward trend.

Secondly, it was desired to ensure chemical equilibrium between the influent and effluent before terminating the test in order to establish the long term hydraulic conductivity. The requirement of chemical equilibrium before terminating a compatibility test has been suggested and used by several authors, and is required when permeating GCLs with potentially incompatible liquids via ASTM D 6766 (Daniel 1994; Shackelford 1994; Jo et al. 2005; Lee and Shackelford 2005a; Katsumi et al. 2008). Two criteria for chemical equilibrium within the specimens were employed, viz., (1) the ratio of effluent to influent electrical conductivity (EC) and (2) the ratio of effluent to influent Ca^{2+} concentration. A ratio of 1.0 ± 0.05 was used for both criteria. Values of EC and Ca^{2+} concentration in the effluent were monitored after every ~0.25 pore volumes of flow (PVF).

In regards to using EC equilibrium as a termination criterion, Shackelford et al. (1999) found that EC breakthrough theoretically occurs at the same time as chemical equilibrium between the influent and effluent. The study found good matching between theoretical and actual EC curves, and concluded that EC curves are a fairly reliable estimate of chemical equilibrium. However, the hydraulic conductivity of a sample can gradually change even after EC equilibrium is reached, indicating that another method is needed to compliment EC readings (Shackelford et al. 2000).

The concentration of Ca^{2+} was used as an additional chemical equilibrium termination criterion in selected tests. Using the salt concentrations in the effluent as a termination criterion has been used previously by studies testing GCLs (Jo et al. 2005; Lee and Shackelford 2005a). In this study, the concentrations of effluent Ca^{2+} (as well as effluent Cl^- and Na^+) were determined using a Dionex (Sunnyvale, CA) ICS-1500 ion chromatograph (IC) in order to ensure complete breakthrough of Ca^{2+}. Once a Ca^{2+} ratio of 1.0 ± 0.05 was achieved (referred to herein as Ca termination), cation exchange was assumed to be complete. Once all these termination criteria were met, the average of the last four *k* readings was taken as the final hydraulic conductivity to the solution of that specific $CaCl_2$ concentration (k_c), and measurements were taken in order to determine the final weight-volume relationships for each specimen.

The decision to run one- and two-stage tests was made in order to assess any "first exposure" effect. Several studies examining GCLs and clay liners exposed to chemical solutions have found that specimens exposed to water before being permeated with a calcium solution have a lower final hydraulic conductivity to the calcium solution than specimens permeated directly with the same calcium solution (Shackelford 1994; Ruhl and Daniel 1997; Stern and Shackelford 1998; Shackelford et al. 2000; Vasko et al. 2001;

Lee and Shackelford 2005a). In these tests, no "first exposure" effect is expected because the bentonite has a chance to hydrate before permeation due to the exposure of the bentonite to water during backfill preparation. Also, a portion of the bentonite in the backfill comes from the bentonite-water slurry, which is subject to high shear mixing. A first exposure effect might possibly exist for slurry walls in which contaminated water and soil is used in creating the backfill, but this study did not examine that possibility. This study did attempt to minimize the amount of time the bentonite had to hydrate for the one-stage tests by only letting the backfill sit for 24 hours before placement into the flexible wall permeameter, and by minimizing consolidation time in order to quickly expose the backfill to the $CaCl_2$ solutions.

3.3 RESULTS AND DISCUSSION

3.3.1 Bentonite Index Tests

The results of swell index and liquid limit tests using $CaCl_2$ solutions on the three tested clays are shown in Figure 3.4. For both tests, MSB had the lowest swell index and liquid limit when exposed to water only (0 M $CaCl_2$), but the highest swell index and liquid limit when exposed to 1.0 M $CaCl_2$. The lower swell index and liquid limit of MSB in water relative to NG and SW101 may be attributed to that fact that the actual fraction of bentonite in 2 g of MSB is reduced due to the addition of PC (Onikata et al. 1996). Overall, MSB had the lowest magnitude of change in swell index and liquid limit across the range of $CaCl_2$ concentrations, showing its decreased sensitivity to electrolyte solutions compared to natural bentonite.

As shown in Figure 3.4a, the MSB experienced an increase in swelling power from distilled water (DW) to 5 mM $CaCl_2$. A similar increase in the swell index of MSB when going from DW to 5 mM $CaCl_2$ was noted by Mazzieri et al. (2005). This "hump" in the swell index and the minimal change in liquid limit for concentrations < 10 mM (see Figure 3.4b) indicate that MSB may perform better in a dilute electrolyte solution than in pure water. The results in Figure 3.4b also show that SW101 experiences an increase in liquid limit from tap water to 10 mM $CaCl_2$. However, SW101 exhibited a jellylike consistency when mixed with the solutions during the liquid limit tests, which made accurate liquid limit testing difficult. Therefore, the liquid limit values for SW101 in Figure 3.4b are considered gross estimates.

The results in Figure 3.4a further show that SW101 had the highest swell index at low concentrations of $CaCl_2$ (≤ 5 mM), but at higher $CaCl_2$ concentrations (≥ 500 mM), SW101 displayed a swell index less than or equal to that of NG. Also, SW101 had the highest liquid limit until 1.0 M $CaCl_2$, but all three clays displayed similar liquid limits at $CaCl_2$ concentrations greater than 0.5 M. The better performance of SW101 at lower concentrations may be explained by the fact that it was designed to be stable in brine solutions, and was not designed to perform as well at such high salt concentrations (≥ 0.5 M $CaCl_2$). Overall, both "contaminant-resistant" bentonites had higher swell indices and liquid limits than natural bentonite (NG) at $CaCl_2$ concentrations less than 0.5 M. These results indicate that both MSB and SW101 may show promise for geoenvironmental containment applications.

3.3.2 Backfill Hydraulic Conductivity

Table 3.4 shows the results of the numerous flexible-wall hydraulic conductivity tests on consolidated SB backfill specimens. This table shows *k* and *K* values at the end of water permeation and $CaCl_2$ permeation, along with the total time and PVFs the specimen was permeated with each liquid. The ratios of final *k* and *K* values at the end of permeation with $CaCl_2$ (k_{fc}, K_{fc}) and tap water (k_{fw}, K_{fw}) for each specimen are also given (k_{fc}/k_{fw}, K_{fc}/K_{fw}). These values give an indication of how much the permeability of the specimen was impacted by the $CaCl_2$ solution. The final void ratio at the completion of permeation is also given.

3.3.2.1 Hydraulic Conductivity to Water

Values of hydraulic conductivity to tap water (k_w) for backfill specimens containing NG, MSB, and SW101 are plotted versus PVF in Figure 3.5. The left column (Figure 3.5a, Figure 3.5c, and Figure 3.5e) shows the hydraulic conductivity of the original backfill mixes created. The backfills containing 4.6 % NG and 4.5 % MSB had higher k_w values than the backfill containing 4.6 % SW101, and some of the NG and MSB backfill specimens exhibited k_w values greater than 10^{-9} m/s. As a result, backfills containing 5.7 % NG and 5.6 % MSB were prepared in order to create specimens with lower k_w values (see Figure 3.5b and Figure 3.5d). The final k_w values (i.e., k_{fw}) for these backfill specimens were all less than 10^{-9} m/s and were similar to the k_{fw} values for the 4.6 % SW101 backfill, as shown in Figure 3.5f. Therefore, the backfills containing 5.7 % NG, 5.6 % MSB, and 4.6 % SW101 were the three backfills subjected to permeation with the $CaCl_2$ solutions.

3.3.2.2 Hydraulic Conductivity to $CaCl_2$ Solutions

The results of the two-stage tests in which specimens were permeated with $CaCl_2$ solutions after tap water are shown in Figure 3.6 (5.7% NG), Figure 3.7 (5.6% MSB), and Figure 3.8 (4.6 % SW101). The results show that all of the specimens exhibited an increase in *k* upon permeation with the $CaCl_2$ solutions. However, the specimens containing 5.6 % MSB appeared to exhibit the smallest increases in *k* (Figure 3.7), whereas the specimens containing 4.6 % SW101 appeared to exhibit the largest increases in *k* (Figure 3.8). Note that for two of the SW101 backfills permeated with $CaCl_2$, the final *k* (i.e., k_{fc}; see Table 3.4) was slightly above 10^{-9} m/s, an undesirably high value for a cutoff wall. Also note that for the specimens permeated with 0.01 M $CaCl_2$, an air compressor malfunction may have caused the sudden jump in *k* towards the end of each test, so results for these tests are inconclusive.

As shown in Figure 3.8, the specimens containing 4.6 % SW101 typically exhibited a gradual increase in *k* during the tap water permeation stage before finally reaching a steady final k_w (i.e., k_{fw}) after >1 PVF, suggesting that a change in the swell behavior or fabric of SW101 occurred during tap water permeation. The SW101 backfill specimen permeated with 1.0 M $CaCl_2$ (Figure 3.8d) did not exhibit this gradual increase in *k* during tap water permeation, but may have done so if the tap water permeation stage was carried out longer before switching to 1.0 M $CaCl_2$. Therefore, the k_{fw} value reported in Table 3.4 for this particular specimen was slightly lower than the k_{fw} values for the other specimens containing 4.6 % SW101.

The final results of these two-stage tests are summarized in Figure 3.9. Figure 3.9a shows each k_{fc} value as a function of the concentration of $CaCl_2$. As seen in this Figure 3.9a, k_{fc} values seem relatively unaffected by $CaCl_2$ concentration, with the distinguishing factor being the type of clay used in the backfill specimens. The 5.6 % MSB backfill maintained the lowest k_{fc} values for all $CaCl_2$ concentrations tested. The 5.7 % NG backfill maintained the next lowest k_{fc}, followed by the 4.6 % SW101 backfill, which had a slightly lower k_{fc} than 5.7 % NG when permeated with 1.0 M $CaCl_2$.

Figure 3.9b normalizes the amount of increase in k by plotting the ratio of k_{fc} to k_{fw} for each specimen as a function of $CaCl_2$ concentration. The k_{fc}/k_{fw} values for the 5.6 % MSB specimens ranged from 1.38 to 2.08. In contrast, the k_{fc}/k_{fw} values for the 5.7 % NG backfill ranged from 2.59 to 3.09, whereas the k_{fc}/k_{fw} values for the 4.6 % SW101 specimens ranged from 2.46 to 4.29. Thus, in general, the 4.6 % SW101 specimens exhibited the greatest k_{fc}/k_{fw} value, while the 5.6 % MSB specimens exhibited the smallest k_{fc}/k_{fw} value. These results are consistent with the liquid limit and swell index results in Figure 3.4a-b, which also showed that MSB was less sensitive to $CaCl_2$ solutions.

The SW101 backfill shows an interesting trend by displaying a decrease in the k_{fc}/k_{fw} ratio as the $CaCl_2$ concentration increases (this decreasing trend may have continued for 1.0 M $CaCl_2$ if the tap water permeation stage was conducted long enough to capture the increase in k_w over time that was observed in the other tests in Figure 3.8). This trend is the opposite of what would be expected for compatibility testing as higher concentrations of electrolyte solutions typically have a more detrimental effect on clay barriers.

Figure 3.9c shows the ratio of the final intrinsic permeability to $CaCl_2$ (K_{fc}) to the final intrinsic permeability to tap water (K_{fw}) – the intrinsic permeability ratio. This plot also shows that the SW101 backfill shows an interesting trend by displaying a decrease in the K_{fc}/K_{fw} ratio as the $CaCl_2$ concentration increases, indicating that this trend is due to actual changes within the backfill. This plot also shows the expected trend for a clay barrier – as the $CaCl_2$ concentration increases, so does the K_{fc}/K_{fw} ratio for NG (higher electrolyte concentrations typically have a more detrimental effect on clay barriers). Finally, the plot of K_{fc}/K_{fw} ratios shows that the permeability increases in MSB are fairly constant regardless of $CaCl_2$ concentration.

The results of permeating backfill specimens with $CaCl_2$ directly (one-stage tests) are shown in Figure 3.10 (5.7 % NG), Figure 3.11 (5.6 % MSB), and Figure 3.12 (4.6 % SW101). Once again, all specimens exhibit increases in k upon permeation with the $CaCl_2$ solutions. However, all specimens maintained a k_{fc} value less than 10^{-9} m/s.

The final results of these one-stage tests are summarized in Figure 3.13. Figure 3.13a shows each k_{fc} value as a function of the concentration of $CaCl_2$. As seen for two-stage tests (Figure 3.9a), Figure 3.13a also shows that for one-stage tests k_{fc} values seem relatively unaffected by $CaCl_2$ concentration, with the distinguishing factor once again being the type of clay used in the backfill specimens. The 5.6 % MSB backfill maintained the lowest k_{fc} values for all $CaCl_2$ concentrations tested. The 5.7 % NG backfill maintained the next lowest k_{fc}, followed much more closely this time by the 4.6

% SW101 backfill, which maintains k_{fc} values less than 10^{-9} m/s for all four SW101 one-stage tests.

Figure 3.13b shows the k_{fc}/k_{fw} ratios for the one-stage test specimens. As a result of its lower k_{fc} values, the k_{fc}/k_{fw} ratios for 4.6 % SW101 specimens (2.30 to 2.45) are reduced in comparison to similar two-stage tests using the same $CaCl_2$ concentration. 5.6 % MSB and 5.7 % NG specimen k_{fc}/k_{fw} ratios (1.96 to 2.15 and 2.24 to 2.36 respectively) are relatively unaffected as both one- and two-stage tests of MSB and NG backfills yielded similar k_c values. In general, the 4.6 % SW101 specimens still exhibit the greatest k_{fc}/k_{fw} value, while the 5.6 % MSB specimens exhibit the smallest k_{fc}/k_{fw} value. Also, k_{fc}/k_{fw} ratios are relatively steady for each clay type.

Figure 3.13c shows the intrinsic permeability ratios. Once again, the NG backfill has a slight increase in the K_{fc}/K_{fw} ratio as the $CaCl_2$ concentration increases. However, unlike the two-stage tests, for the one-stage tests SW101 also displays an increase in the K_{fc}/K_{fw} ratio as the $CaCl_2$ concentration increases. MSB seems to also have an increasing K_{fc}/K_{fw} ratio as the concentration of $CaCl_2$ increases.

3.3.2.3 Influence of Bentonite

A summary of the hydraulic conductivity tests for both one- and two-stage tests is shown in Figure 3.14. From these plots, it can be seen that the MSB backfill maintained the lowest k_c values and experienced the least change in k and K in comparison to the NG and SW101 backfills. Once again, the decreased sensitivity of MSB to $CaCl_2$ as predicted by the initial index testing was proven through multiple flexible wall hydraulic conductivity tests. Both one- and two-stage tests showed similar results for MSB.

NG backfill also performed well, exhibiting lower k_c values and less change in k and K than SW101 backfill in almost every situation. For the range of $CaCl_2$ solutions used for testing, NG backfill appears to be fairly compatible, with k_{fc}/k_{fw} ratios of not much more than 3, and K_{fc}/K_{fw} ratios of less than 4. NG experiences even smaller k_{fc}/k_{fw} and K_{fc}/K_{fw} ratios when exposed directly to the $CaCl_2$ contaminant (one-stage testing). These results indicate that compatibility with inorganic contaminants may not even be a major concern for SB cutoff walls built with natural sodium-bentonite.

Meanwhile, SW101, the other contaminant-resistant bentonite, exhibits high k_{fc} values and large changes in k and K in all tests compared to MSB and NG backfills. However, for the one-stage tests with SW101 backfill, SW101 does perform in a way that indicates it has acceptable compatibility with the $CaCl_2$ solutions (k_{fc}/k_{fw} ratios of less than 2.5, K_{fc}/K_{fw} ratios no greater than 3.0). The k_{fc} values of SW101 are also lower for one-stage tests than for two-stage tests. It is interesting to note that while SW101 showed an overall decrease in k_{fc}/k_{fw} and K_{fc}/K_{fw} ratios with increasing $CaCl_2$ concentrations for two-stage tests, for one-stage tests SW101 showed the opposite trend for K_{fc}/K_{fw} ratios. Overall, the behavior of SW101 backfill is unusual when permeated with $CaCl_2$ solutions.

It should be noted that while SW101 performed the worst in these tests (high k_{fc} values and large k_{fc}/k_{fw} and K_{fc}/K_{fw} ratios) SW101 backfill also utilized the least amount of bentonite and with more bentonite may have performed better than the other clay products tested. Also, the presence of the thinner in the SW101 backfill (from the SW101 slurry) may have negatively impacted the ability of SW101 to maintain a low hydraulic conductivity. As previously mentioned, SW101 has a jellylike consistency when swelling in an aqueous solution. The addition of the thinner to SW101 reduces its jellylike consistency. Ultimately, the cause of the unusual behavior of SW101 may lie in the unknown method with which it was modified.

Additionally, SW101 can be seen as a high quality bentonite in that it maintains a lower hydraulic conductivity to water than other bentonites, but once exposed to a chemical permeant it has a higher hydraulic conductivity than other bentonites (see Lee and Shackelford 2005b). If this is true, the addition of more SW101 may lead to more sensitivity to $CaCl_2$ solutions and larger k_{fc}/k_{fw} ratios as opposed to smaller. In fact, by plotting bentonite content versus the intrinsic permeability ratio in Figure 3.15, a trend towards greater increases in permeability with more bentonite is clearly seen for a variety of bentonite barriers. SW101 falls nearly perfectly along this trend. Although Patton et al. (2007) found that SW101 is capable of producing an acceptable SB backfill for geoenvironmental containment, further testing may be necessary to fully investigate the usefulness of SW101 for SB cutoff walls.

Interestingly, MSB falls below the trend line in Figure 3.15, showing that the permeability of MSB is less affected by 0.5 M $CaCl_2$ than other bentonite clays would be at the same bentonite content. This echoes the results of the liquid limit, swell index, and hydraulic conductivity tests with MSB, all of which indicated the reduced sensitivity of MSB to $CaCl_2$ solutions. Ultimately, however, while MSB does provide the performance showing the most compatibility with $CaCl_2$, NG also provides satisfactory performance, and may display the necessary compatibility for many geoenvironmental containment applications. This lack of a major difference in the performance of MSB versus NG and

SW101 may be explained by the ability of all the clays to undergo osmotic swell before permeation with the $CaCl_2$ solution. Therefore, the advantage of MSB in being able to undergo osmotic swelling in aqueous electrolyte solutions was lost as NG and SW101 had already undergone osmotic before contact with $CaCl_2$.

The results of these hydraulic conductivity tests are comparable to a study conducted by D'Appolonia (1980a) that examined the compatibility of SB backfill with sodium and calcium salt solutions. Results for specimens hydrated with fresh water and then permeated with $CaCl_2$ showed a k_{fc}/k_{fw} ratio of approximately 3 times (k_w and k_c values not given). D'Appolonia and Ryan (1979) also permeated SB backfill with a calcium solution and found that the k_{fc}/k_{fw} ratio was around 3. Evans et al. (1995) permeated a SB backfill specimen with a solution of 4 mg/L of chromium, resulting in a k_{fc}/k_{fw} ratio of approximately 10 times ($k_{fw} \approx 10^{-8}$ m/s). These k_{fc}/k_{fw} ratios for SB backfills permeated with inorganic solutions correspond reasonably well with the magnitudes of change in this study.

Unlike GCL and compacted clay specimens (e.g., Stern and Shackelford 1998; Lee and Shackelford 2005a), it appears that SB backfill does not experience drastic changes in hydraulic conductivity due to permeation with electrolyte solutions (see Figure 3.16), although the effects of chemical compatibility should not be ignored. In fact, these results indicate that SB backfill specimens show only a limited increase in K that is generally constant for specimens containing the same type of clays, regardless of $CaCl_2$ concentration. On the other hand, the K_{fc}/K_{fw} ratios for GCLs and compacted clay specimens are typically much larger and have a concentration dependency as shown in Figure 3.16.

However, these results do agree with several GCL studies that have found when bentonite is allowed to hydrate and undergo osmotic swelling, clay liners maintain a lower *k* to dilute inorganic solutions given that the bentonite does not dry out (Jo et al. 2001; Jo et al. 2005; Benson and Meer 2007; Scalia and Benson 2010). Due to the water present in SB backfills from the bentonite-water slurry and the natural moisture of the soil, the bentonite in the backfills is allowed to hydrate and presumably undergo osmotic swelling before permeation with a contaminant liquid is begun. Therefore, the SB backfills should also be expected to maintain a low *k* to inorganic solutions as well, which these results seem to show.

In addition, once osmotic swell of bentonite occurs it is difficult to undo. Several studies indicate that once bentonite has undergone osmotic swelling, a low *k* can be maintained even if divalent cations replace sodium cations on the bentonite exchange complex (Gleason et al. 1997; Shackelford et al. 2000; Egloffstein 2001; Egloffstein 2002; Jo et al. 2005). Similar results are seen in this study – the effluent ion concentrations indicate that cation exchange occurred by the conclusion of many tests, but a low *k* is still maintained. However, if the bentonite is allowed to dry out after divalent cations have become the predominant cation on the exchange complex, osmotic swell will not occur (Norrish and Quirk 1954; Meer and Benson 2007). Because the bentonite in the SB backfills is presumed to be in an osmotic swell state from the start, and as long as dessication of the backfill does not occur (e.g., due to rise and fall of the groundwater table), various concentrations of $CaCl_2$ appear to have little effect on the swell state of the clay. As a result, these tests exhibit no drastic changes in *k* upon exposure to $CaCl_2$, as well as a lack of major trends with $CaCl_2$ concentration.

3.3.2.4 First Exposure Effects

Once all testing was complete, the results of the one- and two-stage tests were compared to evaluate any potential first exposure effect. The first exposure ratio (FER) is calculated as follows (Lee and Shackelford 2005a):

$$FER = \frac{k_{fc1}}{k_{fc2}} \tag{3.2}$$

where the subscripts 1 and 2 represent one- and two-stage tests, respectively, conducted using the same backfill type and $CaCl_2$ concentration. This equation is often used to evaluate any first exposure effect, such that a FER value of 1.0 indicates no first exposure effect. A FER value greater than 1.0 indicates that specimens maintain lower hydraulic conductivities to a contaminant when permeated with water first, and a FER value less than 1.0 indicates that specimens have higher hydraulic conductivities when permeated with water before the contaminant of interest.

Figure 3.17 shows the FER values for three SB backfill mix types. It can been observed that all three backfill mixes have FER values approximately equal to or less than 1.0, indicating that all SB backfills tested had the same or lower k_{fc} values when permeated directly with a $CaCl_2$ solution as opposed to being permeated with tap water first.

The NG backfill appears to have the overall highest FER, with values around 1.0, which indicates no first exposure effect. Interestingly, MSB has a FER of 0.8 at 0.5 M $CaCl_2$, while SW101 maintains FER values less than 0.8 until 1.0 M $CaCl_2$. The FER value of 1.07 for the SW101 backfill at 1.0 M $CaCl_2$ may be a result of the abnormally low k_c value of the two-stage 1.0 M $CaCl_2$ test due to the low k_w value for this test. Ultimately, it appears that both of the contaminant-resistant bentonites may exhibit a FER value less than 1.0. It is possible that permeation with tap water prior to $CaCl_2$ permeation may negatively affect the ability of these modified clays to resist chemical attack, possibly by washing out some of the additives.

Because all three SB backfills tested yielded FER values equal to or less than 1.0, it appears that SB backfills lack a first exposure effect. In fact, the results suggest that permeating some SB specimens with tap water first may actually yield worse compatibility results (i.e., higher k_{fc} values) than permeating the specimen with the contaminant directly. Therefore, permeating specimens with tap water first may be the conservative approach for compatibility testing of SB backfills.

The lack of a first exposure effect may be explained by the fact that bentonite in SB backfill has a chance to hydrate before permeation due to the presence of moisture in the soil the bentonite is mixed with during backfill creation. Even more, the majority of the bentonite in the backfill comes from the bentonite-water slurry. Therefore, the bentonite has a chance to undergo osmotic swelling before contacting $CaCl_2$ solution, regardless of whether it is permeated with tap water prior to the $CaCl_2$. As previously discussed, once bentonite undergoes osmotic swelling, it is difficult to reverse, even if divalent cations replace sodium in the exchange complex.

The lack of a first exposure effect for SB backfills stands in contrast to other bentonite barriers (e.g., GCLs, compacted barriers), which display FER values much larger than 1.0 (see Figure 3.18). At low concentrations of $CaCl_2$ (≤ 50 mM), the GCL specimens in Figure 3.18 show little first exposure effect. However, as the concentration increases, so does the FER value for both GCLs and the compacted S-A-B specimen. Unlike the SB backfill specimens, the GCL and S-A-B specimens appear to undergo osmotic swelling during permeation with water due to rapid and substantial decreases in k with increasing PVF during the water permeation stage (see Stern and Shackelford 1998; Shackelford et al. 2000; Lee and Shackelford 2005a). As a result, the fabric of the two-stage specimens at the onset of $CaCl_2$ permeation had been changed relative to that of the corresponding one-stage specimens, yielding a first exposure effect. Because the bentonite is SB backfills is allowed to undergo osmotic swelling before permeation with any liquid, the fabric of the one- and two-stage specimens is nearly identical, resulting in FER values of approximately 1.0.

While the bentonite is SB backfills begins in an osmotic swell state, the bentonite in many other bentonite barriers often does not. In fact, unless prehydrated, bentonite in other clay barriers may hydrate in an electrolyte solution, likely limiting the bentonite to crystalline swelling. For clay barriers that are allowed to hydrate prior to permeation with an electrolyte solution, the large amount of clay and compacted nature of the barrier may limit the amount of bentonite that does come into contact with a sufficient amount of water to undergo osmotic swelling, as well as physically constrain the room the bentonite has to swell, thereby imparting external constraining forces on the clay.

3.3.2.5 Effect of Termination Criteria

Table 3.5 shows the PVFs required for each specimen to reach the previously discussed termination criterion, as well as the k_c value when the corresponding termination criterion was met. These results and the trends they reveal are discussed below.

Figure 3.19 shows the PVFs required to reach the termination criteria for each two-stage test specimen. It often took close to or less than one PVF to reach ASTM D 5084 termination criterion, with EC and Ca termination criterion being met closer to two or three PVFs for the majority of the samples. However, as Figure 3.20 shows, even by the time ASTM D 5084 criterion were met, the hydraulic conductivity of the SB backfill specimen was already nearly equivalent to the final hydraulic conductivity of the specimen, regardless of clay type or $CaCl_2$ concentration. Note that several of the points not fitting this trend are due to the air compressor malfunction while the 0.01 M $CaCl_2$ tests were being run, yielding a k_{fc} value that may be inaccurately high.

Figure 3.21 shows the PVFs required to reach the several termination criteria for each one-stage test specimen. Overall, almost every one-stage specimen took longer to reach ASTM D 5084 termination criterion than its corresponding two-stage specimen of the same clay type and $CaCl_2$ concentration. On the other hand, EC and Ca termination criterion took less time from two- to one-stage tests for MSB and NG backfills. In general, one- and two-stage tests were permeated with $CaCl_2$ for relatively similar PVFs.

Examining Figure 3.21 also shows that a slight trend may exist for Ca termination of one-stage specimens. Ca termination was reached with less PVFs as the $CaCl_2$ concentration of the permeant increased. This trend, however, is small but may be due to higher $CaCl_2$ concentration solutions being able to more rapidly replace cations in the clay due to the shear abundance of calcium cations.

Figure 3.22 shows that for one-stage tests, at any termination criterion the hydraulic conductivity of the SB backfill specimen was already nearly equivalent to the final hydraulic conductivity of the specimen, regardless of clay type of $CaCl_2$ concentration. This is similar to the results of the two-stage tests. Overall, these results indicate that ASTM D 5084 termination criteria may provide a reliable initial approximation of k_{fc} for SB backfill compatibility testing with inorganic contaminants.

Additionally, specimens containing bentonite typically require a decreasing number of PVFs to reach termination criterion as the concentration of $CaCl_2$ increases (Lee and Shackelford 2005a; Shackelford 2007). However, this study does not show any strong trends of a similar nature (see Figure 3.19 and Figure 3.21). Ultimately the PVFs required for final termination of the one- and two-stage test specimens were largely unaffected by $CaCl_2$ concentration for all of the SB backfill mixes.

3.4 CONCLUSIONS

In conjunction with Malusis et al. (2010), this study shows that SB backfills can be made using MSB to meet both construction requirements as well as provide acceptable k values to both water and inorganic electrolyte solutions ($CaCl_2$). MSB showed a decreased sensitivity to electrolyte solutions throughout this study, both in the clay index testing and in hydraulic conductivity tests on MSB backfill. Final hydraulic conductivity values to $CaCl_2$ never increased beyond 5.75 x 10^{-10} m/s for MSB backfill specimens.

NG and SW101 backfills also maintained low k_{fc} values, although some SW101 backfill specimens did experience k_{fc} values greater than 10^{-9} m/s when permeated with $CaCl_2$ solutions. NG backfills maintained k_{fc} values less than 7.4 x 10^{-10} m/s, less than 1.3 times greater than MSB k_{fc} values. All backfills had k_{fc}/k_{fw} and K_{fc}/K_{fw} ratios of less than 5 and all but a few had k_{fc} values less 10^{-9} m/s, indicating that compatibility with inorganic contaminants should not be a major concern for SB cutoff wall backfill. In fact, natural sodium-bentonite may produce SB backfills that have acceptable compatibility with inorganic contaminants for many geoenvironmental containment applications.

Along with the lack of major compatibility issues, the backfill specimens showed that what compatibility issues they did face were largely independent of $CaCl_2$ concentration. Hydraulic conductivity values were fairly stable for SB backfills of each bentonite type, regardless of the $CaCl_2$ concentration the specimen was permeated with. Changes were also relatively independent of what liquid the backfill specimen was first permeated with, as the bentonite had already had a chance to undergo osmotic swelling before hydraulic conductivity tests even began. It appears that the osmotic swelling of the bentonite in the SB backfills is largely irreversible, even if cation exchange is allowed to continue to completion.

In addition, this study illustrated that once ASTM D 5084 termination criteria are met, the k_c of the specimen is within close proximity to the k_{fc} value. This indicates that the termination criteria of ASTM D 5084 may be appropriate for initial compatibility testing of SB backfills. For subsequent compatibility testing, when it is desired to reach chemical equilibrium, this study demonstrated that generally only a few (~ 2 to 3) PVFs are needed for SB backfill specimens.

Overall, this study shows that SB cutoff walls are excellent barriers to the migration of inorganic contaminants. Few compatibility issues were experienced with an aggressive inorganic salt ($CaCl_2$), with k_{fc} values generally maintained below 10^{-9} m/s. Results showing that pre-permeation with water or the lack thereof has little effect on the k_{fc} value of the backfill specimen, along with the fact that k_c values at ASTM D 5084 termination are similar to k_{fc} values, will hopefully prove useful to geoenvironmental practitioners.

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Table 3.1. Properties and mineralogy of bentonites tested in study.

Property	Standard	Value		
		MSB	NG	SW101
Soil classification	ASTM D 2487	CH	CH	CH
Liquid limit (%)	ASTM D 4318[a]	547	583	1007
Plastic limit (%)	ASTM D 4318[a]	44.6	52.7	42.7
Plasticity index (%)	ASTM D 4318[a]	502	530	965
Swell Index (mL/2g)	ASTM D 5890[b]	28.5	35.0	43.0
Principal minerals (%)	c			
Montmorillonite		74	69	86
Cristobalite		10	14	6
Quartz		2	12	3
Plagioclase Feldspar		4	2	2
Other		10	3	3
Cation exchange capacity (meq/100 g)	d	49.8	83.4	85.7
Exchangeable metals (meq/100 g)	d			
Ca		7.7	4.9	6.1
Mg		6.1	8.8	10.2
Na		33.3	73.4	64.1
K		0.5	1.1	0.2
Sum		47.6	88.2	80.6
Soluble metals (mg/kg)	d			
Ca		1323	46.1	441
Mg		863	15.3	109
Na		1747	2042	2575
K		<39	58.4	39.1
Soil pH	ASTM D 4972[b]	8.1	8.7	9.7

[a] Measured using tap water (*pH* = 6.6, *EC* = 22.2 mS/m)
[b] Measured using distilled water (*EC* = 0.067 mS/m)
[c] X-ray diffraction analysis performed by Mineralogy, Inc. (Tulsa, OK)
[d] Procedures given by Shackelford and Redmond (1995), performed by Colorado State University (Fort Collins, CO)

Table 3.2. Properties of permeant liquids used in study.

Permeant Liquid	**$CaCl_2$ Concentration (M)**	**Ca^{2+} Concentration (ppm)**	**Absolute Viscosity, μ (mPa·s)**	**Unit Weight, γ (kN/m^3)**	**Electrical Conductivity, *EC* (mS/m)**
Tap Water	---	19.8	1.01	9.81	22.2
$CaCl_2$ Solutions	0.01	381	1.01	9.81	240
	0.05	1857	1.02	9.94	1050
	0.2	7449	1.07	9.92	3680
	0.5	18526	1.17	10.1	8180
	1.0	36628	1.35	10.4	14160

[a] Measured using Dionex (Sunnyvale, CA) ICS-1500 ion chromatograph
[b] Values at 20 °C (from Wahab and Mahiuddin 2001)
[c] Values for $CaCl_2$ solutions computed based on $CaCl_2$ specific gravity of 2.15
[d] Measured using Thermo (Beverly, MA) Orion 162A benchtop EC meter

Table 3.3. Relevant properties of model soil-bentonite backfill mixtures.

Bentonite Type	Dry Bentonite Amendment (dry wt. %)	Total Bentonite Content[a] (dry wt. %)	Sand Content (dry wt. %)	Gravimetric Water Content, *w* (%)	Mean Slump[b] (mm)
MSB	3	4.5	95.5	38.5	127
	4	5.6	94.4	40.0	128
NG	3	4.6	95.4	40.0	115
	4	5.7	94.3	43.0	114
SW101	3	4.6	95.4	39.9	120

[a] Dry bentonite amendment plus bentonite from slurry.
[b] Based on a minimum of two replicates

Table 3.4. Results of flexible-wall hydraulic conductivity tests on consolidated SB backfill specimens (σ' = 34.5 kPa).

Backfill	Specimen No.	e_f	Tap Water (w) k_{fw} (m/s)	K_{fw} (m^2)	Test Duration t (days)	PVF	CaCl$_2$ Solution (c) C (M)	k_{fc} (m/s)	K_{fc} (m^2)	Test Duration t (days)	PVF	k_{fc}/k_{fw}	K_{fc}/K_{fw}
4.6 % NG	1a	0.92	$1.38\text{x}10^{-9}$	$1.42\text{x}10^{-16}$	13.8	1.15	---	---	---	---	---	---	---
	1b	0.90	$5.54\text{x}10^{-10}$	$5.70\text{x}10^{-17}$	13.8	0.44	---	---	---	---	---	---	---
	1c	0.85	$5.76\text{x}10^{-10}$	$5.93\text{x}10^{-17}$	13.8	0.44	---	---	---	---	---	---	---
4.5 % MSB	2a	0.86	$5.02\text{x}10^{-9}$	$5.17\text{x}10^{-16}$	27.4	14.8	---	---	---	---	---	---	---
	2b	---	$1.25\text{x}10^{-8}$	$1.29\text{x}10^{-15}$	10.2	8.12	---	---	---	---	---	---	---
	2c	0.87	$2.01\text{x}10^{-9}$	$2.07\text{x}10^{-16}$	29.8	7.20	---	---	---	---	---	---	---
4.6 % SW101	3a	0.88	$3.12\text{x}10^{-10}$	$3.21\text{x}10^{-17}$	182	2.09	0.01	$1.01\text{x}10^{-9}$	$1.04\text{x}10^{-16}$	95.2	3.66	3.23	3.23
	3b	0.84	$2.47\text{x}10^{-10}$	$2.54\text{x}10^{-17}$	141	1.29	0.05	$1.06\text{x}10^{-9}$	$1.09\text{x}10^{-16}$	101.6	4.28	4.29	4.28
	3c	0.84	$2.65\text{x}10^{-10}$	$2.72\text{x}10^{-17}$	198	1.65	0.2	$9.76\text{x}10^{-10}$	$1.05\text{x}10^{-16}$	84.7	3.83	3.69	3.87
	3d	0.85	$4.36\text{x}10^{-10}$	$4.48\text{x}10^{-17}$	209	2.69	0.5	$1.07\text{x}10^{-9}$	$1.24\text{x}10^{-16}$	68.0	3.50	2.46	2.77
	3e	0.79	$1.76\text{x}10^{-10}$	$1.81\text{x}10^{-17}$	36.4	0.34	1.0	$6.93\text{x}10^{-10}$	$9.00\text{x}10^{-17}$	70.7	2.60	3.95	4.98
	3f	0.88	The given k_{fc}/k_{fw} and K_{fc}/K_{fw} ratios for these specimens are based on k_{fw} and K_{fw} values of Specimen 3a, which was from the same backfill batch				0.05	$7.65\text{x}10^{-10}$	$7.85\text{x}10^{-17}$	208.3	5.77	2.45	2.45
	3g	0.88					0.2	$7.38\text{x}10^{-10}$	$7.96\text{x}10^{-17}$	111.6	3.27	2.37	2.48
	3h	0.84					0.5	$7.18\text{x}10^{-10}$	$8.31\text{x}10^{-17}$	143.3	4.75	2.30	2.59
	3i	0.84					1.0	$7.44\text{x}10^{-10}$	$9.65\text{x}10^{-17}$	76.3	2.30	2.39	3.01
5.7 % NG	4a	0.90	$3.11\text{x}10^{-10}$	$3.20\text{x}10^{-17}$	112	1.46	0.01	$7.78\text{x}10^{-10}$	$8.01\text{x}10^{-17}$	87.9	2.39	2.50	2.50
	4b	0.94	$2.66\text{x}10^{-10}$	$2.74\text{x}10^{-17}$	28.8	0.39	0.05	$6.89\text{x}10^{-10}$	$7.07\text{x}10^{-17}$	92.4	2.73	2.59	2.58
	4c	0.92	$2.25\text{x}10^{-10}$	$2.32\text{x}10^{-17}$	20.5	0.26	0.2	$6.82\text{x}10^{-10}$	$7.35\text{x}10^{-17}$	85.4	2.64	3.03	3.18
	4d	0.84	$2.76\text{x}10^{-10}$	$2.84\text{x}10^{-17}$	29.2	0.41	0.5	$6.82\text{x}10^{-10}$	$7.90\text{x}10^{-17}$	65.0	2.21	2.48	2.79
	4e	0.83	$2.31\text{x}10^{-10}$	$2.38\text{x}10^{-17}$	26.4	0.33	1.0	$7.13\text{x}10^{-10}$	$9.26\text{x}10^{-17}$	61.8	2.28	3.09	3.89
	4f	0.86	k_{fc}/k_{fw} and K_{fc}/K_{fw} ratios are based on k_{fw} and K_{fw} of Specimen 4a, same backfill batch				0.05	$6.97\text{x}10^{-10}$	$7.15\text{x}10^{-17}$	91.3	2.52	2.24	2.24
	4g	0.90					0.2	$7.32\text{x}10^{-10}$	$7.89\text{x}10^{-17}$	120	3.93	2.36	2.47
	4h	0.88					0.5	$7.08\text{x}10^{-10}$	$8.20\text{x}10^{-17}$	83.2	2.75	2.28	2.56
5.6 % MSB	5a	0.90	$2.14\text{x}10^{-10}$	$2.21\text{x}10^{-17}$	181	1.47	0.01	$4.98\text{x}10^{-10}$	$5.12\text{x}10^{-17}$	90.7	1.57	2.32	2.32
	5b	0.87	$2.18\text{x}10^{-10}$	$2.25\text{x}10^{-17}$	18.5	0.21	0.05	$4.22\text{x}10^{-10}$	$4.33\text{x}10^{-17}$	121.9	2.40	1.93	1.93
	5c	0.88	$2.01\text{x}10^{-10}$	$2.07\text{x}10^{-17}$	18.5	0.20	0.2	$4.18\text{x}10^{-10}$	$4.51\text{x}10^{-17}$	111.0	2.15	2.08	2.18
	5d	0.85	$3.14\text{x}10^{-10}$	$3.23\text{x}10^{-17}$	65.3	1.19	0.5	$5.75\text{x}10^{-10}$	$6.67\text{x}10^{-17}$	85.6	2.53	1.84	2.07
	5e	0.83	$2.54\text{x}10^{-10}$	$2.62\text{x}10^{-17}$	82.6	1.00	1.0	$3.51\text{x}10^{-10}$	$4.56\text{x}10^{-17}$	107.5	2.23	1.38	1.74
	5f	0.89	k_{fc}/k_{fw} and K_{fc}/K_{fw} ratios are based on k_{fw} and K_{fw} of Specimen 5a, same backfill batch				0.05	$4.38\text{x}10^{-10}$	$4.49\text{x}10^{-17}$	206	4.12	2.04	2.04
	5g	0.91					0.2	$4.20\text{x}10^{-10}$	$4.53\text{x}10^{-17}$	178	3.51	1.96	2.05
	5h	0.84					0.5	$4.60\text{x}10^{-10}$	$5.33\text{x}10^{-17}$	101	2.27	2.15	2.41

e_f = final void ratio; k_f = final hydraulic conductivity; K_f = final intrinsic permeability; C = source concentration

Table 3.5. Pore volumes of flow (PVF) and hydraulic conductivites to $CaCl_2$ solution (k_c) corresponding to achievement of termination criteria based on ASTM D 5084 (k_{5084}), ratio of effluent to influent EC (k_{EC}), and ratio of effluent to influent Ca^{2+} concentration (k_{Ca}) in one-stage and two-stage tests. Final values of PVF and k_c (i.e., k_{fc}) are shown for comparison.

Backfill	Specimen No.	Termination Criterion						Final Values	
		ASTM D 5084		EC Ratio		Ca^{2+} Ratio			
		PVF	K_{5084} (m/s)	*PVF*	K_{EC} (m/s)	*PVF*	K_{Ca} (m/s)	*PVF*	k_{fc} (m/s)
4.6 % SW101	3a	3.19	9.58×10^{-10}	1.50	7.09×10^{-10}	---	---	3.66	1.01×10^{-9}
	3b	2.27	9.58×10^{-10}	2.11	9.30×10^{-10}	2.96	9.80×10^{-10}	4.28	1.06×10^{-9}
	3c	1.30	9.22×10^{-10}	1.78	9.39×10^{-10}	1.56	9.34×10^{-10}	3.83	9.76×10^{-10}
	3d	1.25	1.07×10^{-9}	2.30	1.04×10^{-9}	1.73	1.08×10^{-9}	3.50	1.07×10^{-9}
	3e	0.57	6.94×10^{-10}	2.60	6.93×10^{-10}	---	---	2.60	6.93×10^{-10}
	3f	4.06	7.49×10^{-10}	2.31	6.27×10^{-10}	3.44	7.16×10^{-10}	5.77	7.65×10^{-10}
	3g	1.68	7.23×10^{-10}	2.33	7.03×10^{-10}	2.79	7.46×10^{-10}	3.27	7.38×10^{-10}
	3h	1.69	7.01×10^{-10}	2.08	6.82×10^{-10}	2.34	6.70×10^{-10}	4.75	7.18×10^{-10}
	3i	1.58	7.52×10^{-10}	2.08	7.59×10^{-10}	2.08	7.59×10^{-10}	2.30	7.44×10^{-10}
5.7 % NG	4a	1.37	4.88×10^{-10}	0.77	4.25×10^{-10}	---	---	2.39	7.78×10^{-10}
	4b	1.23	6.34×10^{-10}	1.80	6.71×10^{-10}	2.46	6.91×10^{-10}	2.73	6.89×10^{-10}
	4c	1.34	6.72×10^{-10}	2.38	6.34×10^{-10}	>2.64	---	2.64	6.82×10^{-10}
	4d	0.52	7.22×10^{-10}	1.71	6.67×10^{-10}	1.47	7.00×10^{-10}	2.21	6.82×10^{-10}
	4e	0.93	7.45×10^{-10}	1.87	7.08×10^{-10}	2.02	7.14×10^{-10}	2.28	7.13×10^{-10}
	4f	1.31	6.45×10^{-10}	1.49	6.47×10^{-10}	2.25	6.92×10^{-10}	2.52	6.97×10^{-10}
	4g	1.10	6.74×10^{-10}	1.47	6.47×10^{-10}	1.95	6.65×10^{-10}	3.93	7.32×10^{-10}
	4h	1.25	7.01×10^{-10}	1.70	7.09×10^{-10}	1.50	6.96×10^{-10}	2.75	7.08×10^{-10}
5.6 % MSB	5a	0.38	2.74×10^{-10}	0.47	2.77×10^{-10}	---	---	1.57	4.98×10^{-10}
	5b	1.18	3.84×10^{-10}	2.06	4.46×10^{-10}	>2.40	---	2.40	4.22×10^{-10}
	5c	0.36	3.37×10^{-10}	2.15	4.18×10^{-10}	>2.15	---	2.15	4.18×10^{-10}
	5d	0.25	5.44×10^{-10}	1.98	5.85×10^{-10}	1.72	5.67×10^{-10}	2.53	5.75×10^{-10}
	5e	0.94	3.93×10^{-10}	2.23	3.51×10^{-10}	2.23	3.51×10^{-10}	2.23	3.51×10^{-10}
	5f	1.47	3.88×10^{-10}	1.80	4.17×10^{-10}	2.32	4.25×10^{-10}	4.12	4.38×10^{-10}
	5g	1.70	3.80×10^{-10}	1.76	3.82×10^{-10}	2.02	3.90×10^{-10}	3.51	4.20×10^{-10}
	5h	0.59	4.26×10^{-10}	2.27	4.60×10^{-10}	2.01	4.51×10^{-10}	2.27	4.60×10^{-10}

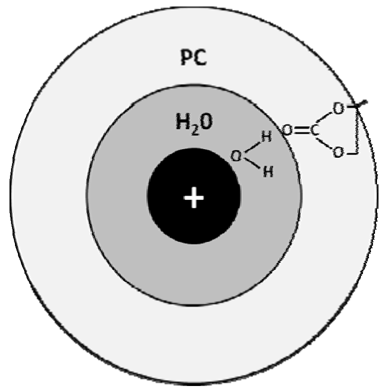

Figure 3.1. Swelling mechanism of MSB (redrawn after Onikata et al. 1999a).

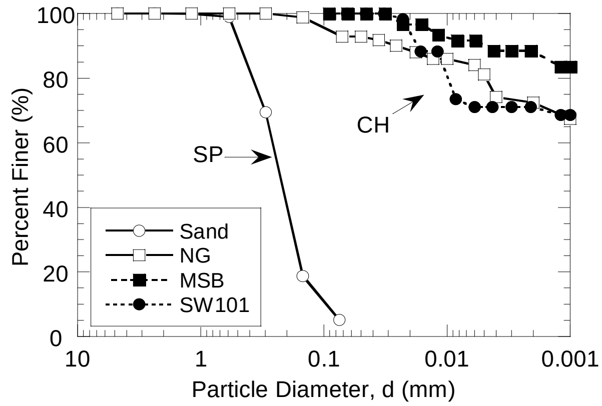

Figure 3.2. Grain size distribution of sand and three bentonites used in study.

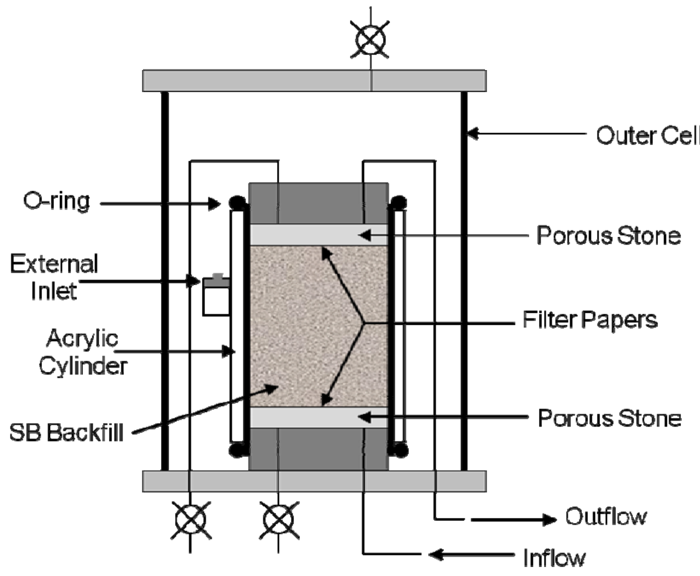

Figure 3.3. Schematic of testing apparatus used (redrawn after Malusis et al. 2009).

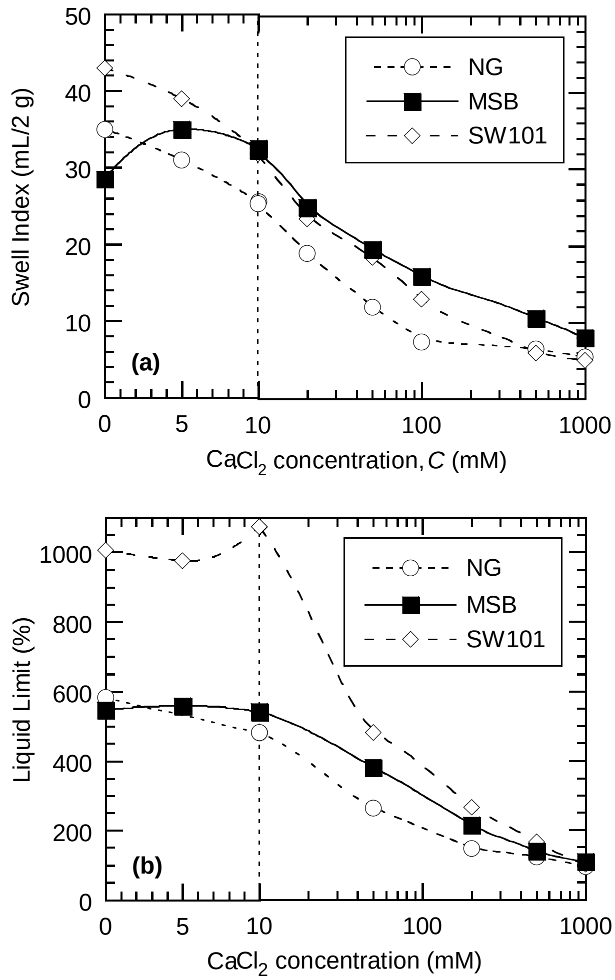

Figure 3.4. (a) Swell index and (b) liquid limit of tested clays as a function of $CaCl_2$ concentration.

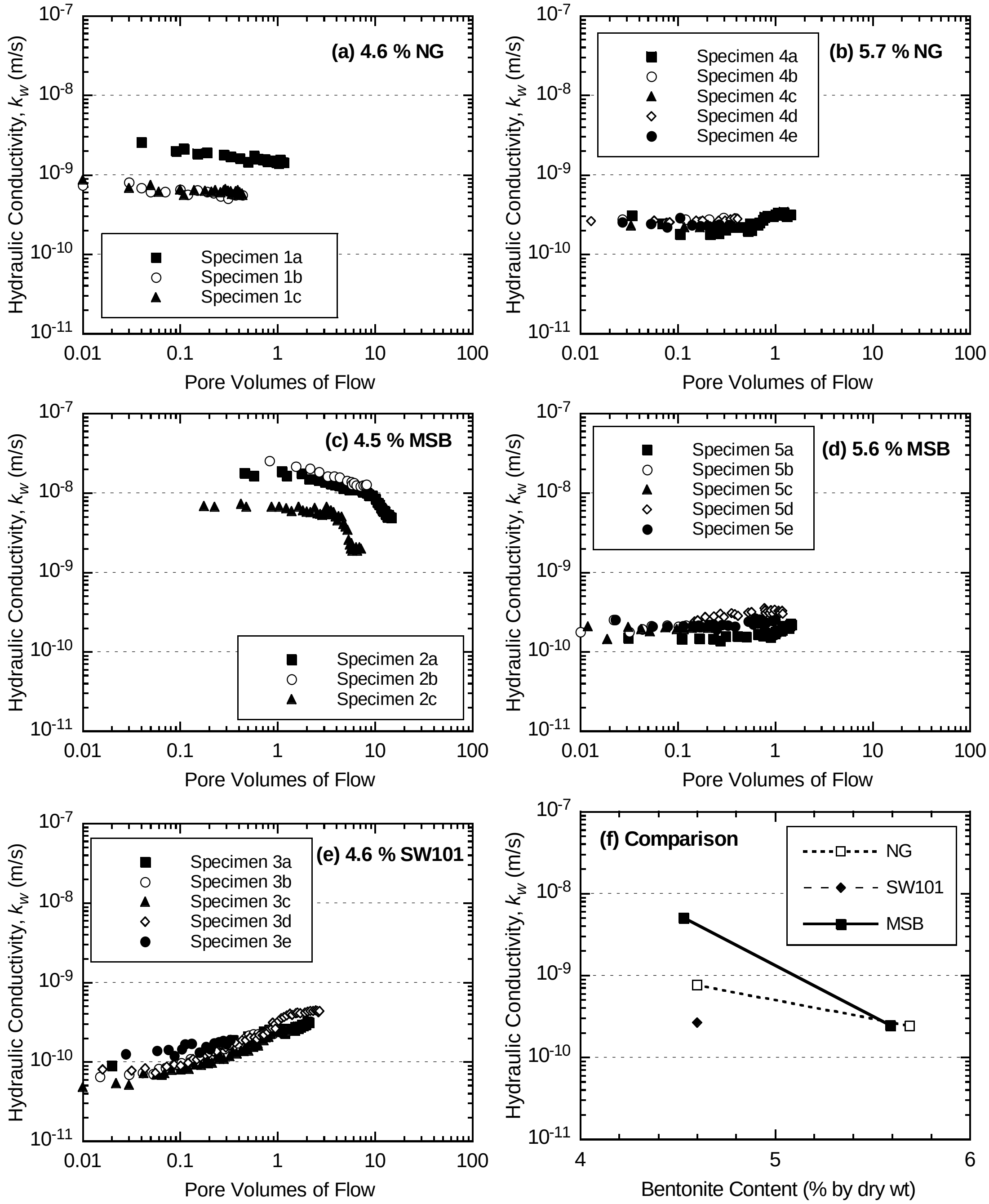

Figure 3.5. (a-e) Hydraulic conductivity as a function of pore volumes of flow (tap water permeant) for backfill specimens amended with 3 % or 4 % dry bentonite (total bentonite contents = 4.5-5.7 % by dry weight); (f) comparison of final values of hydraulic conductivity to tap water as a function of bentonite content.

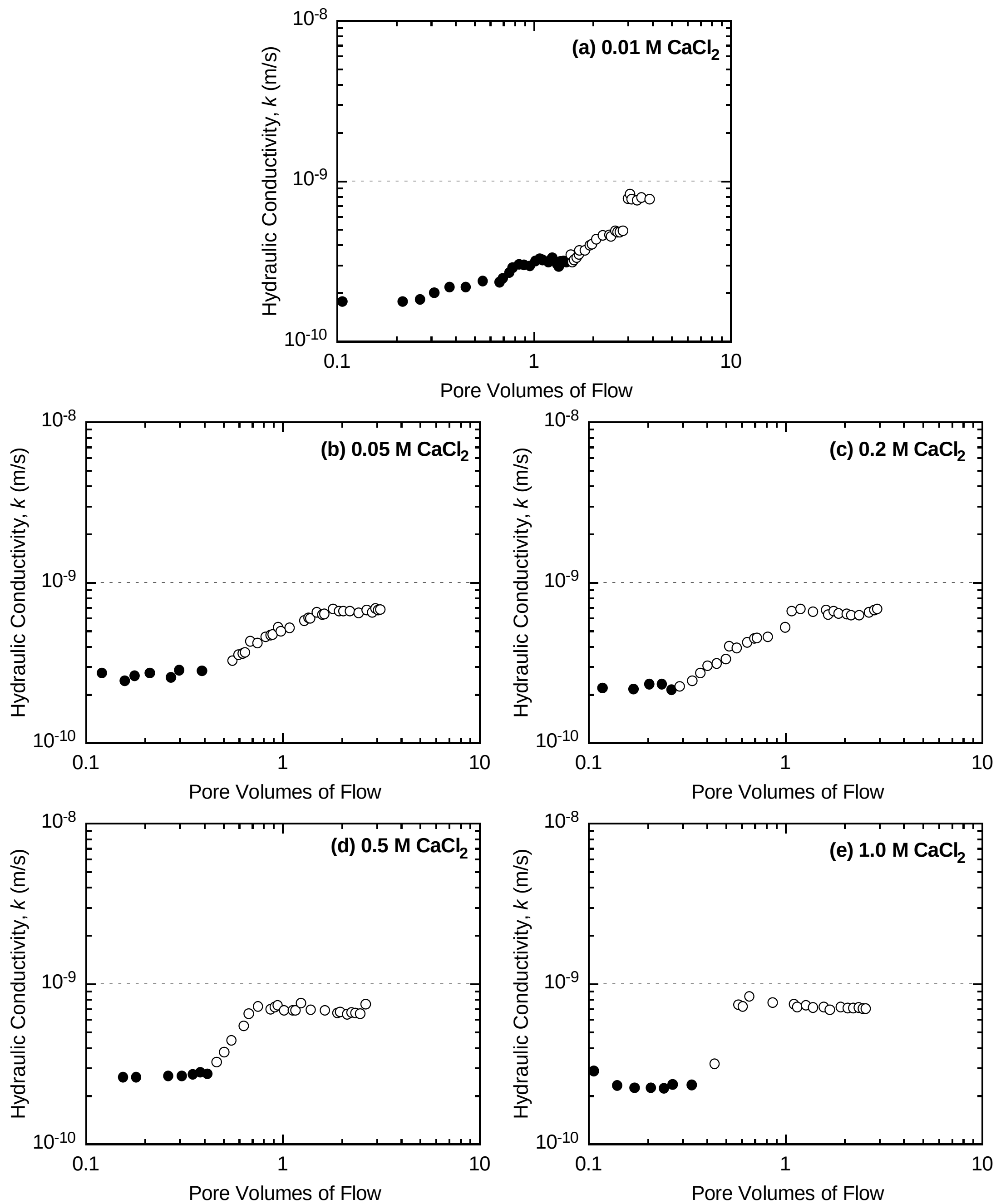

Figure 3.6. Hydraulic conductivity as a function of pore volumes of flow (tap water and $CaCl_2$ permeant) for backfill specimens containing 5.7 % NG. (Closed symbols = tap water, open symbols = $CaCl_2$ solution)

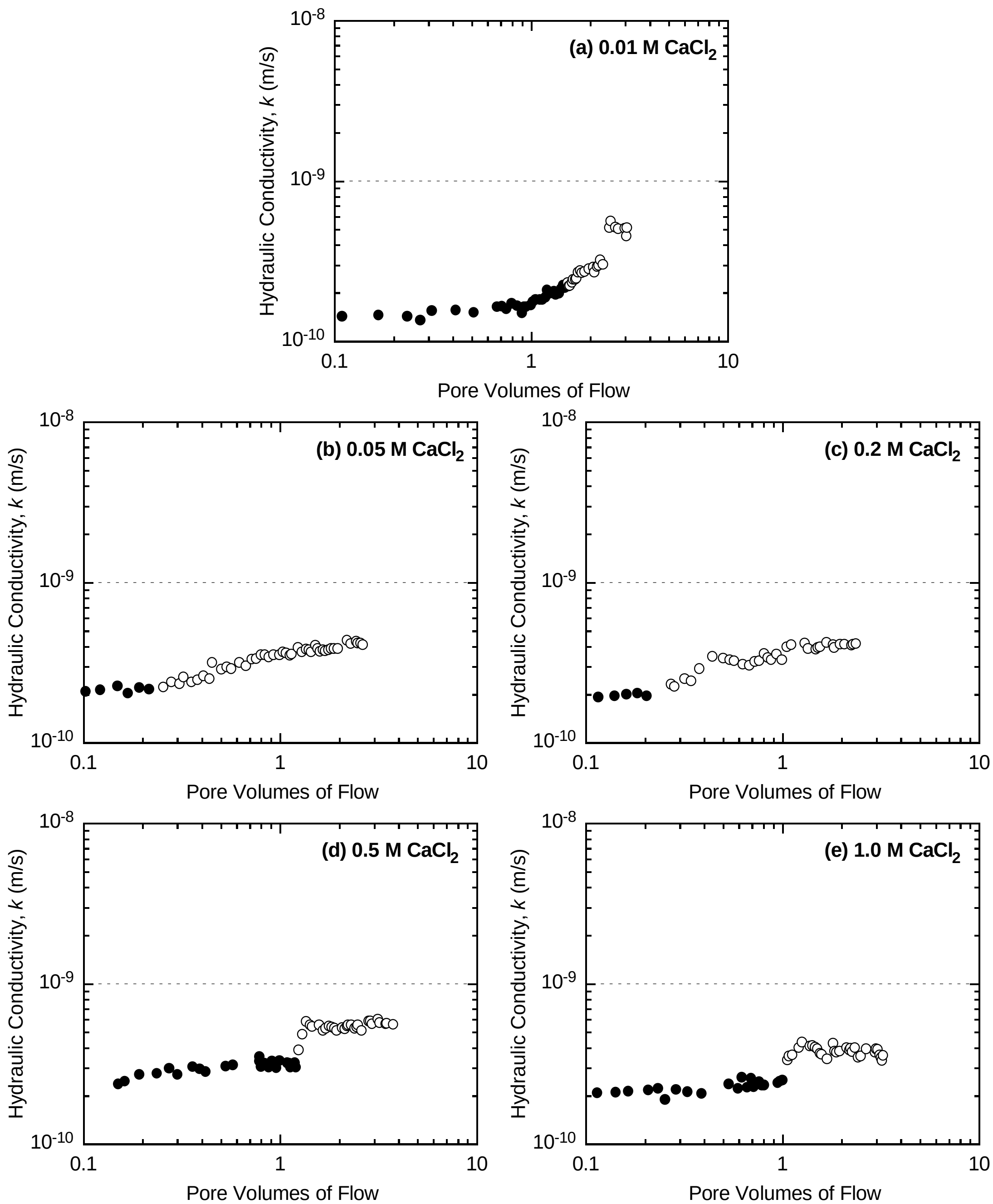

Figure 3.7. Hydraulic conductivity as a function of pore volumes of flow (tap water and $CaCl_2$ permeant) for backfill specimens containing 5.6 % MSB. (Closed circles = tap water, open circles = $CaCl_2$ solution)

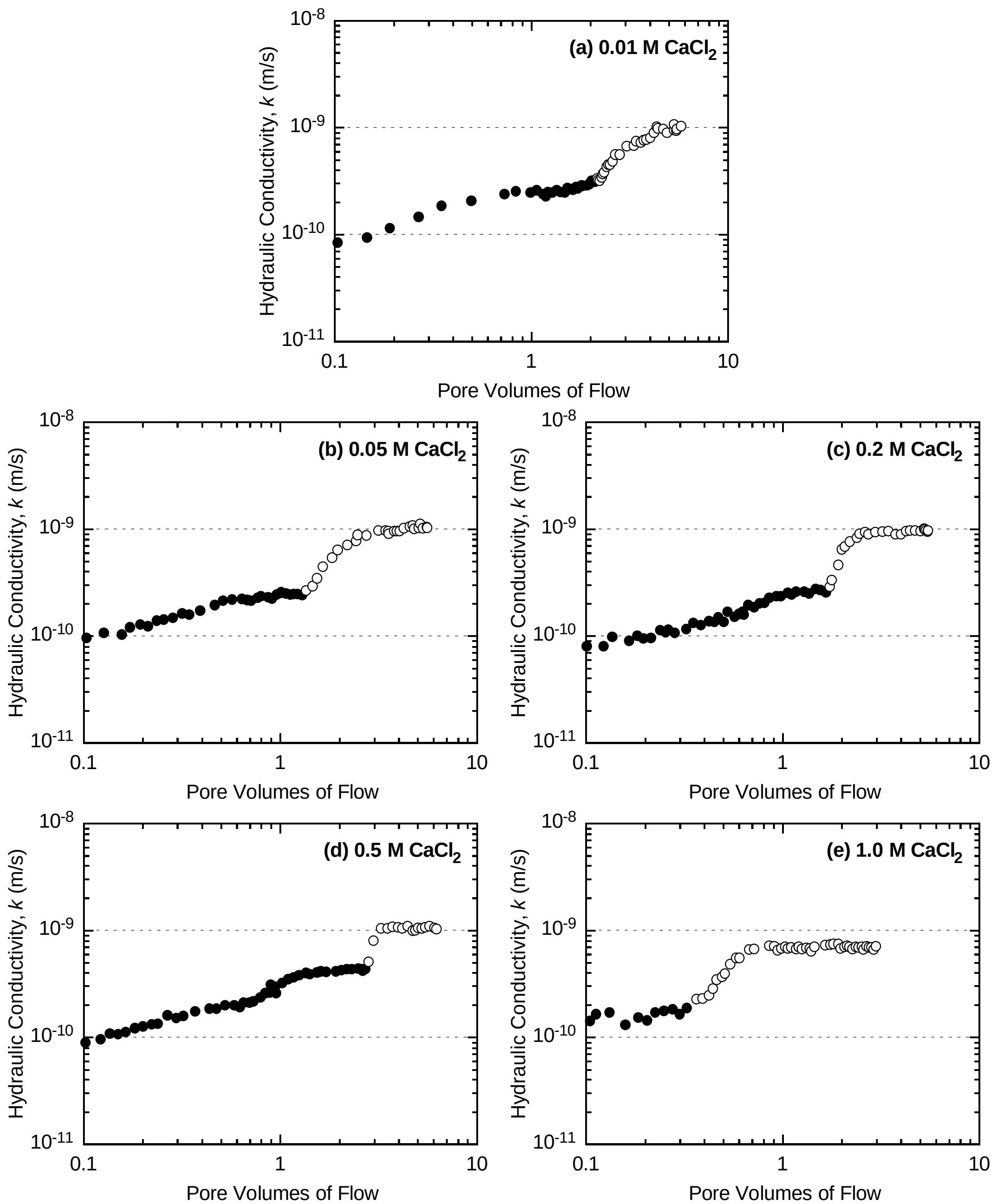

Figure 3.8. Hydraulic conductivity as a function of pore volumes of flow (tap water and $CaCl_2$ permeant) for backfill specimens containing 4.6 % SW101. (Closed circles = tap water, open circles = $CaCl_2$ solution)

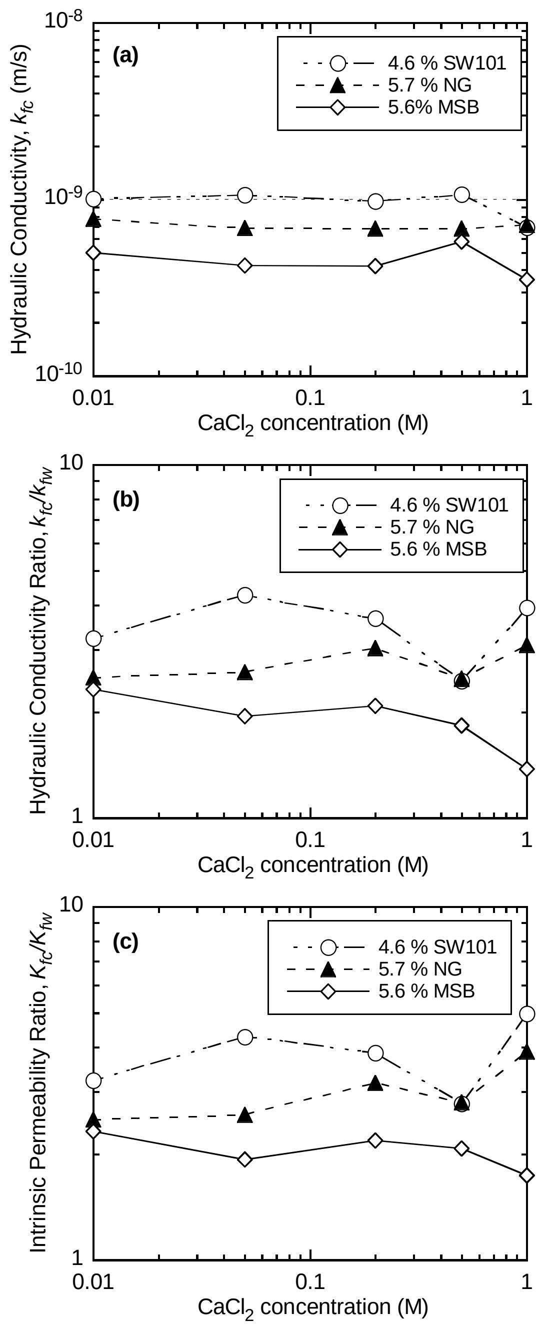

Figure 3.9. Summary of two-stage tests: (a) Final hydraulic conductivity of backfill specimens to $CaCl_2$ (k_{fc}), (b) ratio of k_{fc} to hydraulic conductivity to tap water (k_{fw}) at termination, and (c) ratio of final intrinsic permeability to $CaCl_2$ (K_{fc}) to final intrinsic permeability to tap water (K_{fw}) as a function of $CaCl_2$ concentration for backfill specimens.

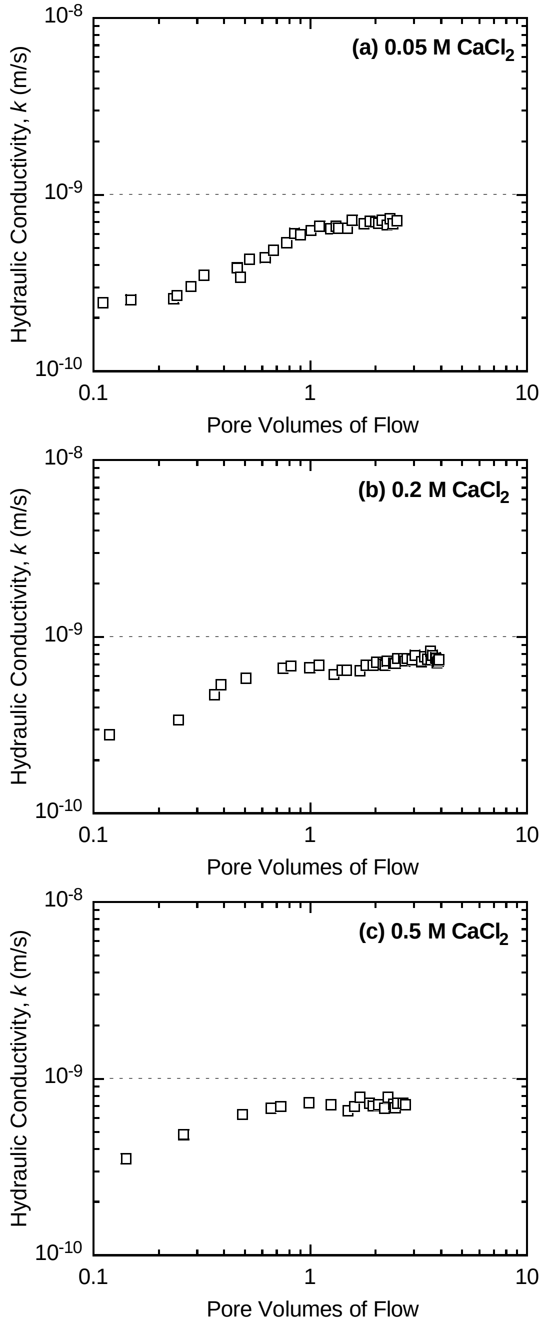

Figure 3.10. Hydraulic conductivity as a function of pore volumes of flow of $CaCl_2$ for one-stage backfill specimens containing 5.7 % NG.

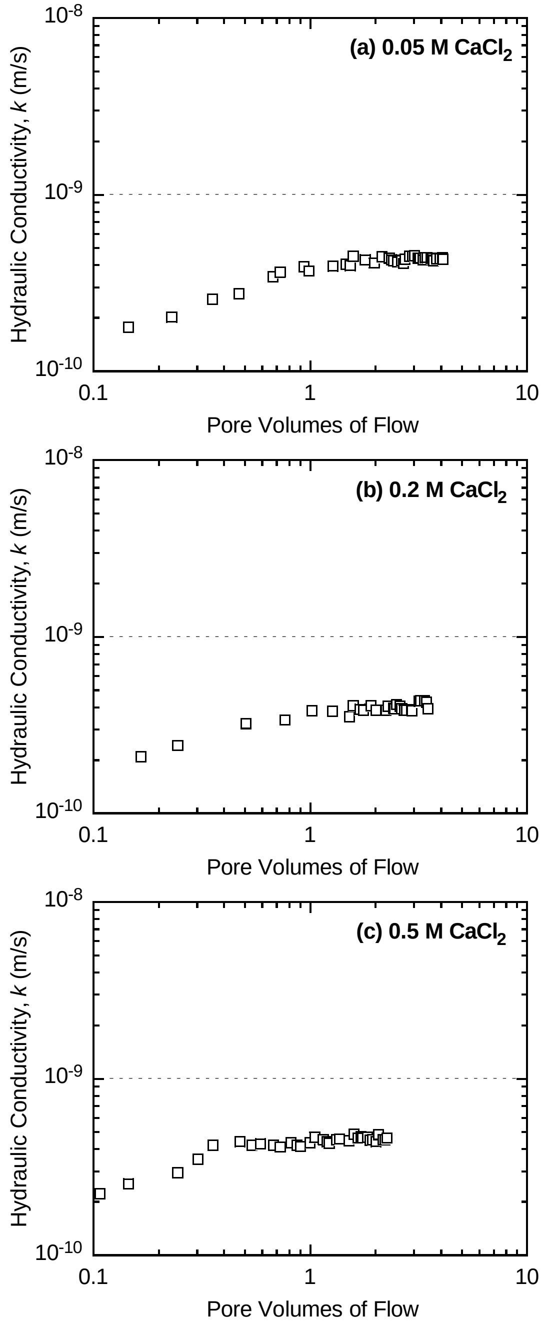

Figure 3.11. Hydraulic conductivity as a function of pore volumes of flow of $CaCl_2$ for one-stage backfill specimens containing 5.6 % MSB.

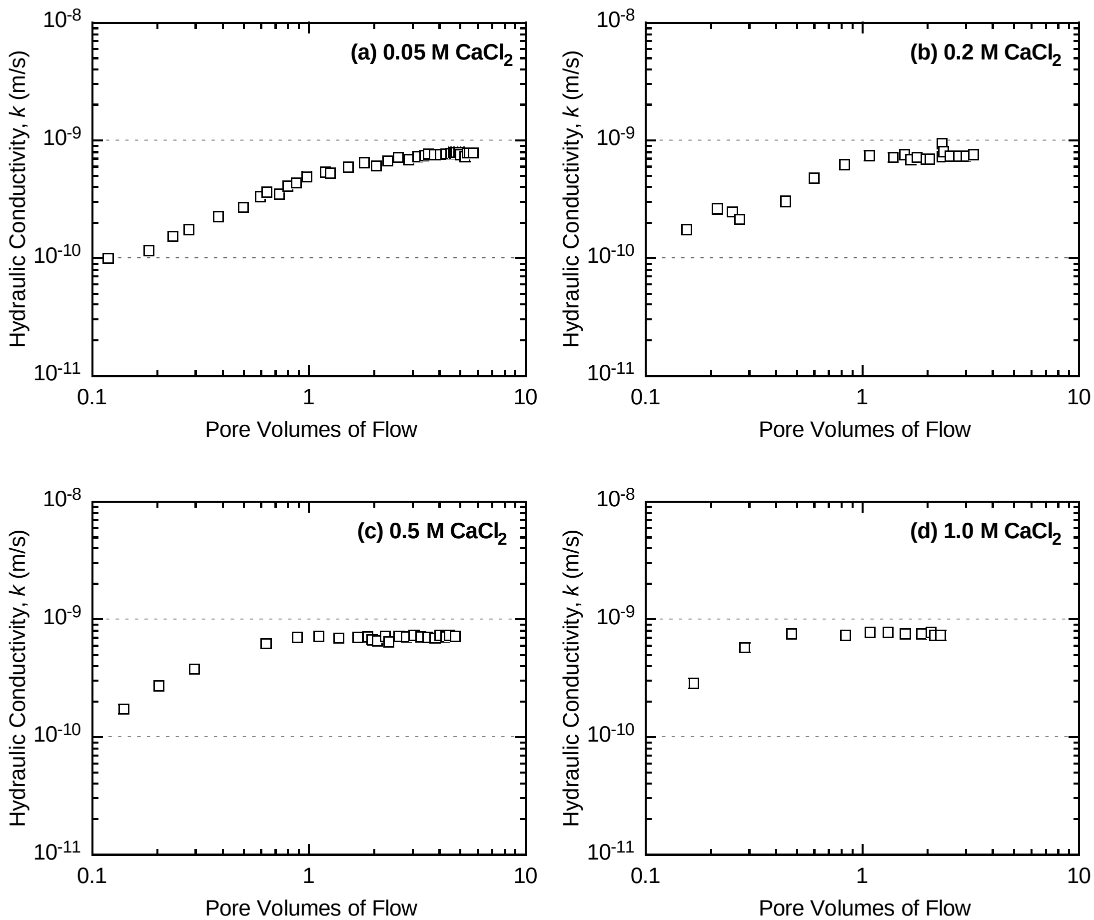

Figure 3.12. Hydraulic conductivity as a function of pore volumes of flow of $CaCl_2$ for one-stage backfill specimens containing 4.6 % SW101.

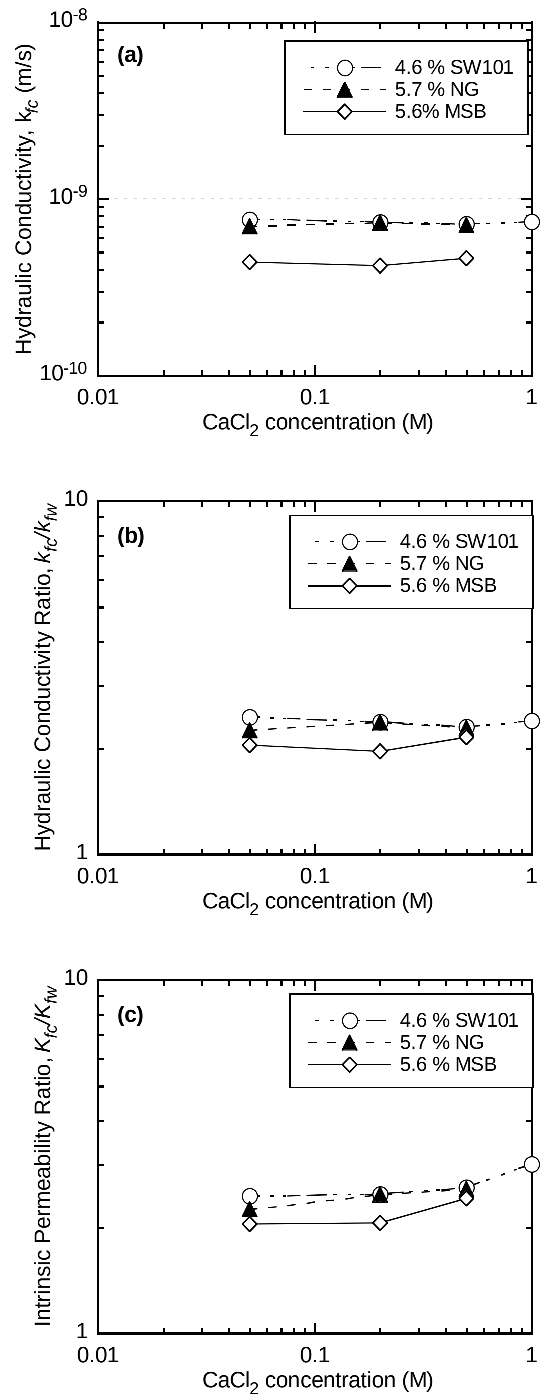

Figure 3.13. Summary of one-stage tests: (a) Hydraulic conductivity of backfill specimens to $CaCl_2$ (k_{fc}), (b) ratio of k_{fc} to k_{fw} and (c) ratio of K_{fc} to K_{fw} as a function of $CaCl_2$ concentration (k_{fw} and K_{fw} values are from three backfill specimens, one for each clay type, prepared with and set up identically to other one-stage tests and then permeated with tap water).

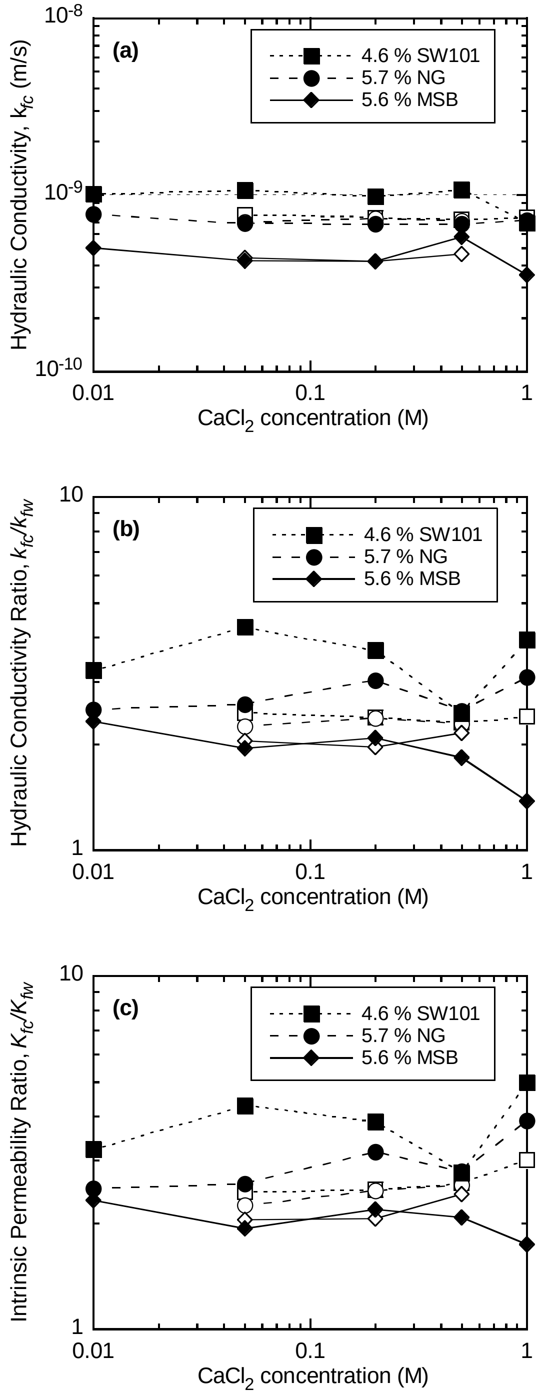

Figure 3.14. Summary of hydraulic conductivity testing: (a) k_{fc}, (b) k_{fc}/k_{fw} ratio, and (c) K_{fc}/K_{fw} ratio as a function of $CaCl_2$ concentration (open symbols = one-stage, closed symbols = two-stage)

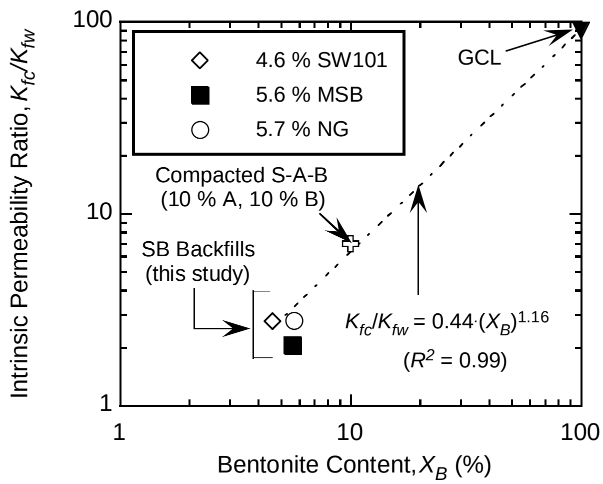

Figure 3.15. Influence of bentonite content on intrinsic permeability ratio, K_{fc}/K_{fw}, for a 0.5 M $CaCl_2$ solution based on the results of the two-stage tests of this study, two granular bentonite GCL studies (GCL1: Lee and Shackelford 2005a; GCL2: Shackelford et al. 2000), and a compacted sand-attapulgite-bentonite (S-A-B) mixture containing 10 % attapulgite (A) and 10 % bentonite (B) (Stern and Shackelford 1998).

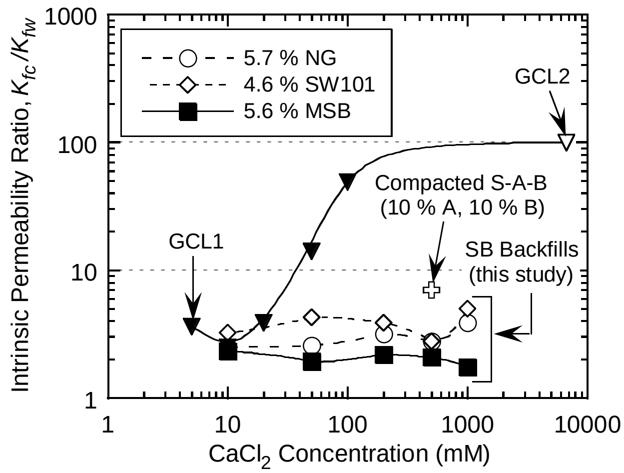

Figure 3.16. Comparison of K_{fc}/K_{fw} values from this study (two-stage tests) with those for granular bentonite GCLs (GCL1: Lee and Shackelford 2005a; GCL2: Shackelford et al. 2000) and a compacted sand-attapulgite-bentonite (S-A-B) mixture containing 10 % attapulgite (A) and 10 % bentonite (B) (Stern and Shackelford 1998) as a function of $CaCl_2$ concentration.

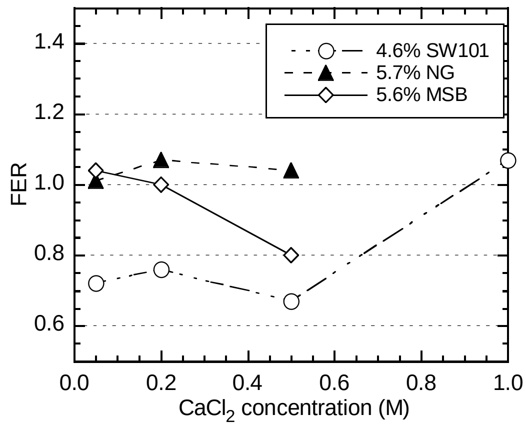

Figure 3.17. FER for SB backfills as a function of $CaCl_2$ concentration.

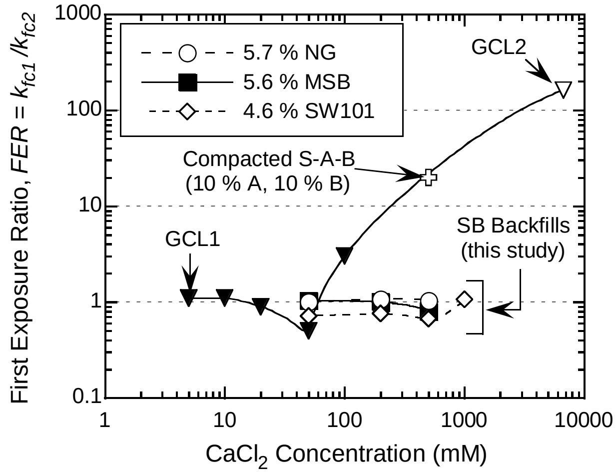

Figure 3.18. Comparison of first exposure ratio (FER) values for SB backfills in this study (5.7 % NG, 5.6 % MSB, and 4.6 % SW101) with those obtained for granular bentonite GCLs (data for GCL1 from Lee and Shackelford 2005a; data for GCL2 from Shackelford et al. 2000) and a compacted sand-attapulgite-bentonite (S-A-B) mixture containing 10 % attapulgite (A) and 10 % bentonite (B) (data from Stern and Shackelford 1998) as a function of $CaCl_2$ concentration. Note: subscripts 1 and 2 represent one-stage tests and two-stage tests, respectively.

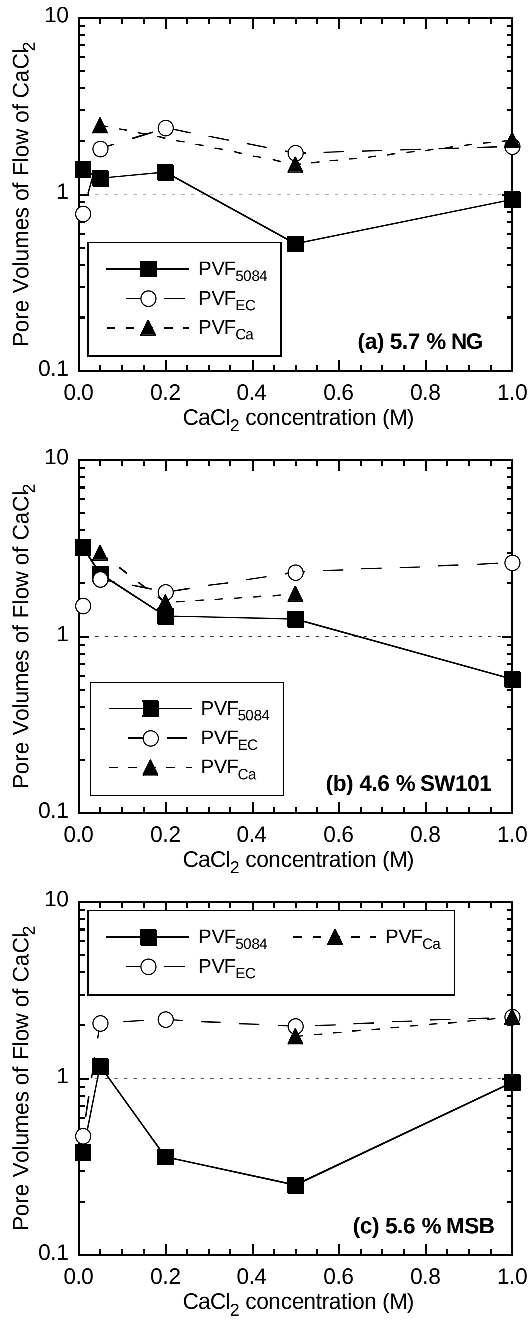

Figure 3.19. Pore volumes of flow of $CaCl_2$ solution for two-stage tests as a function of $CaCl_2$ molar concentration at various termination criteria.

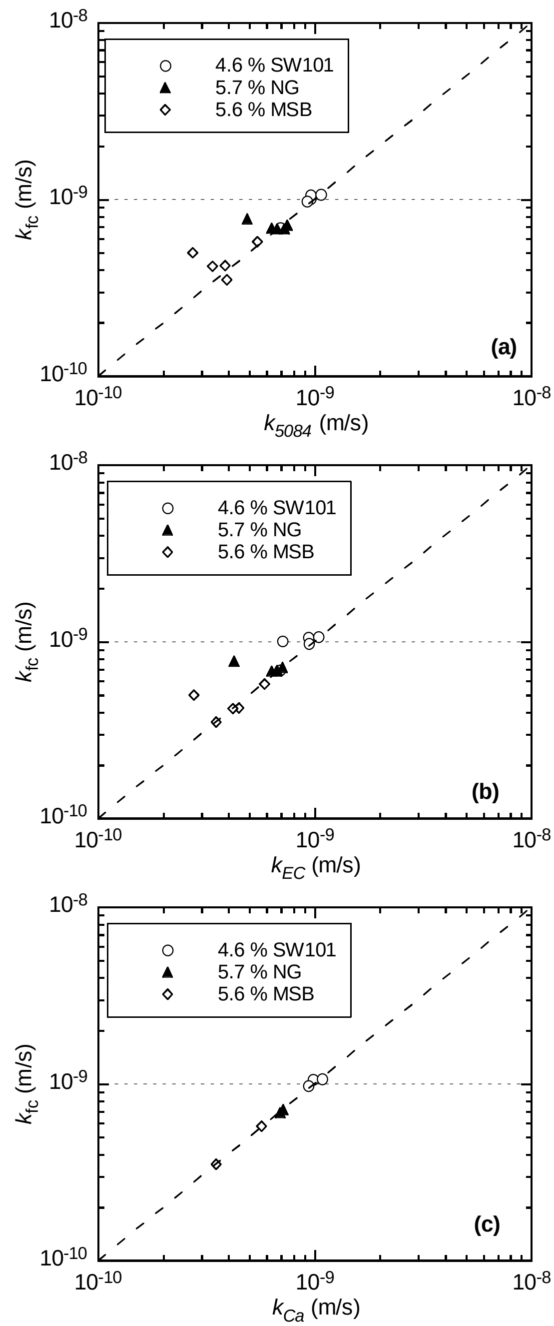

Figure 3.20. Comparison of final hydraulic conductivity (k_{fc}) of two-stage tests relative to hydraulic conductivities corresponding to achievement of the following termination criteria: (a) ASTM D 5084 (k_{5084}), (b) EC ratio (k_{EC}), (c) Ca^{2+} concentration (k_{Ca}).

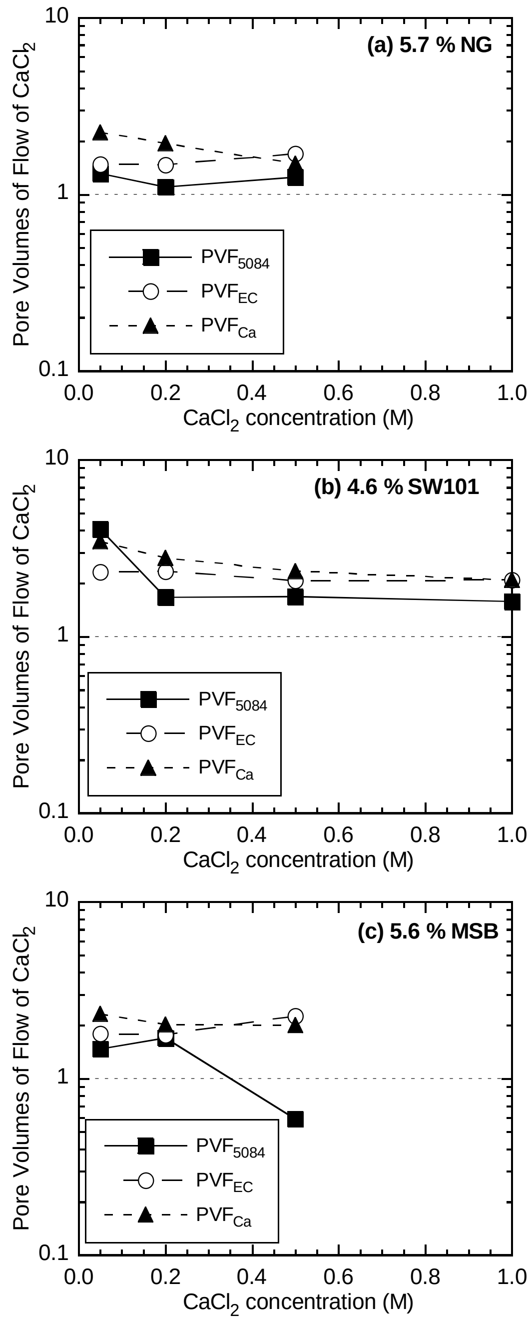

Figure 3.21. Pore volumes of flow of $CaCl_2$ solution for one-stage tests as a function of $CaCl_2$ molar concentration at various termination criteria.

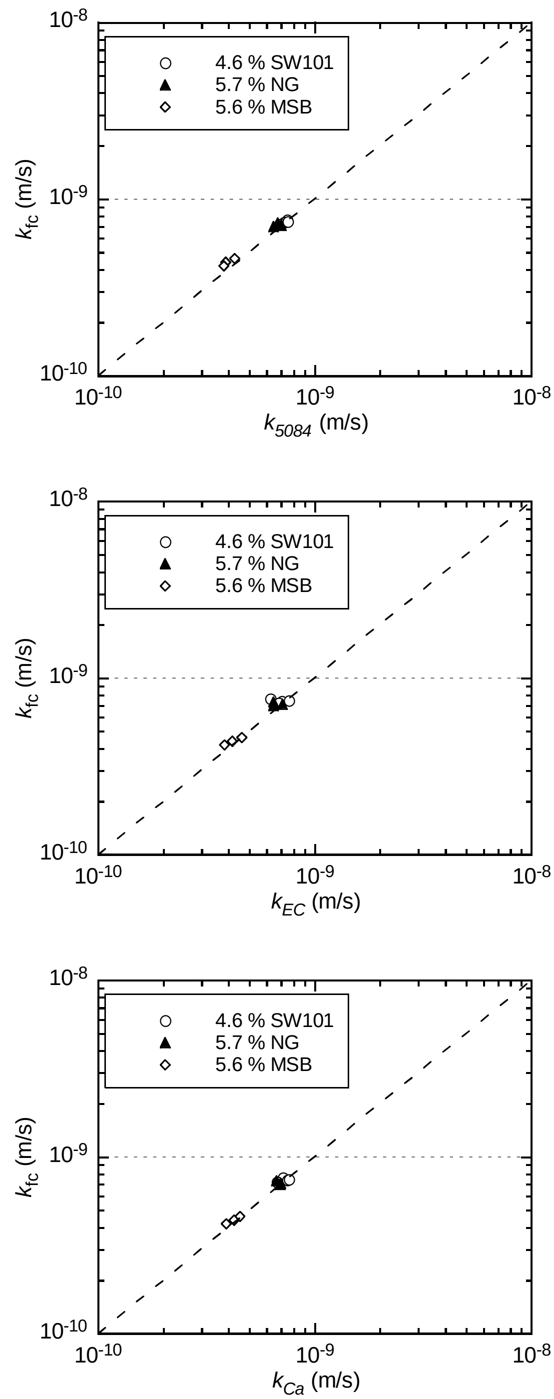

Figure 3.22. Comparison of final hydraulic conductivity (k_{fc}) of one-stage tests relative to hydraulic conductivities corresponding to achievement of the following termination criteria: (a) ASTM D 5084 (k_{5084}), (b) EC ratio (k_{EC}), (c) Ca^{2+} concentration (k_{Ca}).

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONTRIBUTION OF THIS STUDY

The goal of this study was to improve our understanding of soil-bentonite (SB) backfill compatibility with inorganic contaminants, a topic that has received only limited attention in the geoenvironmental research community. Although a few studies on this topic exist, these studies generally are limited in scope and, collectively, do not fully explain the influence of inorganic electrolyte solutions on backfill hydraulic conductivity. In addition, a number of different "modified" (treated) bentonites have been developed for potential use in geoenvironmental containment applications. Investigation into the performance of such modified bentonites relative to natural (untreated) bentonite in SB backfills is necessary in order to evaluate the potential benefit of modified bentonites in terms of improving the long-term effectiveness of SB cutoff walls. The results of this study expand the body of knowledge with respect to these important issues.

This study examined the compatibility of three SB backfill mixtures, each containing a different type of bentonite (i.e., one natural bentonite (NG) and two modified bentonites), with inorganic electrolyte ($CaCl_2$) solutions. The modified bentonites included SW101 (a modified, contaminant-resistant bentonite developed for use in drilling and cutoff wall applications where exposure to seawater is expected) and MSB (a recently developed “multiswellable” bentonite that has the ability to exhibit osmotic swelling in electrolyte solutions).

The primary objectives of this study were to (1) create model SB backfill mixtures, containing each type of bentonite, that meet the conventional requirements SB cutoff walls in terms of constructability and hydraulic conductivity (k) to water, (2) evaluate changes in k of the model backfill mixtures upon permeation with $CaCl_2$ solutions encompassing a wide range of concentrations (i.e., 10 to 1000 mM), and (3) compare the results for the backfills containing the two modified bentonites with those for the backfill containing the untreated bentonite. The hydraulic performance of the backfills is also assessed relative to that of other types of bentonite-rich barriers (i.e., geosynthetic clay liners and compacted sand-bentonite mixtures) tested under similar conditions in prior studies. The primary findings of this study are summarized below, and recommendations for future work are provided where applicable.

4.2 CREATION OF MODEL SB BACKFILLS

As shown in Chapter 2, model bentonite-water slurries and SB backfill mixtures were successfully created to meet typical construction specifications using each type of bentonite examined in this study. The "native" soil for the backfill was chosen to simulate a worst case aquifer for geoenvironmental containment (a predominantly fine, poorly graded sand with a minimal fines content and high k to water). This necessitated, in addition to the bentonite in the slurry, additional dry bentonite (3 or 4 % by dry weight) to increase the bentonite content of the backfill in order to achieve k to water ≤ 10^{-9} m/s. With 3 % additional dry bentonite (by dry weight), the backfill containing 4.6 % SW101 (by dry weight) had the lowest k to water, followed by the backfills containing 4.6 % NG and 4.5 % MSB. The addition of another 1 % dry bentonite to the NG and

MSB backfills ensured all three backfill types had a similar *k* to water. The final SB backfill designs contained 5.6 % MSB, 5.7 % NG, and 4.6 % SW101. Thus, the construction of SB cutoff walls using all three clays was found to be feasible, although the large bentonite contents of the backfills posed possible compatibility issues.

4.3 EVALUATION OF CHANGES IN HYDRAULIC CONDUCTIVITY

The results showed that the three SB backfills tested in this study exhibited only minor compatibility issues with inorganic contaminants. While all of the backfills experienced increases in *k* when permeated with $CaCl_2$ solutions, nearly all of the backfill specimens maintained $k \leq 10^{-9}$ m/s (i.e., the typical regulatory requirement), regardless of bentonite type. In addition, the increases in *k* were less than five-fold in all cases, regardless of the $CaCl_2$ concentration. These results suggest that compatibility of SB backfill with water rich in electrolytes may be only a minor concern, even if the backfill contains minimal native fines and a relatively high bentonite fraction (i.e., in this case, 4.6 to 5.7 %).

All of the backfills were shown to be considerably less vulnerable to increases in *k* than both GCLs and compacted sand-bentonite mixtures. In addition, the backfills exhibited no first exposure effect (i.e., specimens permeated with water before introducing the $CaCl_2$ solution had approximately the same final *k* as specimens permeated directly with $CaCl_2$). These results also differ from GCLs and compacted sand-bentonite mixtures, which often exhibit much lower increases in *k* when permeated with water prior to introducing the chemical solution. Because the bentonite in the SB backfills was allowed to hydrate extensively with water during backfill mixing, the bentonite likely had already undergone osmotic swelling before consolidation and permeation of the specimens. Permeation with $CaCl_2$ solutions, even at concentrations as high as 1000 mM that led to complete cation exchange, apparently could not cause an appreciable reversal of osmotic swell of the bentonite as the backfill maintained *k* values several orders of magnitude lower than the *k* of the sand. However, further study is needed to understand the role of osmotic swell in bentonite clay and its contribution to the performance of clay barriers.

4.4 COMPARISON OF MODIFIED AND CONVENTIONAL BENTONITES

MSB performed better than both NG and SW101 in this study by maintaining the lowest *k* values and exhibiting the smallest increase in *k* across the range of $CaCl_2$ concentrations. NG overall performed second best, with SW101 performing the worst out of the three clays utilized in creating SB backfills. However, all three clays still performed acceptably with a few exceptions.

Given the similarity in performance, natural sodium-bentonite is likely acceptable for use in most SB backfills exposed to inorganic contaminants. The extra expense for modified bentonites may not be necessary since SB backfills experience minimal compatibility issues. It is recommended that further studies be undertaken to examine the performance (i.e., filtrate loss, filter cake thickness, etc.) of natural bentonite-water slurry in the presence of electrolyte solutions to verify the performance of natural bentonite from start to finish of SB cutoff wall construction.

4.5 ADDITIONAL CONCLUSIONS AND RECOMMENDATIONS

The results of this study also indicated that ASTM D 5084 termination criteria may be appropriate for initial compatibility testing of SB backfills as *k* values to $CaCl_2$ at ASTM D 5084 termination criteria were nearly equivalent to final *k* values for the SB backfills. In this manner, an estimate of the final *k* value of a proposed SB backfill mix to a contaminant may be obtained quickly without chemical equilibrium verification. For subsequent testing, this study found that chemical equilibrium does not take long to achieve (i.e., ~ 2 to 3 pore volumes of flow) and is a reasonable requirement for SB backfill compatibility testing. ASTM D 5084 termination criteria should not be abandoned however, as a few specimens in this study reached equilibrium between the influent and effluent electrical conductivities before ASTM D 5084 termination criteria were achieved.

Overall, this study provides a large volume of data that assists in filling the gap in the understanding of SB cutoff wall compatibility. However, this study has its own limitations. While three bentonite types were examined, only one "native soil" was examined, although it did attempt to simulate a worst case aquifer for geoenvironmental containment. Further studies may be needed to understand the compatibility of SB backfills that contain different soil gradations (e.g., a soil with a higher percentage of native fines that necessitates less bentonite). In addition, while the case was made for why $CaCl_2$ may be generalized to all inorganic contaminants, testing with other inorganic chemicals and combinations of inorganic chemicals may be needed to verify the results of this study. Also, while this study provided much information on inorganic compatibility, further compatibility testing of SB backfills with organic liquids would be beneficial to an overall understanding of SB backfill compatibility. Overall, it is hoped that this study has contributed greatly to the understanding of SB cutoff wall compatibility and their potential use of modified bentonites.

Appendix A
Index Test Results

Swell Index A-2
Liquid Limit A-3
Plastic Limit A-3
Plasticity Index A-3

Swell Index

$CaCl_2$

$CaCl_2$ concentration (mM)	Swell Index (mL/2g)		
	NG	MSB	SW101
0	35.0	28.5	43.0
5	31.0	35.0	39.0
10	25.5	32.5	32.0
20	19.0	25.0	23.5
50	12.0	19.5	18.5
100	7.5	16.0	13.0
500	6.5	10.5	6.0
1000	5.5	8.0	5.0
2000	5.0	3.5	5.0

NaCl

NaCl concentration (mM)	Swell Index (mL/2g)		
	NG	MSB	SW101
0	35.0	28.5	43.0
50	33.0	39.5	35.0
100	29.0	38.0	31.0
500	10.5	27.0	12.0

NH_4Cl

NH_4Cl concentration (mM)	Swell Index (mL/2g)		
	NG	MSB	SW101
0	35.0	28.5	43.0
50	30.5	34.0	31.5
100	22.5	22.0	25.5
500	6.0	5.5	7.0

Liquid Limit

$CaCl_2$

$CaCl_2$ concentration (mM)	Standard	Liquid Limit (%)		
		NG	MSB	SW101
Tap Water	ASTM D4318	582.8	546.6	1007
5	Modified ASTM D4318		558.4	975.5
10		482.1	541.0	1074
50		263.3	380.6	480.8
200		146.6	213.4	266.0
500		122.9	139.9	166.2
1000		95.28	109.8	100.9

Plastic Limit

$CaCl_2$

$CaCl_2$ concentration (mM)	Standard	Plastic Limit (%)		
		NG	MSB	SW101
Tap Water	ASTM D4318	52.7	44.6	42.7

Plasticity Index

$CaCl_2$

$CaCl_2$ concentration (mM)	Standard	Plasticity Index (%)		
		NG	MSB	SW101
Tap Water	ASTM D4318	530	502	965

Appendix B
Recipes for Bentonite-Water Slurries and Soil-Bentonite Backfills

Bentonite-Water Slurry Recipe B-2
Soil-Bentonite Backfill Recipe B-2

Bentonite-Water Slurry Recipe

Slurry Type	Clay Content	Water Content	Thinner* Content
MSB	5 %	95 %	---
NB	5 %	95 %	---
SW101	5 %	94.7 %	0.3 %

*chromium-free lignosulfate thinner (Sersene® CF, M-I SWACO, Houston, TX)

Soil-Bentonite Backfill Recipe

Backfill Batch

Mass (g)	4.6 % NG	4.5 % MSB	4.6 % SW101	5.7 % NG	5.6 % MSB
Dry Sand	1703.5	1730.1	1703.5	1660.3	1685.9
Water*	153.3	155.7	153.3	149.4	151.7
Dry Bentonite	52.7	53.4	52.7	69.2	70.2
Slurry	590.5	560.7	590.5	621.1	592.2
Total	2500.0	2499.9	2500.0	2500.0	2500.0

* Water was added to dry sand to approximate natural moisture content of 9 %

Overall

Mass (g)	4.6 % NG	4.5 % MSB	4.6 % SW101	5.7 % NG	5.6 % MSB
Sand	1703.5	1730.1	1703.5	1660.3	1685.9
Bentonite	82.2	81.4	82.2	100.2	99.9
Water	714.3	688.4	712.5	739.4	714.3
Total	2500.0	2499.9	2498.2	2500.0	2500.0

Appendix C
Hydraulic Conductivity Test Results

Specimen 1a C-2
Specimen 1b C-4
Specimen 1c C-6
Specimen 2a C-8
Specimen 2b C-11
Specimen 2c C-13
Specimen 3a C-16
Specimen 3b C-21
Specimen 3c C-26
Specimen 3d C-31
Specimen 3e C-36
Specimen 3f C-41
Specimen 3g C-45
Specimen 3h C-48
Specimen 3i C-51
Specimen 4a C-54
Specimen 4b C-58
Specimen 4c C-62
Specimen 4d C-66
Specimen 4e C-70
Specimen 4f C-74
Specimen 4g C-78
Specimen 4h C-82
Specimen 5a C-85
Specimen 5b C-89
Specimen 5c C-94
Specimen 5d C-99
Specimen 5e C-104
Specimen 5f C-109
Specimen 5g C-113
Specimen 5h C-117

Specimen 1a
4.6 % NG Backfill
Tap Water

Phase Diagram (Specimen 1a)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	137.04	96.32
Mass Solids (g)	342.60	279.35
Total Mass (g)	479.64	375.67
Volume Air (cm^3)	16.94	0.00
Volume Water (cm^3)	137.04	96.32
Volume Solids (cm^3)	128.31	104.63
Total Volume (cm^3)	282.29	200.95
Water Content (%)	40.00%	34.48%
Volume Voids (cm^3)	153.98	96.32
Void Ratio	1.20	0.92
Porosity	0.55	0.48
Saturation (%)	89.00%	100%

Flexible Wall Test Results (Specimen 1a)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.11
Sample Diameter (cm): 7.11
Sample Cross-Sectional Area (cm^2): 39.70

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.55

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.3	4.9	2.0	21.3	2.049	5.0	3.0	19.8	2.020	5.16	7.82	2.58E-09	0.042
0.7	5.0	3.0	19.8	2.020	5.1	4.5	18.4	1.987	7.74	7.29	1.98E-09	0.091
0.9	5.1	4.5	18.4	1.987	5.1	5.0	18.0	1.976	2.58	2.08	2.12E-09	0.106
1.3	5.1	5.0	18.0	1.976	5.2	6.4	16.8	1.947	7.22	6.25	1.84E-09	0.150
1.7	5.2	6.4	16.8	1.947	5.4	7.7	15.7	1.919	6.71	5.73	1.91E-09	0.190
2.7	5.4	7.7	15.7	1.919	5.6	10.7	13.1	1.855	15.48	13.55	1.77E-09	0.284
3.2	5.6	10.7	13.1	1.855	5.6	12.0	11.9	1.826	6.71	6.25	1.70E-09	0.327
4.1	5.6	0.5	24.4	2.101	5.9	3.0	22.1	2.046	12.90	11.98	1.62E-09	0.407
5.3	5.9	3.0	22.1	2.046	6.2	6.3	19.8	1.982	17.03	11.98	1.44E-09	0.502
6.2	6.2	6.3	19.8	1.982	6.4	8.6	17.3	1.927	11.87	13.03	1.72E-09	0.582
6.7	6.4	8.6	17.3	1.927	6.5	10.0	16.0	1.896	7.22	6.77	1.60E-09	0.628
6.9	6.5	10.0	16.0	1.896	6.5	10.3	15.8	1.890	1.55	1.04	1.20E-09	0.636
7.8	6.5	0.8	23.0	2.082	6.7	3.2	20.9	2.030	12.38	10.94	1.53E-09	0.712
8.2	6.7	3.2	20.9	2.030	6.8	4.3	19.9	2.006	5.68	5.21	1.57E-09	0.747
8.7	6.8	4.3	19.9	2.006	6.9	5.8	18.8	1.976	7.74	5.73	1.48E-09	0.791
9.2	6.9	5.8	18.8	1.976	7.2	7.0	17.5	1.948	6.19	6.77	1.51E-09	0.833
9.8	7.2	7.0	17.5	1.948	7.5	8.1	16.4	1.923	5.68	5.73	1.31E-09	0.870
10.2	7.5	8.1	16.4	1.923	7.7	9.2	15.4	1.898	5.42	5.47	1.46E-09	0.906
11.3	7.7	9.2	15.4	1.898	8.0	11.5	13.2	1.847	12.13	11.20	1.43E-09	0.981
11.8	8.0	11.5	13.2	1.847	8.2	12.7	12.2	1.822	5.93	5.47	1.41E-09	1.018
12.3	8.2	12.7	12.2	1.822	8.3	13.8	11.1	1.796	5.93	5.47	1.54E-09	1.055
12.7	8.3	13.8	11.1	1.796	8.4	14.8	10.2	1.775	5.16	4.69	1.45E-09	1.087
13.2	8.4	14.8	10.2	1.775	8.8	15.5	9.4	1.758	3.61	4.17	1.10E-09	1.113
13.8	8.8	15.5	9.4	1.758	9.1	16.7	8.1	1.729	6.19	6.77	1.42E-09	1.155

Specimen 1b
4.6 % NG Backfill
Tap Water

Phase Diagram (Specimen 1b)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	137.04	110.90
Mass Solids (g)	342.60	330.32
Total Mass (g)	479.64	441.22
Volume Air (cm^3)	16.94	0.00
Volume Water (cm^3)	137.04	110.90
Volume Solids (cm^3)	128.31	123.72
Total Volume (cm^3)	282.29	234.62
Water Content (%)	40.00%	33.57%
Volume Voids (cm^3)	153.98	110.90
Void Ratio	1.20	0.90
Porosity	0.55	0.47
Saturation (%)	89.00%	100%

Flexible Wall Test Results (Specimen 1b)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.11
Sample Diameter (cm): 7.11
Sample Cross-Sectional Area (cm^2): 39.70

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.22

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	k (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.3	5.0	0.8	22.6	2.077	5.1	1.2	22.3	2.069	2.06	1.56	7.36E-10	0.012
0.7	5.1	1.2	22.3	2.069	5.1	1.8	21.7	2.055	3.10	3.13	8.00E-10	0.032
0.9	5.1	1.8	21.7	2.055	5.1	2.0	21.6	2.052	1.03	0.52	6.82E-10	0.037
1.3	5.1	2.0	21.6	2.052	5.2	2.4	21.1	2.042	2.06	2.61	6.09E-10	0.053
1.7	5.2	2.4	21.1	2.042	5.2	2.8	20.7	2.033	2.06	2.08	6.06E-10	0.066
2.7	5.2	2.8	20.7	2.033	5.3	3.9	19.6	2.007	5.68	5.73	6.51E-10	0.104
3.2	5.3	3.9	19.6	2.007	5.3	4.3	19.1	1.997	2.06	2.61	5.60E-10	0.119
4.1	5.3	4.3	19.1	1.997	5.4	5.2	18.2	1.976	4.64	4.69	6.37E-10	0.150
5.3	5.4	5.2	18.2	1.976	5.5	6.3	17.0	1.950	5.68	6.25	6.08E-10	0.189
6.2	5.5	6.3	17.0	1.950	5.5	7.1	16.2	1.931	4.13	4.43	5.91E-10	0.217
6.7	5.5	7.1	16.2	1.931	5.6	7.6	15.6	1.919	2.58	2.87	6.15E-10	0.235
7.7	5.6	7.6	15.6	1.919	5.6	8.4	14.7	1.900	4.13	4.69	5.40E-10	0.263
8.1	5.6	8.4	14.7	1.900	5.6	8.8	14.3	1.890	2.06	2.08	6.38E-10	0.277
8.7	5.6	8.8	14.3	1.890	5.7	9.3	13.8	1.879	2.58	2.61	6.01E-10	0.294
9.2	5.7	9.3	13.8	1.879	5.7	9.7	13.4	1.870	2.06	2.08	5.06E-10	0.308
9.7	5.7	9.7	13.4	1.870	5.8	10.2	12.9	1.858	2.58	2.61	6.21E-10	0.325
10.2	5.8	10.2	12.9	1.858	5.8	10.6	12.5	1.849	2.06	2.08	5.73E-10	0.338
11.2	5.8	10.6	12.5	1.849	5.8	11.4	11.6	1.830	4.13	4.69	5.50E-10	0.367
11.8	5.8	11.4	11.6	1.830	5.9	11.8	11.2	1.821	2.06	2.08	5.15E-10	0.381
12.3	5.9	11.8	11.2	1.821	5.9	12.3	10.8	1.810	2.32	2.34	6.30E-10	0.396
12.7	5.9	12.3	10.8	1.810	5.9	12.6	10.4	1.802	1.81	2.08	5.65E-10	0.409
13.2	5.9	12.6	10.4	1.802	5.9	12.9	10.0	1.794	1.55	1.82	4.69E-10	0.420
13.8	5.9	12.9	10.0	1.794	5.9	13.4	9.5	1.783	2.58	2.61	5.52E-10	0.437

Specimen 1c
4.6 % NG Backfill
Tap Water

Phase Diagram (Specimen 1c)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	136.46	106.95
Mass Solids (g)	341.16	334.20
Total Mass (g)	477.62	441.15
Volume Air (cm^3)	16.87	0.00
Volume Water (cm^3)	136.46	106.95
Volume Solids (cm^3)	127.77	125.17
Total Volume (cm^3)	281.10	232.12
Water Content (%)	40.00%	32.00%
Volume Voids (cm^3)	153.33	106.95
Void Ratio	1.20	0.85
Porosity	0.55	0.46
Saturation (%)	89.00%	100%

Flexible Wall Test Results (Specimen 1c)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.59

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.31

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.3	2.9	0.9	23.0	2.081	2.9	1.3	22.6	2.072	2.06	2.08	8.73E-10	0.013
0.7	2.9	1.3	22.6	2.072	2.9	1.7	22.2	2.062	2.06	2.08	5.35E-10	0.027
0.9	2.9	1.7	22.2	2.062	2.9	1.9	22.1	2.059	1.03	0.52	6.77E-10	0.031
1.3	2.9	1.9	22.1	2.059	2.9	2.4	21.5	2.046	2.58	3.13	7.44E-10	0.050
1.7	2.9	2.4	21.5	2.046	2.9	2.8	21.1	2.037	2.06	2.08	6.07E-10	0.063
2.7	2.9	2.8	21.1	2.037	3.0	3.9	20.0	2.012	5.68	5.73	6.50E-10	0.099
3.2	3.0	3.9	20.0	2.012	3.0	4.3	19.5	2.002	2.06	2.61	5.58E-10	0.114
4.1	3.0	4.3	19.5	2.002	3.0	5.2	18.6	1.981	4.64	4.69	6.37E-10	0.144
5.3	3.0	5.2	18.6	1.981	3.1	6.4	17.4	1.953	6.19	6.25	6.34E-10	0.184
6.2	3.1	6.4	17.4	1.953	3.1	7.2	16.5	1.934	4.13	4.69	6.09E-10	0.212
6.7	3.1	7.2	16.5	1.934	3.1	7.8	16.0	1.921	3.10	2.61	6.45E-10	0.230
7.7	3.1	7.8	16.0	1.921	3.1	8.7	15.0	1.900	4.64	5.21	6.04E-10	0.262
8.1	3.1	8.7	15.0	1.900	3.1	9.1	14.6	1.890	2.06	2.08	6.42E-10	0.275
8.7	3.1	9.1	14.6	1.890	3.2	9.6	14.0	1.878	2.58	3.13	6.60E-10	0.294
9.2	3.2	9.6	14.0	1.878	3.2	10.1	13.5	1.866	2.58	2.61	6.34E-10	0.310
9.7	3.2	10.1	13.5	1.866	3.2	10.6	13.0	1.855	2.58	2.61	6.23E-10	0.327
10.2	3.2	10.6	13.0	1.855	3.2	11.0	12.6	1.846	2.06	2.08	5.76E-10	0.340
11.2	3.2	11.0	12.6	1.846	3.2	12.0	11.7	1.824	4.90	4.95	6.17E-10	0.371
11.8	3.2	12.0	11.7	1.824	3.2	12.5	11.2	1.813	2.58	2.61	6.45E-10	0.388
12.2	3.2	12.5	11.2	1.813	3.3	12.9	10.8	1.803	2.06	2.08	5.65E-10	0.401
12.7	3.3	12.9	10.8	1.803	3.3	13.2	10.3	1.794	1.81	2.34	6.04E-10	0.415
13.2	3.3	13.2	10.3	1.794	3.4	13.6	9.9	1.785	2.06	2.08	5.82E-10	0.428
13.8	3.4	13.6	9.9	1.785	3.4	14.1	9.4	1.774	2.58	2.61	5.55E-10	0.444

Specimen 2a
4.5 % MSB Backfill
Tap Water

Phase Diagram (Specimen 2a)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	142.34	114.51
Mass Solids (g)	369.73	353.61
Total Mass (g)	512.07	468.12
Volume Air (cm^3)	0.28	0.00
Volume Water (cm^3)	142.34	114.51
Volume Solids (cm^3)	138.47	132.44
Total Volume (cm^3)	281.10	246.95
Water Content (%)	38.50%	32.38%
Volume Voids (cm^3)	142.63	114.51
Void Ratio	1.03	0.86
Porosity	0.51	0.46
Saturation (%)	99.80%	100%

Flexible Wall Test Results (Specimen 2a)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.59

Cell Pressure (psi): 50.5 for first 2 readings, then 45.5
Head Pressure (psi): 46.8 for first 2 readings, then 41.8
Tail Pressure (psi): 44.2 for first 2 readings, then 39.2
Max Gradient: 29.66

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.4	3.2	0.9	22.1	2.070	3.2	12.1	11.5	1.821	57.79	55.23	1.79E-08	0.459
0.5	3.2	12.1	11.5	1.821	3.2	14.9	8.9	1.759	14.45	13.55	1.65E-08	0.573
0.9	3.2	0.8	24.2	2.096	3.2	13.8	11.8	1.805	67.08	64.60	1.88E-08	1.109
1.1	3.2	13.8	11.8	1.805	3.2	17.4	8.9	1.730	18.58	15.11	1.65E-08	1.245
1.9	3.2	1.0	23.7	2.088	3.2	13.7	11.5	1.802	65.53	63.56	1.75E-08	1.770
2.4	3.2	13.7	11.5	1.802	3.2	22.4	3.2	1.607	44.89	43.24	1.49E-08	2.128
2.9	3.2	1.0	23.6	2.086	3.2	13.2	11.4	1.807	62.95	63.56	1.44E-08	2.643
3.4	3.2	13.2	11.4	1.807	3.2	23.4	2.2	1.584	52.63	47.93	1.37E-08	3.052
3.9	3.2	0.2	24.5	2.106	3.2	11.5	13.6	1.851	58.31	56.79	1.30E-08	3.519
4.4	3.2	0.6	23.8	2.093	3.2	10.5	14.4	1.872	51.08	48.97	1.27E-08	3.926
4.9	3.2	0.4	24.5	2.104	3.3	9.6	15.7	1.897	47.47	45.85	1.23E-08	4.306
5.5	3.3	9.6	15.7	1.897	3.3	19.7	6.6	1.677	52.12	47.41	1.14E-08	4.710
6.0	3.3	0.5	24.5	2.102	3.3	10.5	15.0	1.879	51.60	49.50	1.17E-08	5.121
6.5	3.3	10.5	15.0	1.879	3.3	18.6	7.3	1.698	41.80	40.12	1.11E-08	5.454
6.9	3.3	0.5	24.6	2.104	3.3	9.1	16.3	1.910	44.38	43.24	1.17E-08	5.810
7.4	3.3	9.1	16.3	1.910	3.3	17.8	8.5	1.721	44.89	40.64	1.16E-08	6.158
8.0	3.3	0.4	24.0	2.098	3.4	12.0	13.2	1.841	59.86	56.27	1.14E-08	6.630
8.2	3.4	12.0	13.2	1.841	3.4	15.2	10.2	1.770	16.51	15.63	1.10E-08	6.761
8.5	3.4	0.6	24.4	2.100	3.4	5.9	19.3	1.981	27.35	26.57	1.10E-08	6.980
8.9	3.4	5.9	19.3	1.981	3.4	13.2	12.4	1.818	37.67	35.95	1.08E-08	7.279
9.2	3.4	13.2	12.4	1.818	3.4	17.8	8.0	1.715	23.74	22.92	1.03E-08	7.469
9.8	3.4	0.4	24.1	2.099	3.4	10.5	14.4	1.872	52.12	50.54	1.03E-08	7.886
10.4	3.4	0.6	24.1	2.097	3.4	10.0	15.1	1.886	48.50	46.89	1.01E-08	8.274

10.9	3.4	10.0	15.1	1.886	3.4	18.0	7.4	1.706	41.28	40.12	9.63E-09	8.605
11.2	3.4	18.0	7.4	1.706	3.4	21.1	4.5	1.637	16.00	15.11	9.29E-09	8.731
12.3	3.4	0.8	24.3	2.097	3.5	17.2	8.7	1.730	84.62	81.28	9.18E-09	9.406
13.6	0.7	0.9	24.1	2.093	0.8	11.1	14.3	1.864	52.63	51.06	4.97E-09	9.827
14.1	0.8	0.5	24.5	2.102	0.8	7.5	17.5	1.942	36.12	36.47	8.37E-09	10.122
15.1	0.8	7.5	17.5	1.942	0.8	19.6	6.2	1.674	62.44	58.87	7.47E-09	10.615
16.1	0.8	0.8	24.1	2.094	0.8	12.3	13.2	1.838	59.34	56.79	7.13E-09	11.087
17.2	0.8	12.3	13.2	1.838	0.8	21.8	4.1	1.625	49.02	47.41	6.46E-09	11.479
18.1	0.8	0.8	24.0	2.093	0.9	10.5	14.7	1.876	50.05	48.45	6.28E-09	11.880
18.5	0.9	10.5	14.7	1.876	0.9	14.4	10.9	1.787	20.12	19.80	5.98E-09	12.042
18.9	0.9	14.4	10.9	1.787	0.9	17.3	8.2	1.723	14.96	14.07	5.89E-09	12.160
19.9	0.9	1.3	23.7	2.084	0.9	11.5	13.8	1.854	52.63	51.58	5.92E-09	12.584
20.9	0.9	11.5	13.8	1.854	0.9	19.4	6.8	1.683	40.76	36.47	5.38E-09	12.898
22.9	0.9	0.3	24.3	2.102	0.9	10.6	14.4	1.871	53.15	51.58	5.40E-09	13.323
23.1	0.9	10.6	14.4	1.871	0.9	11.6	13.5	1.849	5.16	4.69	4.96E-09	13.363
24.0	0.9	1.1	23.6	2.085	1.0	9.1	16.0	1.906	41.28	39.60	5.25E-09	13.692
25.1	1.0	9.1	16.0	1.906	1.0	17.3	8.2	1.723	42.31	40.64	5.02E-09	14.029
27.4	1.0	1.3	23.1	2.077	1.0	18.7	6.5	1.688	89.78	86.49	4.86E-09	14.746

Specimen 2b
4.5 % MSB Backfill
Tap Water

Phase Diagram (Specimen 2b)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume

Property	Before permeation	After permeation
Mass Air (g)	0.00	---
Mass Water (g)	142.34	---
Mass Solids (g)	369.73	---
Total Mass (g)	512.07	---
Volume Air (cm^3)	0.28	---
Volume Water (cm^3)	142.34	---
Volume Solids (cm^3)	138.47	---
Total Volume (cm^3)	281.10	---
Water Content (%)	38.50%	---
Volume Voids (cm^3)	142.63	---
Void Ratio	1.03	---
Porosity	0.51	---
Saturation (%)	99.80%	---

Flexible Wall Test Results (Specimen 2b)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.59

Cell Pressure (psi): 50.0
Head Pressure (psi): 46.3
Tail Pressure (psi): 43.7
Max Gradient: 29.37

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.1	2.9	3.6	21.0	2.027	2.5	4.0	21.0	2.022	2.06	0.00	8.73E-10	0.008
1.0	2.5	4.0	21.0	2.022	2.8	4.8	21.0	2.013	4.13	0.00	2.79E-10	0.024
1.4	2.8	4.8	21.0	2.013	2.9	5.1	21.0	2.010	1.55	0.00	2.23E-10	0.030
2.0	2.9	5.1	21.0	2.010	3.0	5.6	21.0	2.004	2.58	0.00	2.85E-10	0.041
2.5	3.5	1.0	23.4	2.084	3.8	19.2	3.1	1.643	93.91	105.76	2.53E-08	0.825
3.0	3.8	0.6	24.0	2.096	4.0	17.0	5.4	1.694	84.62	96.91	2.15E-08	1.538
3.5	4.0	0.5	24.0	2.097	4.2	14.4	8.4	1.759	71.72	81.28	2.02E-08	2.139
3.9	4.2	0.4	24.4	2.102	4.3	12.6	10.4	1.802	62.95	72.94	1.83E-08	2.673
4.5	4.3	0.4	24.4	2.102	4.5	14.2	8.6	1.763	71.21	82.32	1.63E-08	3.276
5.0	4.5	0.5	24.4	2.101	4.7	12.8	10.3	1.799	63.47	73.46	1.61E-08	3.814
5.5	4.7	0.6	24.5	2.101	4.9	12.0	11.4	1.821	58.82	68.25	1.58E-08	4.313
6.0	4.9	0.9	24.1	2.093	5.0	10.8	12.7	1.849	51.08	59.39	7.03E-09	4.747
6.5	5.0	10.8	12.7	1.849	5.2	19.6	2.3	1.629	45.41	54.18	1.42E-08	5.139
7.1	5.2	0.4	23.8	2.096	5.4	13.2	9.6	1.786	66.05	73.98	1.39E-08	5.689
7.3	5.4	13.2	9.6	1.786	5.4	16.5	5.9	1.706	17.03	19.28	1.28E-08	5.832
7.6	5.4	0.7	24.5	2.100	5.5	6.5	17.8	1.957	29.93	34.91	1.33E-08	6.086
8.0	5.5	6.5	17.8	1.957	6.0	13.9	8.9	1.770	38.18	46.37	1.26E-08	6.418
8.3	6.0	13.9	8.9	1.770	6.3	18.7	2.2	1.638	24.77	34.91	1.36E-08	6.653
8.9	6.3	0.7	23.7	2.091	6.5	11.2	11.4	1.830	54.18	64.08	1.21E-08	7.117
9.5	6.5	1.2	23.7	2.085	8.4	10.8	10.7	1.826	49.54	67.73	1.26E-08	7.578
10.0	1.7	0.9	24.2	2.094	3.6	9.8	11.9	1.851	45.92	64.08	1.26E-08	8.010
10.2	3.6	9.8	11.9	1.851	4.2	12.1	8.6	1.787	11.87	17.19	1.28E-08	8.125

Specimen 2c
4.5 % MSB Backfill
Tap Water

Phase Diagram (Specimen 2c)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	142.34	105.53
Mass Solids (g)	369.73	323.00
Total Mass (g)	512.07	428.53
Volume Air (cm^3)	0.28	0.00
Volume Water (cm^3)	142.34	105.53
Volume Solids (cm^3)	138.47	120.97
Total Volume (cm^3)	281.10	226.50
Water Content (%)	38.50%	32.67%
Volume Voids (cm^3)	142.63	105.53
Void Ratio	1.03	0.87
Porosity	0.51	0.47
Saturation (%)	99.80%	100%

Flexible Wall Test Results (Specimen 2c)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.59

Cell Pressure (psi): 50.0
Head Pressure (psi): 46.3
Tail Pressure (psi): 43.7
Max Gradient: 29.58

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.4	5.0	2.5	23.5	2.068	5.0	6.5	19.0	1.971	20.64	23.45	6.88E-09	0.176
0.5	5.0	6.5	19.0	1.971	5.0	7.8	17.8	1.942	6.71	6.25	6.75E-09	0.227
0.9	5.0	7.8	17.8	1.942	5.0	12.6	13.1	1.833	24.77	24.49	7.28E-09	0.423
1.1	5.0	12.6	13.1	1.833	5.0	14.0	11.8	1.802	7.22	6.77	6.66E-09	0.479
1.9	5.0	0.7	23.2	2.085	5.1	10.0	13.7	1.870	47.99	49.50	6.68E-09	0.867
2.3	5.1	10.0	13.7	1.870	5.1	14.3	9.9	1.777	22.19	19.80	6.69E-09	1.034
2.9	5.1	14.3	9.9	1.777	5.1	19.2	5.2	1.667	25.28	24.49	6.35E-09	1.233
3.4	5.1	19.2	5.2	1.667	5.1	23.2	1.2	1.575	20.64	20.84	5.88E-09	1.398
3.9	5.1	0.6	24.0	2.096	5.1	6.6	18.2	1.960	30.96	30.22	6.74E-09	1.641
4.4	5.1	6.6	18.2	1.960	5.1	11.0	13.9	1.861	22.70	22.40	6.03E-09	1.821
4.9	5.1	11.0	13.9	1.861	5.1	14.9	10.0	1.771	20.12	20.32	5.80E-09	1.982
5.4	5.1	14.9	10.0	1.771	5.1	19.6	5.5	1.666	24.25	23.45	5.71E-09	2.172
6.0	5.1	0.3	23.6	2.094	5.1	6.3	18.4	1.966	30.70	27.35	6.53E-09	2.403
6.4	5.1	6.3	18.4	1.966	5.2	10.5	14.2	1.870	21.67	21.62	5.52E-09	2.576
6.9	5.2	10.5	14.2	1.870	5.2	14.1	10.6	1.787	18.83	18.76	5.42E-09	2.725
7.4	5.2	14.1	10.6	1.787	5.2	17.7	7.1	1.706	18.58	18.24	5.25E-09	2.872
8.0	5.2	0.2	24.0	2.100	5.2	6.6	18.9	1.968	33.02	26.57	5.64E-09	3.109
8.2	5.2	6.6	18.9	1.968	5.2	8.4	16.6	1.921	9.29	11.98	6.69E-09	3.194
8.5	5.2	8.4	16.6	1.921	5.2	11.0	14.1	1.863	13.42	13.03	5.82E-09	3.299
8.9	5.2	11.0	14.1	1.863	5.2	14.4	10.7	1.785	17.54	17.71	5.39E-09	3.440
9.2	5.2	14.4	10.7	1.785	5.2	17.1	8.1	1.724	13.93	13.55	6.04E-09	3.549
9.8	5.2	0.8	24.1	2.094	5.2	6.4	18.5	1.966	28.90	29.18	5.74E-09	3.780
10.4	5.2	6.4	18.5	1.966	5.2	10.9	14.1	1.864	23.22	22.92	5.05E-09	3.964

10.9	5.2	10.9	14.1	1.864	5.2	14.7	10.4	1.778	19.61	19.28	4.53E-09	4.119
11.2	5.2	14.7	10.4	1.778	5.2	16.4	8.7	1.739	8.77	8.86	5.08E-09	4.189
12.3	5.2	1.5	23.9	2.084	5.3	10.8	15.0	1.876	47.99	46.37	5.00E-09	4.565
13.0	5.3	10.8	15.0	1.876	5.3	15.2	10.6	1.775	22.70	22.92	4.02E-09	4.747
14.1	5.3	15.2	10.6	1.775	5.3	21.0	5.7	1.652	29.93	25.53	3.76E-09	4.967
15.1	5.3	1.0	24.1	2.092	5.4	7.1	18.1	1.953	31.48	31.26	3.44E-09	5.217
16.1	5.4	7.1	18.1	1.953	5.4	11.1	14.2	1.863	20.64	20.32	2.59E-09	5.380
17.2	5.4	11.1	14.2	1.863	5.4	14.5	10.8	1.785	17.54	17.71	2.23E-09	5.521
18.1	5.4	14.5	10.8	1.785	5.4	17.2	8.2	1.724	13.93	13.55	1.99E-09	5.630
18.5	5.4	17.2	8.2	1.724	5.4	18.6	6.8	1.692	7.22	7.29	2.34E-09	5.688
18.9	5.4	18.6	6.8	1.692	5.4	19.5	5.8	1.670	4.64	5.21	2.07E-09	5.727
19.9	5.4	19.5	5.8	1.670	5.4	22.2	3.2	1.610	13.93	13.55	1.88E-09	5.837
20.8	5.4	1.4	23.9	2.085	5.4	9.9	15.5	1.892	43.86	43.76	6.35E-09	6.186
22.9	5.4	9.9	15.5	1.892	5.4	13.4	12.0	1.811	18.06	18.24	1.08E-09	6.330
23.0	5.4	13.4	12.0	1.811	5.4	13.8	11.7	1.803	2.06	1.56	1.86E-09	6.345
24.0	5.4	13.8	11.7	1.803	5.5	16.5	9.0	1.741	13.93	14.07	2.05E-09	6.456
25.0	5.5	16.5	9.0	1.741	5.5	19.4	6.3	1.677	14.96	14.07	1.87E-09	6.572
27.3	5.5	1.4	23.2	2.077	5.5	9.1	15.6	1.902	39.73	39.60	2.06E-09	6.888
28.4	5.5	9.1	15.6	1.902	5.5	12.4	12.4	1.827	17.03	16.67	2.13E-09	7.022
29.8	5.5	12.4	12.4	1.827	5.5	16.6	8.2	1.731	21.67	21.88	1.99E-09	7.195

Specimen 3a
4.6 % SW101 Backfill
Tap Water followed by 0.01 M $CaCl_2$

Phase Diagram (Specimen 3a)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	134.90	111.61
Mass Solids (g)	339.80	337.53
Total Mass (g)	474.70	449.14
Volume Air (cm^3)	19.35	0.00
Volume Water (cm^3)	134.90	111.61
Volume Solids (cm^3)	127.27	126.42
Total Volume (cm^3)	281.52	238.03
Water Content (%)	39.70%	33.07%
Volume Voids (cm^3)	154.25	111.61
Void Ratio	1.21	0.88
Porosity	0.55	0.47
Saturation (%)	87.46%	100%

Flexible Wall Test Results (Specimen 3a)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.60
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.7	10.0	2.0	23.0	2.068	10.6	1.9	22.6	2.065	-0.52	2.08	1.21E-10	0.005
3.7	10.6	1.9	22.6	2.065	11.3	2.1	21.9	2.054	1.03	3.65	9.00E-11	0.020
14.8	11.3	2.1	21.9	2.054	11.9	3.4	20.6	2.025	6.71	6.77	7.07E-11	0.064
23.2	11.9	3.4	20.6	2.025	12.2	4.5	19.4	1.998	5.68	6.25	8.45E-11	0.103
31.7	12.2	4.5	19.4	1.998	12.4	5.8	18.1	1.968	6.71	6.77	9.42E-11	0.146
38.9	12.4	5.8	18.1	1.968	12.6	7.1	16.8	1.939	6.71	6.77	1.15E-10	0.190
48.8	12.7	7.1	16.8	1.939	13.0	9.3	14.5	1.887	11.35	11.98	1.47E-10	0.266
56.7	10.0	2.0	23.0	2.068	10.2	4.4	20.5	2.012	12.38	13.03	1.87E-10	0.348
69.8	10.2	4.4	20.5	2.012	10.5	8.7	16.1	1.912	22.19	22.92	2.08E-10	0.494
87.8	10.0	2.0	23.0	2.068	10.3	8.9	16.0	1.909	35.60	36.47	2.40E-10	0.728
95.0	10.0	2.0	23.0	2.068	10.1	5.0	19.9	1.998	15.48	16.15	2.55E-10	0.830
107.1	10.1	5.0	19.9	1.998	10.3	9.8	15.2	1.889	24.77	24.49	2.48E-10	0.990
111.7	10.0	2.0	23.0	2.068	10.1	4.0	21.0	2.022	10.32	10.42	2.62E-10	1.057
118.1	10.1	4.0	21.0	2.022	10.2	6.5	18.5	1.965	12.90	13.03	2.41E-10	1.141
121.2	10.2	6.5	18.5	1.965	10.2	7.6	17.4	1.940	5.68	5.73	2.30E-10	1.178
123.4	10.2	7.6	17.4	1.940	10.3	8.5	16.5	1.919	4.64	4.69	2.53E-10	1.209
128.4	10.3	8.5	16.5	1.919	10.4	10.4	14.6	1.876	9.80	9.90	2.49E-10	1.272
133.2	10.0	2.0	23.0	2.068	10.1	4.1	20.9	2.020	10.84	10.94	2.63E-10	1.343
137.1	10.1	4.1	20.9	2.020	10.2	5.7	19.3	1.983	8.26	8.34	2.52E-10	1.397
143.2	10.2	5.7	19.3	1.983	10.3	8.1	16.9	1.928	12.38	12.50	2.48E-10	1.477
146.0	10.0	2.0	23.0	2.068	10.0	3.3	21.7	2.038	6.71	6.77	2.74E-10	1.521
150.1	10.0	3.3	21.7	2.038	10.1	5.1	19.9	1.997	9.29	9.38	2.69E-10	1.582
153.1	10.1	5.1	19.9	1.997	10.1	6.3	18.6	1.968	6.19	6.77	2.64E-10	1.624

157.1	10.1	6.3	18.6	1.968	10.2	8.1	16.8	1.927	9.29	9.38	2.81E-10	1.684
159.1	10.2	8.1	16.8	1.927	10.2	9.0	16.0	1.908	4.39	4.43	2.72E-10	1.713
164.1	10.0	2.0	23.0	2.068	10.1	4.4	20.6	2.013	12.38	12.50	2.92E-10	1.793
166.0	10.1	4.4	20.6	2.013	10.1	5.3	19.7	1.992	4.64	4.69	2.86E-10	1.824
172.1	10.1	5.3	19.7	1.992	10.1	8.1	16.9	1.928	14.45	14.59	2.90E-10	1.918
175.0	10.1	8.1	16.9	1.928	10.2	9.4	15.5	1.897	6.71	7.29	2.97E-10	1.963
178.0	10.0	2.0	23.0	2.068	10.1	3.6	21.4	2.031	8.26	8.34	3.20E-10	2.017
180.1	10.1	3.6	21.4	2.031	10.1	4.7	20.3	2.006	5.68	5.73	3.19E-10	2.054
182.1	10.1	4.7	20.3	2.006	10.2	5.7	19.3	1.983	5.16	5.21	3.11E-10	2.088
CHANGED PERMEANT FROM TAP WATER TO 0.01 M $CaCl_2$												
185.0	10.0	2.1	23.0	2.067	10.1	3.8	21.5	2.030	8.77	7.82	3.35E-10	2.141
187.0	10.1	3.8	21.5	2.030	10.1	4.9	20.5	2.006	5.68	5.21	3.24E-10	2.177
189.1	10.1	4.9	20.5	2.006	10.2	6.0	19.4	1.981	5.68	5.73	3.22E-10	2.214
192.1	10.2	6.0	19.4	1.981	10.1	7.7	17.8	1.944	8.51	8.34	3.45E-10	2.268
194.0	10.1	7.7	17.8	1.944	10.1	8.8	16.7	1.918	5.93	5.73	3.72E-10	2.306
195.0	10.1	8.8	16.7	1.918	10.1	9.4	16.1	1.904	3.10	3.13	3.81E-10	2.326
198.2	10.0	2.0	23.0	2.068	10.1	4.4	20.8	2.016	12.13	11.46	4.32E-10	2.403
200.1	10.1	4.4	20.8	2.016	10.1	5.8	19.4	1.983	7.48	7.29	4.54E-10	2.451
202.1	10.1	5.8	19.4	1.983	10.1	7.3	18.0	1.949	7.74	7.55	4.54E-10	2.500
205.2	10.1	7.3	18.0	1.949	10.2	9.7	15.7	1.896	12.38	11.72	4.87E-10	2.578
208.2	10.0	2.0	23.0	2.068	10.0	4.8	20.3	2.005	14.45	14.07	5.61E-10	2.671
212.3	10.0	4.8	20.3	2.005	10.1	8.5	16.6	1.920	19.09	19.28	5.65E-10	2.795
219.1	10.0	2.0	23.0	2.068	10.1	9.5	15.7	1.898	38.70	38.03	6.70E-10	3.044
226.5	10.0	2.0	23.0	2.068	10.1	10.1	15.1	1.885	41.80	41.16	6.82E-10	3.313
228.1	10.0	2.0	23.0	2.068	10.0	4.1	20.9	2.020	10.84	10.94	7.46E-10	3.383
233.2	10.0	4.1	20.9	2.020	10.0	10.1	15.0	1.884	30.96	30.74	7.36E-10	3.583
236.3	10.0	2.0	23.0	2.068	10.1	5.9	19.2	1.980	20.12	19.80	7.67E-10	3.713
239.3	10.1	5.9	19.2	1.980	10.1	9.5	15.6	1.897	18.58	18.76	7.75E-10	3.834
243.4	10.0	2.0	23.0	2.068	10.0	7.4	17.6	1.944	27.86	28.13	8.02E-10	4.015
247.3	10.0	7.4	17.6	1.944	10.0	12.8	12.3	1.822	27.86	27.61	9.02E-10	4.195
249.2	10.0	2.0	23.0	2.068	10.1	5.4	19.7	1.991	17.54	17.19	1.03E-09	4.308
250.4	10.1	5.4	19.7	1.991	10.1	7.3	17.8	1.948	9.80	9.90	9.92E-10	4.372
256.3	10.0	2.0	23.0	2.068	10.1	11.2	13.9	1.858	47.47	47.41	9.82E-10	4.679
260.2	10.0	2.0	23.0	2.068	10.0	7.7	17.3	1.937	29.41	29.70	9.01E-10	4.871
268.4	10.0	2.1	23.0	2.068	10.1	14.3	10.8	1.787	63.21	63.56	9.56E-10	5.282

268.9	10.0	2.0	23.0	2.068	10.0	3.0	22.0	2.045	5.16	5.21	1.07E-09	5.315
271.4	10.0	3.0	22.0	2.045	10.0	6.8	18.3	1.959	19.61	19.28	9.47E-10	5.441
271.9	10.0	6.8	18.3	1.959	10.0	7.7	17.4	1.939	4.64	4.69	9.76E-10	5.472
277.3	10.0	7.7	17.4	1.939	10.0	16.0	9.0	1.747	42.83	43.76	1.04E-09	5.752

Chemical Equilibrium Analysis (Specimen 3a)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^{+}	Ca^{2+}	Cl^{-}	
Tap Water	0.266	0.1784	3.77	21.13	---	---	---	---
	0.494		4.96	27.80	1301.26	186.69	99.57	942.65%
	0.728		4.79	26.85	1223.01	215.42	90.99	1087.76%
	0.990		3.98	22.31	832.70	96.11	61.24	485.29%
	1.272		2.94	16.48	654.78	117.65	57.10	594.07%
	1.477	0.1974	2.26	11.45	521.89	31.93	37.81	161.23%
	1.713		1.902	9.64	405.17	56.23	22.76	283.94%
	1.963		1.635	8.28	310.33	50.21	14.98	253.55%
	2.088		1.129	5.72	288.94	53.68	38.05	271.05%
0.01 M $CaCl_2$	0.239	2.34	1.329	0.57	---	---	---	---
	0.491		1.396	0.60	---	---	---	---
	0.708		1.659	0.71	219.72	98.47	250.20	25.82%
	0.956	2.37	1.934	0.82	201.99	129.55	382.82	33.98%
	1.225		2.07	0.87	170.13	167.54	498.37	43.94%
	1.496		2.33	0.98	---	---	---	---
	1.746	2.36	2.40	1.02	---	---	---	---
	2.107		2.68	1.14	---	---	---	---
	2.284		2.59	1.10	---	---	---	---
	2.592	2.45	2.62	1.07	---	---	---	---
	2.783		2.57	1.05	---	---	---	---
	3.194		2.57	1.05	---	---	---	---
	3.665	2.41	2.56	1.06	---	---	---	---

* EC ratio = $EC_{effluent}/EC_{influent}$
** Influent ion concentrations for tap water: 9.29 ppm Na^{+}, 19.80 ppm Ca^{2+}, 51.29 ppm Cl^{-}
Influent ion concentrations for 0.01 M $CaCl_2$: 8.20 ppm Na^{+}, 381.31 ppm Ca^{2+}, 645.62 ppm Cl^{-}

Specimen 3b
4.6 % SW101 Backfill
Tap Water followed by 0.05 M $CaCl_2$

Phase Diagram (Specimen 3b)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	132.73	104.21
Mass Solids (g)	333.51	332.03
Total Mass (g)	466.24	436.24
Volume Air (cm^3)	23.87	0.00
Volume Water (cm^3)	132.73	104.21
Volume Solids (cm^3)	124.91	124.36
Total Volume (cm^3)	281.52	225.64
Water Content (%)	39.80%	31.39%
Volume Voids (cm^3)	156.61	104.21
Void Ratio	1.25	0.84
Porosity	0.56	0.46
Saturation (%)	84.76%	100%

Flexible Wall Test Results (Specimen 3b)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.16

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.0	9.6	4.2	21.0	2.020	9.7	4.5	20.8	2.014	1.55	1.04	7.61E-11	0.008
3.9	9.7	4.5	20.8	2.014	9.8	4.7	20.6	2.010	1.03	1.04	6.46E-11	0.015
7.9	9.8	4.7	20.6	2.010	10.1	5.1	20.1	1.999	2.06	2.61	6.94E-11	0.030
10.9	10.1	5.1	20.1	1.999	10.1	5.5	19.8	1.991	2.06	1.56	7.24E-11	0.041
13.8	9.8	2.0	23.2	2.070	9.9	2.4	22.9	2.062	2.06	1.56	7.04E-11	0.053
15.3	9.9	2.4	22.9	2.062	10.0	2.6	22.7	2.058	1.03	1.04	8.14E-11	0.060
17.8	8.4	2.6	21.9	2.049	8.5	3.0	21.6	2.041	2.06	1.56	8.46E-11	0.071
20.8	8.5	3.0	21.6	2.041	8.5	3.4	21.1	2.030	2.06	2.61	9.06E-11	0.086
22.1	8.5	3.4	21.1	2.030	8.6	3.6	20.9	2.026	1.03	1.04	9.44E-11	0.093
24.0	8.6	3.6	20.9	2.026	8.7	3.9	20.6	2.019	1.55	1.56	9.68E-11	0.103
28.2	8.7	3.9	20.6	2.019	8.8	4.6	19.8	2.002	3.61	4.17	1.08E-10	0.127
33.3	8.8	4.6	19.8	2.002	8.9	5.4	18.9	1.982	4.13	4.69	1.04E-10	0.156
35.8	8.9	5.4	18.9	1.982	9.0	5.9	18.4	1.971	2.58	2.61	1.22E-10	0.172
39.0	9.0	5.9	18.4	1.971	9.1	6.5	17.7	1.956	3.10	3.65	1.29E-10	0.194
41.8	9.1	6.5	17.7	1.956	9.2	7.0	17.1	1.943	2.58	3.13	1.24E-10	0.212
45.0	9.2	7.0	17.1	1.943	9.3	7.7	16.4	1.927	3.61	3.65	1.40E-10	0.235
47.7	9.3	7.7	16.4	1.927	9.4	8.3	15.8	1.913	3.10	3.13	1.43E-10	0.255
51.4	9.4	8.3	15.8	1.913	9.5	9.1	14.9	1.894	4.13	4.69	1.48E-10	0.283
55.4	9.5	9.1	14.9	1.894	9.5	10.1	13.9	1.871	5.16	5.21	1.64E-10	0.316
58.5	10.0	2.0	23.0	2.068	10.0	2.8	22.1	2.049	4.13	4.69	1.60E-10	0.344
63.4	10.0	2.8	22.1	2.049	10.2	4.2	20.7	2.017	7.22	7.29	1.73E-10	0.391
70.4	10.2	4.2	20.7	2.017	10.3	6.3	18.4	1.966	10.84	11.98	1.96E-10	0.464
74.5	10.3	6.3	18.4	1.966	10.3	7.7	17.0	1.934	7.22	7.29	2.17E-10	0.510

79.5	10.3	7.7	17.0	1.934	10.4	9.4	15.2	1.894	8.77	9.38	2.22E-10	0.568
85.6	10.4	9.4	15.2	1.894	10.5	11.4	13.1	1.847	10.32	10.94	2.23E-10	0.636
89.7	10.5	11.4	13.1	1.847	10.5	12.7	11.7	1.816	6.71	7.29	2.19E-10	0.680
92.6	10.5	12.7	11.7	1.816	10.5	13.6	10.8	1.795	4.64	4.69	2.16E-10	0.710
97.5	10.5	13.6	10.8	1.795	10.6	15.2	9.1	1.758	8.26	8.86	2.30E-10	0.765
100.5	10.6	15.2	9.1	1.758	10.6	16.2	8.1	1.735	5.16	5.21	2.37E-10	0.798
106.6	10.6	16.2	8.1	1.735	10.7	18.1	6.1	1.690	9.80	10.42	2.32E-10	0.863
110.8	10.7	18.1	6.1	1.690	10.7	19.3	4.7	1.660	6.19	7.29	2.27E-10	0.906
115.5	10.7	19.3	4.7	1.660	10.7	20.8	3.1	1.625	7.74	8.34	2.45E-10	0.957
118.4	10.0	2.0	23.0	2.068	10.0	3.2	21.7	2.039	6.19	6.77	2.56E-10	0.998
119.1	10.0	3.2	21.7	2.039	10.0	3.5	21.4	2.033	1.55	1.56	2.59E-10	1.008
123.4	10.0	3.5	21.4	2.033	10.0	5.2	19.6	1.992	8.77	9.38	2.52E-10	1.066
127.3	10.0	5.2	19.6	1.992	10.0	6.7	18.0	1.957	7.74	8.34	2.46E-10	1.118
131.3	10.0	6.7	18.0	1.957	10.1	8.2	16.4	1.921	7.74	8.34	2.48E-10	1.169
135.4	10.1	8.2	16.4	1.921	10.1	9.8	14.8	1.885	8.26	8.34	2.50E-10	1.222
141.3	10.1	9.8	14.8	1.885	10.1	11.9	12.6	1.835	10.84	11.46	2.44E-10	1.293
CHANGED PERMEANT FROM TAP WATER TO 0.05 M $CaCl_2$												
145.2	10.0	2.0	23.0	2.068	10.0	3.8	21.3	2.028	9.29	8.86	2.68E-10	1.351
152.2	10.0	3.8	21.3	2.028	10.1	7.1	18.0	1.952	17.03	17.19	2.93E-10	1.460
156.4	10.1	7.1	18.0	1.952	10.1	9.4	15.7	1.900	11.87	11.98	3.47E-10	1.536
160.9	10.0	2.0	23.0	2.068	10.0	5.3	19.6	1.991	17.03	17.71	4.49E-10	1.647
167.5	10.0	5.3	19.6	1.991	10.1	10.8	14.0	1.864	28.38	29.18	5.43E-10	1.831
171.0	10.0	2.0	23.0	2.068	10.0	5.7	19.2	1.982	19.09	19.80	6.43E-10	1.955
177.3	10.0	5.7	19.2	1.982	10.1	12.6	12.2	1.823	35.60	36.47	7.16E-10	2.185
183.2	10.0	2.0	23.0	2.068	10.0	9.2	15.5	1.900	37.15	39.08	7.77E-10	2.429
184.0	10.2	2.4	23.0	2.063	10.2	3.7	21.8	2.035	6.71	6.25	8.90E-10	2.470
190.0	10.2	3.7	21.8	2.035	10.2	11.8	13.5	1.847	41.80	43.24	8.73E-10	2.742
198.0	10.0	2.1	23.0	2.067	10.0	14.0	10.6	1.788	61.40	64.60	9.74E-10	3.144
203.0	10.0	2.0	23.0	2.068	10.1	9.7	15.0	1.888	39.73	41.68	9.81E-10	3.404
205.0	10.0	2.0	23.0	2.068	10.0	5.2	19.6	1.992	16.51	17.71	9.69E-10	3.513
206.0	10.0	5.3	19.6	1.991	10.0	6.7	18.2	1.959	7.22	7.29	9.09E-10	3.559
210.1	10.0	2.1	23.0	2.067	10.0	8.3	16.5	1.921	31.99	33.87	9.64E-10	3.770
212.7	10.0	2.0	23.0	2.068	10.0	6.2	18.7	1.971	21.67	22.40	9.64E-10	3.910
214.9	10.0	6.2	18.7	1.971	10.0	9.4	15.3	1.895	16.51	17.71	9.68E-10	4.020
219.1	10.0	2.0	23.0	2.068	10.0	8.8	15.9	1.909	35.09	36.99	1.02E-09	4.250

224.7	10.0	2.0	23.0	2.068	10.0	11.2	13.4	1.853	47.47	50.02	1.06E-09	4.561
226.8	10.0	2.0	23.0	2.068	10.0	5.7	19.2	1.982	19.09	19.80	1.09E-09	4.685
228.9	10.0	5.7	19.2	1.982	10.0	8.9	15.9	1.908	16.51	17.19	1.01E-09	4.793
233.0	10.0	2.0	23.0	2.068	10.0	8.8	16.0	1.910	35.09	36.47	1.04E-09	5.021
234.8	10.0	2.0	23.0	2.068	10.0	5.4	19.7	1.991	17.54	17.19	1.13E-09	5.132
238.1	10.0	5.4	19.7	1.991	10.0	10.6	14.2	1.869	26.83	28.66	1.02E-09	5.309
242.2	10.0	2.0	23.0	2.068	10.1	8.8	16.0	1.910	35.09	36.47	1.05E-09	5.538
242.8	10.1	8.8	16.0	1.910	10.1	9.8	15.0	1.887	5.16	5.21	1.04E-09	5.571

Chemical Equilibrium Analysis (Specimen 3b)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.05 M $CaCl_2$	0.243	9.74	1.507	0.15	311.09	107.47	840.42	5.79%
	0.538		2.69	0.28	445.61	160.51	1105.23	8.64%
	0.892		4.58	0.47	480.37	390.36	1702.41	21.02%
	1.136	9.60	6.48	0.68	411.67	728.77	2366.50	39.24%
	1.449		7.69	0.80	369.72	1195.50	2717.20	64.37%
	1.851	9.64	8.83	0.92	332.02	1545.41	3062.16	83.21%
	2.111		9.16	0.95	195.97	1666.56	3234.96	89.73%
	2.266		9.63	1.00	151.32	1669.09	3452.78	89.87%
	2.477	9.95	9.87	0.99	72.30	1726.32	3540.95	92.95%
	2.727		9.83	0.99	69.83	1734.36	3413.33	93.38%
	2.957		10.55	1.06	51.38	1777.04	3904.55	95.68%
	3.268	10.44	10.49	1.00	44.46	1772.15	3426.72	95.42%
	3.500		10.60	1.02	39.63	1794.60	3364.31	96.63%
	3.728		10.40	1.00	53.26	1883.63	3393.00	101.42%
	4.016	10.16	10.46	1.03	47.93	1896.94	3390.35	102.14%
	4.278		10.22	1.01	48.75	1934.85	3417.44	104.18%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.05 M $CaCl_2$: 41.20 ppm Na^+, 1857.27 ppm Ca^{2+}, 3387.45 ppm Cl^-

Specimen 3c
4.6 % SW101 Backfill
Tap Water followed by 0.2 M $CaCl_2$

Phase Diagram (Specimen 3c)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:

Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	135.33	107.20
Mass Solids (g)	340.03	340.19
Total Mass (g)	475.36	447.39
Volume Air (cm^3)	18.83	0.00
Volume Water (cm^3)	135.33	107.20
Volume Solids (cm^3)	127.35	127.41
Total Volume (cm^3)	281.52	239.69
Water Content (%)	39.80%	31.51%
Volume Voids (cm^3)	154.16	107.20
Void Ratio	1.21	0.84
Porosity	0.55	0.45
Saturation (%)	87.78%	100%

Flexible Wall Test Results (Specimen 3c)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.14

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.0	10.4	3.0	21.8	2.043	10.6	3.2	21.7	2.039	1.03	0.52	4.51E-11	0.005
3.9	10.6	3.2	21.7	2.039	10.7	3.4	21.6	2.036	1.03	0.52	4.78E-11	0.010
7.9	10.7	3.4	21.6	2.036	11.0	3.9	21.4	2.028	2.58	1.04	5.34E-11	0.022
10.9	11.0	3.9	21.4	2.028	11.2	4.2	21.2	2.022	1.55	1.04	5.10E-11	0.030
13.8	11.2	4.2	21.2	2.022	11.3	4.6	20.9	2.014	2.06	1.56	7.18E-11	0.042
17.8	11.3	4.6	20.9	2.014	11.5	5.0	20.4	2.004	2.06	2.61	6.95E-11	0.057
20.8	11.5	5.0	20.4	2.004	11.6	5.4	20.1	1.996	2.06	1.56	7.10E-11	0.069
24.0	11.6	5.4	20.1	1.996	11.9	5.8	19.7	1.987	2.06	2.08	7.85E-11	0.082
28.3	11.9	5.8	19.7	1.987	12.1	6.4	19.2	1.974	3.10	2.61	8.02E-11	0.101
33.3	12.1	6.4	19.2	1.974	12.3	7.1	18.6	1.959	3.61	3.13	8.08E-11	0.123
35.8	12.3	7.1	18.6	1.959	12.4	7.5	18.2	1.950	2.06	2.08	9.85E-11	0.136
41.8	12.4	7.5	18.2	1.950	12.6	8.4	17.4	1.931	4.64	4.17	9.05E-11	0.165
45.0	12.6	8.4	17.4	1.931	12.7	9.0	17.0	1.919	3.10	2.08	1.01E-10	0.182
47.7	12.7	9.0	17.0	1.919	12.8	9.4	16.6	1.910	2.06	2.08	9.57E-11	0.195
51.4	12.8	9.4	16.5	1.909	13.0	10.0	16.0	1.896	3.10	2.61	9.63E-11	0.213
55.4	13.0	10.0	16.0	1.896	13.1	10.8	15.4	1.880	4.13	3.13	1.14E-10	0.237
58.4	13.1	10.8	15.4	1.880	13.1	11.3	14.9	1.869	2.58	2.61	1.09E-10	0.254
59.5	13.1	11.3	14.9	1.869	13.2	11.5	14.7	1.864	1.03	1.04	1.15E-10	0.261
63.5	13.2	11.5	14.7	1.864	13.2	12.2	14.1	1.849	3.61	3.13	1.08E-10	0.282
70.4	13.2	12.2	14.1	1.849	13.4	13.5	13.0	1.822	6.71	5.73	1.17E-10	0.323
74.5	13.4	13.5	13.0	1.822	13.5	14.3	12.2	1.803	4.13	4.17	1.34E-10	0.350
79.6	13.5	14.3	12.2	1.803	13.5	15.3	11.3	1.782	5.16	4.69	1.28E-10	0.382
85.6	13.5	15.3	11.3	1.782	13.6	16.6	10.2	1.754	6.71	5.73	1.38E-10	0.422

89.7	13.6	16.6	10.2	1.754	13.7	17.4	9.4	1.736	4.13	4.17	1.36E-10	0.449
92.6	13.7	17.4	9.4	1.736	13.7	18.0	8.8	1.722	3.10	3.13	1.51E-10	0.469
97.6	13.7	18.0	8.8	1.722	13.8	19.0	7.9	1.700	5.16	4.69	1.37E-10	0.501
100.6	13.8	19.0	7.9	1.700	13.8	19.7	7.2	1.684	3.61	3.65	1.69E-10	0.524
106.6	13.8	19.7	7.2	1.684	13.9	21.0	6.0	1.656	6.71	6.25	1.53E-10	0.567
110.8	13.9	21.0	6.0	1.656	13.9	21.9	5.1	1.635	4.64	4.69	1.61E-10	0.597
114.6	13.9	21.9	5.1	1.635	13.9	22.8	4.3	1.615	4.64	4.17	1.70E-10	0.625
115.5	13.9	22.8	4.3	1.615	13.9	23.0	4.1	1.611	1.03	1.04	1.59E-10	0.632
118.4	10.0	2.0	23.1	2.069	10.0	3.0	22.2	2.047	5.16	4.69	1.95E-10	0.664
119.1	10.0	3.0	22.2	2.047	10.0	3.2	21.9	2.042	1.03	1.56	2.15E-10	0.672
123.4	10.0	3.2	21.9	2.042	10.1	4.6	20.7	2.012	7.22	6.25	1.86E-10	0.716
127.3	10.1	4.6	20.7	2.012	10.1	6.0	19.5	1.982	7.22	6.25	2.04E-10	0.760
131.3	10.1	6.0	19.5	1.982	10.1	7.4	18.3	1.952	7.22	6.25	2.05E-10	0.804
135.4	10.1	7.4	18.3	1.952	10.2	9.0	16.9	1.918	8.26	7.29	2.30E-10	0.854
141.3	10.2	9.0	16.9	1.918	10.2	11.3	14.9	1.869	11.87	10.42	2.38E-10	0.926
145.2	10.2	11.3	14.9	1.869	10.2	12.8	13.6	1.837	7.74	6.77	2.37E-10	0.973
152.2	10.2	12.8	13.6	1.837	10.3	15.6	11.2	1.777	14.45	12.50	2.54E-10	1.061
156.5	10.3	15.6	11.2	1.777	10.3	17.3	9.9	1.743	8.77	6.77	2.46E-10	1.111
161.0	10.3	17.3	9.9	1.743	10.3	19.0	8.3	1.705	8.77	8.34	2.61E-10	1.167
171.1	10.3	19.0	8.3	1.705	10.4	22.9	5.1	1.623	20.12	16.67	2.60E-10	1.286
177.4	10.4	22.9	5.1	1.623	10.4	25.0	3.1	1.576	10.84	10.42	2.51E-10	1.355
184.3	10.0	2.0	23.1	2.069	10.1	5.4	20.2	1.997	17.54	15.11	2.77E-10	1.461
190.1	10.1	5.4	20.2	1.997	10.1	8.2	17.9	1.939	14.45	11.98	2.71E-10	1.547
198.1	10.1	8.2	17.9	1.939	10.2	11.7	15.0	1.865	18.06	15.11	2.59E-10	1.654
CHANGED PERMEANT FROM TAP WATER TO 0.2 M $CaCl_2$												
202.4	10.0	2.1	23.0	2.067	10.0	4.4	21.2	2.020	11.87	9.38	2.92E-10	1.723
205.1	10.0	4.4	21.2	2.020	10.1	6.1	19.9	1.986	8.77	6.77	3.36E-10	1.774
210.9	10.1	6.1	19.9	1.986	10.1	10.7	16.1	1.889	23.74	19.80	4.62E-10	1.915
212.9	10.0	2.0	23.0	2.068	10.0	4.4	21.1	2.019	12.38	9.90	6.49E-10	1.987
215.1	10.0	4.4	21.1	2.019	10.0	7.0	18.8	1.963	13.42	11.98	6.92E-10	2.069
218.2	10.0	7.0	18.8	1.963	10.0	11.0	15.4	1.878	20.64	17.71	7.68E-10	2.194
222.1	10.0	2.0	23.0	2.068	10.1	7.9	18.1	1.944	30.44	25.53	8.39E-10	2.375
222.9	9.8	3.5	22.5	2.045	9.9	4.4	21.7	2.026	4.64	4.17	6.95E-10	2.404
223.9	10.3	8.8	17.3	1.925	10.3	10.4	15.9	1.890	8.26	7.29	9.05E-10	2.454
227.0	10.0	2.0	23.0	2.068	10.0	6.8	18.5	1.962	24.77	23.45	9.41E-10	2.611

229.0	10.0	6.8	18.5	1.962	10.0	9.8	15.7	1.895	15.48	14.59	9.03E-10	2.708
233.9	10.0	2.0	23.0	2.068	10.0	9.7	15.8	1.897	39.73	37.51	9.41E-10	2.959
238.8	10.0	2.0	23.0	2.068	10.0	9.7	15.7	1.896	39.73	38.03	9.49E-10	3.211
243.0	10.0	2.0	23.0	2.068	10.1	8.7	16.7	1.919	34.57	32.82	9.61E-10	3.430
249.3	10.0	2.0	23.0	2.068	10.0	11.3	14.2	1.861	47.99	45.85	8.97E-10	3.734
254.2	10.0	2.0	23.0	2.068	10.0	9.2	16.1	1.906	37.15	35.95	9.03E-10	3.971
259.2	10.0	2.0	23.0	2.068	10.0	10.0	15.4	1.889	41.28	39.60	9.63E-10	4.233
263.2	10.0	2.0	23.0	2.068	10.0	8.5	16.9	1.924	33.54	31.78	9.74E-10	4.445
267.8	10.0	2.0	23.0	2.068	10.0	9.4	16.0	1.903	38.18	36.47	9.82E-10	4.687
274.1	10.0	2.0	23.0	2.068	10.0	11.9	13.6	1.847	51.08	48.97	9.63E-10	5.012
277.8	10.0	2.0	23.0	2.068	10.0	8.2	17.1	1.929	31.99	30.74	1.01E-09	5.215
278.8	10.0	2.0	23.0	2.068	10.0	3.8	21.3	2.028	9.29	8.86	1.00E-09	5.274
279.8	10.0	3.8	21.3	2.028	10.0	5.4	19.8	1.992	8.26	7.82	9.74E-10	5.326
281.7	10.0	5.4	19.8	1.992	10.0	8.4	17.0	1.926	15.48	14.59	9.52E-10	5.424
282.9	10.0	8.4	17.0	1.926	10.0	10.1	15.3	1.887	8.77	8.86	9.77E-10	5.481

Chemical Equilibrium Analysis (Specimen 3c)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.2 M $CaCl_2$	0.261	33.7	1.413	0.04	262.84	83.42	892.38	1.12%
	0.540		6.97	0.21	516.33	577.89	2255.77	7.76%
	0.800		17.37	0.52	458.56	2146.70	5612.25	28.82%
	1.054	36.4	25.8	0.71	322.86	3928.32	8482.54	52.74%
	1.305		30.3	0.83	280.15	5900.67	11930.14	79.22%
	1.557		33.1	0.91	255.24	7137.46	13168.78	95.82%
	1.775	35.3	34.7	0.98	236.42	7985.71	14252.92	107.21%
	2.080		33.2	0.94	220.14	8392.18	14565.75	112.67%
	2.317		35.4	1.00	204.76	8199.36	14120.74	110.08%
	2.579	35.3	35.9	1.02	201.48	8312.65	14123.53	111.60%
	2.791		35.4	1.00	187.17	7874.65	13223.82	105.72%
	3.033		35.7	1.01	186.68	8005.27	13385.74	107.47%
	3.358	35.3	35.5	1.01	186.43	8023.33	13273.20	107.71%
	3.561		35.9	1.02	223.26	7591.05	13828.45	101.91%
	3.827		36.0	1.02	219.65	7585.10	14000.11	101.83%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.2 M $CaCl_2$: 155.34 ppm Na^+, 7448.77 ppm Ca^{2+}, 13547.08 ppm Cl^-

Specimen 3d
4.6 % SW101 Backfill
Tap Water followed by 0.5 M $CaCl_2$

Phase Diagram (Specimen 3d)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	125.52	101.06
Mass Solids (g)	315.36	316.11
Total Mass (g)	440.88	417.17
Volume Air (cm^3)	37.89	0.00
Volume Water (cm^3)	125.52	101.06
Volume Solids (cm^3)	118.11	118.39
Total Volume (cm^3)	281.52	229.17
Water Content (%)	39.80%	31.97%
Volume Voids (cm^3)	163.40	101.06
Void Ratio	1.38	0.85
Porosity	0.58	0.44
Saturation (%)	76.81%	100%

Flexible Wall Test Results (Specimen 3d)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.0	10.3	3.2	20.8	2.029	10.4	3.4	20.5	2.023	1.03	1.56	7.57E-11	0.008
3.9	10.4	3.4	20.5	2.023	10.6	3.7	20.3	2.018	1.55	1.04	8.03E-11	0.016
7.9	10.6	3.7	20.3	2.018	10.8	4.2	19.8	2.006	2.58	2.61	7.69E-11	0.032
10.9	10.8	4.2	19.8	2.006	10.9	4.6	19.4	1.997	2.06	2.08	8.26E-11	0.044
13.8	10.9	4.6	19.4	1.997	11.0	5.0	19.1	1.989	2.06	1.56	7.27E-11	0.056
17.8	11.0	5.0	19.1	1.989	11.1	5.5	18.5	1.976	2.58	3.13	8.61E-11	0.073
20.8	11.1	5.5	18.5	1.976	11.2	5.9	18.0	1.966	2.06	2.61	9.24E-11	0.087
24.0	11.2	5.9	18.0	1.966	11.5	6.4	17.6	1.956	2.58	2.08	8.98E-11	0.102
28.3	11.5	6.4	17.6	1.956	11.6	7.0	16.9	1.941	3.10	3.65	9.63E-11	0.122
30.9	11.6	7.0	16.9	1.941	11.7	7.5	16.5	1.931	2.58	2.08	1.09E-10	0.136
33.3	11.7	7.5	16.5	1.931	11.8	7.9	16.1	1.921	2.06	2.08	1.07E-10	0.149
35.9	11.8	7.9	16.1	1.921	11.9	8.3	15.6	1.911	2.06	2.61	1.13E-10	0.163
39.0	11.9	8.3	15.6	1.911	12.0	8.9	15.0	1.897	3.10	3.13	1.23E-10	0.182
41.8	12.0	8.9	15.0	1.897	12.1	9.4	14.4	1.885	2.58	3.13	1.28E-10	0.200
45.0	12.1	9.4	14.4	1.885	12.2	10.1	13.8	1.870	3.61	3.13	1.34E-10	0.221
47.7	12.2	10.1	13.8	1.870	12.3	10.6	13.2	1.857	2.58	3.13	1.35E-10	0.238
51.4	12.4	10.6	13.2	1.857	12.5	11.5	12.3	1.837	4.64	4.69	1.62E-10	0.267
55.4	12.5	11.5	12.3	1.837	12.6	12.4	11.4	1.816	4.64	4.69	1.52E-10	0.295
58.4	9.5	2.0	23.0	2.068	9.6	2.8	22.2	2.050	4.13	4.17	1.60E-10	0.321
63.5	9.6	2.8	22.2	2.050	9.7	4.3	20.7	2.015	7.74	7.82	1.76E-10	0.368
70.4	9.7	4.3	20.7	2.015	9.9	6.4	18.6	1.967	10.84	10.94	1.88E-10	0.435
74.5	9.9	6.4	18.6	1.967	9.9	7.6	17.4	1.940	6.19	6.25	1.86E-10	0.473
79.6	9.9	7.6	17.4	1.940	10.0	9.2	15.8	1.903	8.26	8.34	2.01E-10	0.524

85.6	10.0	9.2	15.8	1.903	10.1	11.1	14.0	1.861	9.80	9.38	2.01E-10	0.582
89.7	10.1	11.1	14.0	1.861	10.2	12.3	12.8	1.833	6.19	6.25	1.94E-10	0.620
92.6	10.2	12.3	12.8	1.833	10.2	13.2	11.9	1.813	4.64	4.69	2.14E-10	0.649
97.6	10.2	13.2	11.9	1.813	10.3	14.7	10.3	1.777	7.74	8.34	2.14E-10	0.698
100.6	10.3	14.7	10.3	1.777	10.3	15.7	9.4	1.755	5.16	4.69	2.19E-10	0.728
106.6	10.3	15.7	9.4	1.755	10.3	17.7	7.4	1.709	10.32	10.42	2.37E-10	0.792
110.8	10.3	17.7	7.4	1.709	10.4	19.2	5.9	1.675	7.74	7.82	2.61E-10	0.839
114.6	10.4	19.2	5.9	1.675	10.5	20.5	4.5	1.644	6.71	7.29	2.64E-10	0.882
115.5	10.5	20.5	4.5	1.644	10.6	20.9	4.1	1.635	2.06	2.08	3.12E-10	0.895
118.4	10.0	2.0	23.0	2.068	10.1	3.4	21.5	2.035	7.22	7.82	2.99E-10	0.941
119.1	10.1	3.4	21.5	2.035	10.1	3.7	21.2	2.028	1.55	1.56	2.60E-10	0.950
123.4	10.1	3.7	21.2	2.028	10.3	5.9	18.9	1.976	11.35	11.98	3.25E-10	1.022
127.3	10.3	5.9	18.9	1.976	10.4	8.1	16.7	1.926	11.35	11.46	3.54E-10	1.092
131.3	10.4	8.1	16.7	1.926	10.5	10.3	14.4	1.874	11.35	11.98	3.67E-10	1.163
135.4	10.5	10.3	14.4	1.874	10.6	12.7	12.0	1.819	12.38	12.50	3.86E-10	1.239
141.3	10.6	12.7	12.0	1.819	10.7	16.1	8.6	1.741	17.54	17.71	4.01E-10	1.347
145.2	10.7	16.1	8.6	1.741	10.7	18.2	6.4	1.692	10.84	11.46	3.93E-10	1.415
152.2	10.7	18.2	6.4	1.692	10.9	22.0	2.6	1.605	19.61	19.80	4.07E-10	1.536
156.4	10.9	22.0	2.6	1.605	10.9	24.2	0.3	1.554	11.35	11.98	4.15E-10	1.607
161.1	10.0	2.0	23.0	2.068	10.1	5.2	19.8	1.995	16.51	16.67	4.12E-10	1.709
171.1	10.1	5.2	19.8	1.995	10.2	11.7	13.3	1.846	33.54	33.87	4.18E-10	1.915
177.4	10.2	11.7	13.3	1.846	10.3	15.6	9.3	1.755	20.12	20.84	4.27E-10	2.040
184.1	10.3	15.6	9.3	1.755	10.4	19.7	5.3	1.662	21.16	20.84	4.36E-10	2.169
190.1	10.0	2.0	23.0	2.068	10.1	6.3	18.7	1.970	22.19	22.40	4.36E-10	2.305
198.2	10.1	6.3	18.7	1.970	10.2	11.8	13.2	1.843	28.38	28.66	4.42E-10	2.480
203.1	10.2	11.8	13.2	1.843	10.2	15.0	10.1	1.771	16.51	16.15	4.38E-10	2.580
205.1	10.2	15.0	10.1	1.771	10.3	16.2	8.8	1.743	6.19	6.77	4.24E-10	2.620
209.0	10.3	16.2	8.8	1.743	10.3	18.6	6.5	1.689	12.38	11.98	4.38E-10	2.694
CHANGED PERMEANT FROM TAP WATER TO 0.5 M $CaCl_2$												
212.9	10.0	2.1	23.0	2.067	10.1	5.5	19.8	1.991	17.54	16.67	5.12E-10	2.799
216.9	10.1	5.5	19.8	1.991	10.1	10.6	14.7	1.874	26.32	26.57	8.09E-10	2.961
222.1	10.0	2.0	23.0	2.068	10.1	10.8	14.4	1.869	45.41	44.81	1.05E-09	3.237
226.9	10.0	2.0	23.0	2.068	10.1	10.2	15.0	1.882	42.31	41.68	1.05E-09	3.494
230.9	10.0	2.0	23.0	2.068	10.1	9.2	16.0	1.905	37.15	36.47	1.09E-09	3.719
235.0	10.0	2.0	23.0	2.068	10.1	9.2	16.0	1.905	37.15	36.47	1.08E-09	3.944

239.1	10.0	2.0	23.0	2.068	10.1	9.0	16.1	1.909	36.12	35.95	1.05E-09	4.165
243.8	10.0	2.0	23.0	2.068	10.1	10.6	15.1	1.879	44.38	41.16	1.10E-09	4.426
249.4	10.0	2.0	23.0	2.068	10.1	11.2	14.5	1.865	47.47	44.29	1.00E-09	4.707
251.9	10.0	2.0	23.0	2.068	10.1	6.3	19.0	1.973	22.19	20.84	1.01E-09	4.839
254.9	10.1	6.3	19.0	1.973	10.1	11.4	14.1	1.858	26.32	25.53	1.06E-09	4.998
259.2	10.0	2.0	23.0	2.068	10.1	9.4	15.8	1.901	38.18	37.51	1.05E-09	5.229
263.2	10.0	2.0	23.0	2.068	10.1	9.0	16.1	1.909	36.12	35.95	1.08E-09	5.450
267.8	10.0	2.0	23.0	2.068	10.1	10.1	15.1	1.885	41.80	41.16	1.10E-09	5.704
274.1	10.0	2.0	23.0	2.068	10.1	12.7	12.5	1.825	55.21	54.71	1.06E-09	6.040
277.0	10.0	2.0	23.0	2.068	10.1	7.1	18.1	1.953	26.32	25.53	1.04E-09	6.199

Chemical Equilibrium Analysis (Specimen 3d)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.5 M $CaCl_2$	0.267	79.0	0.967	0.01	84.55	192.74	1750.60	1.04%
	0.543		8.46	0.11	213.53	866.69	3023.80	4.68%
	0.800		31.0	0.39	250.83	5170.67	10516.21	27.91%
	1.025	82.3	50.6	0.61	288.13	10354.13	19388.59	55.89%
	1.250		64.5	0.78	390.03	14710.83	26746.42	79.41%
	1.471		72.4	0.88	398.22	17242.87	30382.79	93.07%
	1.732	79.8	74.3	0.93	421.10	18782.28	33045.94	101.38%
	2.013		73.1	0.92	456.08	19594.45	34906.64	105.77%
	2.303		78.7	0.99	439.69	18994.20	33547.03	102.53%
	2.535	79.5	79.0	0.99	438.25	19093.58	33690.08	103.06%
	2.756		78.6	0.99	406.16	19593.04	33607.33	105.76%
	3.009	77.3	78.4	1.01	392.97	19118.28	32462.17	103.20%
	3.346		78.2	1.01	427.38	20640.61	34531.84	111.42%
	3.504		77.3	1.00	523.33	18847.14	31995.89	101.73%

* EC ratio = $EC_{effluent}/EC_{influent}$
** Influent ion concentrations for 0.5 M $CaCl_2$: 402.73 ppm Na^+, 18525.87 ppm Ca^{2+}, 34377.04 ppm Cl^-

Specimen 3e
4.6 % SW101 Backfill
Tap Water followed by 1.0 M $CaCl_2$

Phase Diagram (Specimen 3e)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	145.65	102.96
Mass Solids (g)	364.12	347.78
Total Mass (g)	509.76	450.74
Volume Air (cm^3)	0.27	0.00
Volume Water (cm^3)	145.65	102.96
Volume Solids (cm^3)	136.37	130.25
Total Volume (cm^3)	282.29	233.21
Water Content (%)	40.00%	29.60%
Volume Voids (cm^3)	145.92	102.96
Void Ratio	1.07	0.79
Porosity	0.52	0.44
Saturation (%)	99.81%	100%

Flexible Wall Test Results (Specimen 3e)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.11
Sample Diameter (cm): 7.11
Sample Cross-Sectional Area (cm^2): 39.70

Cell Pressure (psi): 50.0
Head Pressure (psi): 46.3
Tail Pressure (psi): 43.7
Max Gradient: 29.62

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.4	2.6	0.9	24.1	2.093	2.6	1.0	24.0	2.091	0.52	0.52	1.49E-10	0.004
0.9	2.6	1.0	24.0	2.091	2.6	1.1	23.9	2.089	0.52	0.52	1.08E-10	0.008
3.4	2.6	1.1	23.9	2.089	2.7	1.6	23.4	2.077	2.58	2.87	1.25E-10	0.028
6.9	2.7	1.6	23.4	2.077	2.8	2.4	22.6	2.058	4.13	4.17	1.37E-10	0.058
8.9	2.8	2.4	22.6	2.058	2.9	2.9	22.1	2.047	2.58	2.34	1.42E-10	0.076
10.4	2.9	2.9	22.1	2.047	2.9	3.2	21.8	2.041	1.55	1.56	1.20E-10	0.087
12.3	2.9	3.2	21.8	2.041	3.0	3.7	21.4	2.030	2.58	2.08	1.44E-10	0.104
13.0	3.0	3.7	21.4	2.030	3.0	3.9	21.2	2.026	1.03	1.04	1.66E-10	0.112
14.1	3.0	3.9	21.2	2.026	3.0	4.1	21.0	2.021	1.03	1.04	1.17E-10	0.120
15.2	3.0	4.1	21.0	2.021	3.0	4.4	20.7	2.014	1.55	1.56	1.71E-10	0.131
16.1	3.0	4.4	20.7	2.014	3.0	4.6	20.5	2.010	1.03	1.04	1.24E-10	0.139
17.2	3.0	4.6	20.5	2.010	3.0	4.9	20.2	2.003	1.55	1.56	1.78E-10	0.150
18.1	3.0	4.9	20.2	2.003	3.1	5.1	20.0	1.998	1.03	1.04	1.32E-10	0.158
20.9	3.1	5.1	20.0	1.998	3.1	5.8	19.3	1.982	3.61	3.65	1.55E-10	0.184
23.1	3.1	5.8	19.3	1.982	3.1	6.3	18.8	1.971	2.58	2.61	1.45E-10	0.203
25.1	3.1	6.3	18.8	1.971	3.2	6.8	18.2	1.958	2.58	3.13	1.72E-10	0.224
27.4	3.2	6.8	18.2	1.958	3.2	7.5	17.6	1.943	3.61	3.13	1.78E-10	0.249
28.4	3.2	7.5	17.6	1.943	3.2	7.7	17.4	1.939	1.03	1.04	1.26E-10	0.256
30.1	3.2	7.7	17.4	1.939	3.3	8.2	16.9	1.927	2.58	2.61	1.85E-10	0.275
32.4	3.3	8.2	16.9	1.927	3.3	8.8	16.3	1.913	3.10	3.13	1.66E-10	0.298
34.8	3.3	8.8	16.3	1.913	3.4	9.5	15.6	1.897	3.61	3.65	1.89E-10	0.325
36.4	3.4	9.5	15.6	1.897	3.4	9.9	15.2	1.888	2.06	2.08	1.62E-10	0.340
CHANGED PERMEANT FROM TAP WATER TO 1.0 M $CaCl_2$												

38.1	3.6	0.4	24.7	2.106	3.6	1.3	24.3	2.091	4.64	2.08	2.29E-10	0.365
39.2	3.6	1.3	24.3	2.091	3.7	1.7	24.0	2.083	2.06	1.56	1.96E-10	0.378
40.1	3.7	1.7	24.0	2.083	3.7	2.1	23.7	2.075	2.06	1.56	2.32E-10	0.391
41.1	3.7	2.1	23.7	2.075	3.7	2.4	23.3	2.067	1.55	2.08	1.97E-10	0.405
42.2	3.7	2.4	23.3	2.067	3.7	2.9	22.9	2.057	2.58	2.08	2.48E-10	0.422
43.3	3.7	2.9	22.9	2.057	3.7	3.4	22.4	2.045	2.58	2.61	2.87E-10	0.441
44.1	3.7	3.4	22.4	2.045	3.7	3.9	21.9	2.034	2.58	2.61	3.47E-10	0.460
45.4	3.7	3.9	21.9	2.034	3.7	4.7	21.1	2.015	4.13	4.17	3.68E-10	0.490
46.1	3.7	4.7	21.1	2.015	3.7	5.2	20.7	2.005	2.58	2.08	3.97E-10	0.507
47.3	3.7	5.2	20.7	2.005	3.8	6.1	19.8	1.984	4.64	4.69	4.90E-10	0.541
48.4	3.8	6.1	19.8	1.984	3.8	7.1	18.8	1.962	5.16	5.21	5.58E-10	0.579
49.0	3.8	7.1	18.8	1.962	3.8	7.7	18.3	1.949	3.10	2.61	5.59E-10	0.600
50.9	3.8	7.7	18.3	1.949	3.8	9.7	16.3	1.903	10.32	10.42	6.63E-10	0.676
51.9	3.8	9.7	16.3	1.903	3.9	10.7	15.3	1.880	5.16	5.21	6.77E-10	0.714
55.1	3.9	1.3	21.8	2.062	3.9	5.0	18.1	1.978	19.09	19.28	7.21E-10	0.855
56.1	3.9	5.0	18.1	1.978	3.9	6.3	16.9	1.949	6.71	6.25	7.19E-10	0.902
57.0	3.9	6.3	16.9	1.949	3.9	7.2	16.0	1.928	4.64	4.69	6.58E-10	0.937
58.2	3.9	7.2	16.0	1.928	4.0	8.5	14.8	1.900	6.71	6.25	6.81E-10	0.984
59.2	4.0	8.5	14.8	1.900	4.0	9.6	13.7	1.874	5.68	5.73	7.08E-10	1.026
60.1	4.0	9.6	13.7	1.874	4.0	10.5	12.8	1.854	4.64	4.69	6.78E-10	1.060
61.1	4.0	1.4	22.9	2.074	4.0	2.6	21.8	2.047	6.19	5.73	7.00E-10	1.104
62.5	4.0	2.6	21.8	2.047	4.0	4.2	20.2	2.011	8.26	8.34	6.77E-10	1.165
63.5	4.0	4.2	20.2	2.011	4.0	5.3	19.1	1.986	5.68	5.73	7.03E-10	1.206
64.5	4.0	5.3	19.1	1.986	4.0	6.4	18.0	1.960	5.68	5.73	6.77E-10	1.248
66.2	4.0	6.4	18.0	1.960	4.1	8.3	16.2	1.918	9.80	9.38	6.89E-10	1.318
67.4	4.1	8.3	16.2	1.918	4.1	9.6	14.9	1.888	6.71	6.77	6.84E-10	1.368
68.1	4.1	9.6	14.9	1.888	4.1	10.3	14.2	1.872	3.61	3.65	6.45E-10	1.394
69.4	4.1	1.8	22.3	2.062	4.1	3.3	20.8	2.028	7.74	7.82	7.05E-10	1.451
71.3	4.1	3.3	20.8	2.028	4.2	5.0	19.2	1.990	8.77	8.34	5.29E-10	1.514
73.0	4.2	5.0	19.2	1.990	4.2	5.0	19.2	1.990	0.00	0.00	0.0E+00	1.514
74.1	4.2	5.1	19.2	1.989	4.2	6.0	18.4	1.970	4.64	4.17	8.38E-10	1.546
76.4	4.2	6.0	18.4	1.970	4.2	8.7	15.7	1.908	13.93	14.07	7.33E-10	1.649
78.5	4.2	8.7	15.7	1.908	4.2	11.1	13.4	1.854	12.38	11.98	7.43E-10	1.738
80.0	4.2	1.6	23.2	2.075	4.3	3.5	21.3	2.031	9.80	9.90	7.50E-10	1.811
82.4	4.3	3.5	21.3	2.031	4.3	6.4	18.4	1.965	14.96	15.11	7.47E-10	1.921

83.4	4.3	6.4	18.4	1.965	4.3	7.5	17.4	1.941	5.68	5.21	6.86E-10	1.961
85.4	4.3	7.5	17.4	1.941	4.3	9.8	15.1	1.888	11.87	11.98	7.10E-10	2.048
87.0	4.3	1.1	23.6	2.085	4.4	3.0	21.7	2.042	9.80	9.90	7.27E-10	2.120
88.1	4.4	3.0	21.7	2.042	4.4	4.3	20.5	2.013	6.71	6.25	7.10E-10	2.168
90.3	4.4	4.3	20.5	2.013	4.4	6.7	18.1	1.958	12.38	12.50	6.76E-10	2.259
92.3	4.4	6.7	18.1	1.958	4.4	9.0	15.9	1.906	11.87	11.46	7.07E-10	2.344
94.2	4.4	1.6	23.6	2.080	4.5	3.7	21.4	2.030	10.84	11.46	6.95E-10	2.426
96.3	4.5	3.7	21.4	2.030	4.5	6.2	19.0	1.974	12.90	12.50	7.07E-10	2.519
97.4	4.5	6.2	19.0	1.974	4.5	7.4	17.8	1.947	6.19	6.25	6.63E-10	2.565
99.5	4.5	1.3	23.6	2.083	4.5	3.7	21.2	2.028	12.38	12.50	7.11E-10	2.656
101.4	4.5	3.7	21.2	2.028	4.5	5.9	19.0	1.978	11.35	11.46	6.95E-10	2.740
103.4	4.5	5.9	19.0	1.978	4.6	8.1	16.9	1.928	11.35	10.94	6.96E-10	2.821
105.4	4.6	8.1	16.9	1.928	4.6	10.2	14.8	1.880	10.84	10.94	6.66E-10	2.901
107.1	4.6	10.2	14.8	1.880	4.6	12.0	13.0	1.839	9.29	9.38	7.15E-10	2.969

Chemical Equilibrium Analysis (Specimen 3e)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent
					Na^+	Ca^{2+}	Cl^-	
1.0 M $CaCl_2$	0.350	56.1	2.88	0.05	---	---	---	---
	0.695		13.09	0.23	---	---	---	---
	1.030		29.7	0.53	---	---	---	---
	1.374	57.9	38.7	0.67	---	---	---	---
	1.683		42.8	0.74	---	---	---	---
	1.980		47.4	0.82	---	---	---	---
	2.291	54.8	51.9	0.95	---	---	---	---
	2.605		52.7	0.96	---	---	---	---

* EC ratio = $EC_{effluent}/EC_{influent}$

Specimen 3f
4.6 % SW101 Backfill
0.05 M $CaCl_2$

Phase Diagram (Specimen 3f)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:

Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	142.10	115.10
Mass Solids (g)	352.62	350.27
Total Mass (g)	494.72	465.37
Volume Air (cm^3)	5.36	0.00
Volume Water (cm^3)	142.10	115.10
Volume Solids (cm^3)	132.07	131.19
Total Volume (cm^3)	279.53	246.95
Water Content (%)	40.30%	32.86%
Volume Voids (cm^3)	147.47	115.10
Void Ratio	1.12	0.88
Porosity	0.53	0.47
Saturation (%)	96.36%	100%

Flexible Wall Test Results (Specimen 3f)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.37

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
3.2	10.8	2.9	23.0	2.058	11.6	3.2	22.5	2.049	1.55	2.61	7.61E-11	0.014
8.2	11.6	3.2	22.5	2.049	12.1	3.6	21.9	2.037	2.06	3.13	5.98E-11	0.031
12.2	12.1	3.6	21.9	2.037	12.4	4.0	21.5	2.028	2.06	2.08	6.13E-11	0.045
19.1	12.4	4.0	21.5	2.028	12.7	4.8	20.7	2.010	4.13	4.17	6.99E-11	0.073
23.2	12.7	4.8	20.7	2.010	12.8	5.4	20.2	1.997	3.10	2.61	8.33E-11	0.093
27.9	12.8	5.4	20.2	1.997	12.9	6.1	19.4	1.980	3.61	4.17	9.84E-11	0.119
38.0	12.9	6.1	19.4	1.980	13.1	8.0	17.6	1.937	9.80	9.38	1.15E-10	0.183
44.3	13.1	8.0	17.6	1.937	13.3	9.5	16.1	1.903	7.74	7.82	1.53E-10	0.236
49.1	13.3	9.5	16.1	1.903	13.4	10.8	14.8	1.873	6.71	6.77	1.74E-10	0.281
57.0	10.0	2.0	23.0	2.068	10.2	4.9	20.1	2.002	14.96	15.11	2.23E-10	0.382
65.0	10.2	4.9	20.1	2.002	10.3	8.3	16.7	1.924	17.54	17.71	2.67E-10	0.501
70.0	10.0	2.0	23.0	2.068	10.1	4.7	20.2	2.005	13.93	14.59	3.32E-10	0.597
72.1	10.1	4.7	20.2	2.005	10.1	5.9	19.0	1.978	6.19	6.25	3.60E-10	0.639
76.9	10.1	5.9	19.0	1.978	10.2	8.5	16.3	1.917	13.42	14.07	3.48E-10	0.731
79.8	10.0	2.0	23.2	2.070	10.0	4.0	21.2	2.025	10.32	10.42	4.08E-10	0.801
82.8	10.0	4.0	21.2	2.025	10.1	6.0	19.0	1.976	10.32	11.46	4.30E-10	0.875
86.8	10.1	6.0	19.0	1.976	10.1	9.0	15.8	1.905	15.48	16.67	4.90E-10	0.983
93.9	10.0	2.0	23.6	2.075	10.1	8.0	17.3	1.934	30.96	32.82	5.34E-10	1.198
96.0	10.1	8.0	17.3	1.934	10.1	9.6	15.6	1.896	8.26	8.86	5.21E-10	1.255
103.8	10.0	2.0	24.1	2.081	10.1	9.4	16.4	1.908	38.18	40.12	5.92E-10	1.519
111.8	10.0	2.0	24.1	2.081	10.1	10.3	15.8	1.890	42.83	43.24	6.45E-10	1.809
118.9	10.0	2.0	23.0	2.068	10.1	8.9	16.1	1.910	35.60	35.95	6.07E-10	2.050
126.0	10.0	2.0	23.0	2.068	10.1	9.6	15.4	1.894	39.22	39.60	6.63E-10	2.315

133.0	10.0	2.0	23.0	2.068	10.1	10.0	15.0	1.885	41.28	41.68	7.13E-10	2.594
141.1	10.0	2.0	23.0	2.068	10.1	10.9	14.2	1.865	45.92	45.85	6.86E-10	2.903
147.8	10.0	2.0	23.0	2.068	10.1	9.8	15.2	1.889	40.25	40.64	7.25E-10	3.175
154.2	10.0	2.0	23.0	2.068	10.0	9.6	15.4	1.894	39.22	39.60	7.40E-10	3.441
157.1	10.0	2.0	23.0	2.068	10.0	5.6	19.4	1.986	18.58	18.76	7.56E-10	3.566
162.9	10.0	2.0	23.0	2.068	10.1	9.1	15.9	1.905	36.64	36.99	7.50E-10	3.814
168.7	10.0	2.0	23.0	2.068	10.0	9.0	16.0	1.908	36.12	36.47	7.48E-10	4.059
174.0	10.0	2.0	23.0	2.068	10.0	8.5	16.5	1.919	33.54	33.87	7.60E-10	4.286
179.8	10.0	2.0	23.0	2.068	10.1	9.2	15.7	1.902	37.15	38.03	7.71E-10	4.539
182.0	10.0	2.0	23.0	2.068	10.1	4.9	20.2	2.003	14.96	14.59	7.85E-10	4.638
183.7	10.1	4.9	20.2	2.003	10.1	6.9	18.2	1.957	10.32	10.42	7.69E-10	4.708
185.6	10.1	6.9	18.2	1.957	10.1	9.3	15.8	1.902	12.38	12.50	7.89E-10	4.792
188.7	10.0	2.0	23.0	2.068	10.1	6.0	19.0	1.976	20.64	20.84	7.92E-10	4.932
190.7	10.1	6.0	19.0	1.976	10.1	8.4	16.6	1.921	12.38	12.50	7.51E-10	5.015
197.0	10.0	2.0	23.0	2.068	10.0	9.4	15.7	1.900	38.18	38.03	7.27E-10	5.272
200.1	10.0	2.0	23.0	2.068	10.0	6.0	19.0	1.976	20.64	20.84	7.78E-10	5.412
202.4	10.0	6.0	19.0	1.976	10.1	8.8	16.3	1.913	14.45	14.07	7.75E-10	5.508
208.3	10.1	0.5	23.0	2.085	10.2	8.0	15.6	1.915	38.70	38.55	7.79E-10	5.768

Chemical Equilibrium Analysis (Specimen 3f)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.05 M $CaCl_2$	0.281	9.68	3.10	0.32	771.90	146.36	899.86	7.88%
	0.501		5.02	0.52	1224.12	208.95	1122.50	11.25%
	0.731		6.40	0.66	1383.99	328.83	1424.47	17.71%
	0.983	9.79	7.83	0.80	1301.96	410.54	1626.77	22.10%
	1.255		8.77	0.90	1084.26	589.81	1859.41	31.76%
	1.519		9.03	0.92	797.43	612.54	2571.78	32.98%
	1.809	10.00	9.06	0.91	538.85	948.25	2910.59	51.06%
	2.050		9.07	0.91	426.24	1173.81	3194.04	63.20%
	2.315		9.90	0.99	310.32	1427.30	3334.40	76.85%
	2.594	10.08	10.12	1.00	239.38	1663.18	3327.79	89.55%
	2.903		10.01	0.99	158.18	1803.95	3373.16	97.13%
	3.175		10.18	1.01	113.01	1749.80	3048.16	94.21%
	3.441	10.06	10.34	1.03	89.87	1788.35	3402.08	96.29%
	3.566		10.08	1.00	76.58	1817.19	3521.26	97.84%
	3.814		10.15	1.01	70.09	1810.04	3449.30	97.46%
	4.059	10.08	10.08	1.00	67.63	1815.78	3440.59	97.77%
	4.286		10.11	1.00	53.42	1819.19	3260.00	97.95%
	4.539		10.41	1.03	50.16	1835.22	3247.03	98.81%
	4.792	10.34	10.19	0.99	48.39	1869.79	3291.60	100.67%
	5.015		10.18	0.98	50.85	1841.58	3237.61	99.16%
	5.272		9.56	0.92	45.70	1858.82	3268.67	100.08%
	5.508	9.45	10.23	1.08	65.59	1819.25	3337.41	97.95%
	5.768		10.11	1.07	67.83	1946.70	3531.54	104.82%

* EC ratio = $EC_{effluent}/EC_{influent}$
** Influent ion concentrations for 0.05 M $CaCl_2$: 41.20 ppm Na^+, 1857.27 ppm Ca^{2+}, 3387.45 ppm Cl^-

Specimen 3g
4.6 % SW101 Backfill
0.2 M $CaCl_2$

Phase Diagram (Specimen 3g)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	139.44	113.68
Mass Solids (g)	345.99	346.22
Total Mass (g)	485.43	459.90
Volume Air (cm^3)	10.51	0.00
Volume Water (cm^3)	139.44	113.68
Volume Solids (cm^3)	129.59	129.67
Total Volume (cm^3)	279.53	252.40
Water Content (%)	40.30%	32.83%
Volume Voids (cm^3)	149.95	113.68
Void Ratio	1.16	0.88
Porosity	0.54	0.45
Saturation (%)	92.99%	100%

Flexible Wall Test Results (Specimen 3g)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.14

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
3.1	10.0	2.0	23.0	2.068	11.4	2.4	22.0	2.052	2.06	5.21	1.36E-10	0.024
8.1	11.4	2.4	22.0	2.052	12.5	3.0	20.7	2.030	3.10	6.77	1.14E-10	0.057
12.1	12.5	3.0	20.7	2.030	13.6	3.5	19.4	2.010	2.58	6.77	1.39E-10	0.088
19.1	13.6	3.5	19.4	2.010	15.5	4.7	16.7	1.965	6.19	14.07	1.73E-10	0.155
23.3	15.5	4.7	16.7	1.965	17.4	5.7	14.2	1.925	5.16	13.03	2.60E-10	0.215
26.1	17.4	5.7	14.2	1.925	18.3	6.4	12.8	1.901	3.61	7.29	2.45E-10	0.251
27.9	18.3	6.4	12.8	1.901	18.6	6.8	12.0	1.887	2.06	4.17	2.12E-10	0.272
37.9	10.0	2.0	23.0	2.068	11.3	6.5	17.6	1.955	23.22	28.13	3.03E-10	0.442
44.2	11.3	6.5	17.6	1.955	12.0	10.9	12.8	1.849	22.70	25.01	4.77E-10	0.600
51.0	10.9	2.0	23.0	2.068	11.5	8.8	16.2	1.912	35.09	35.43	6.21E-10	0.833
56.9	10.9	2.0	23.0	2.068	11.6	9.0	15.8	1.905	36.12	37.51	7.40E-10	1.077
64.9	10.0	2.0	23.0	2.068	10.5	11.1	13.9	1.860	46.96	47.41	7.16E-10	1.390
69.2	10.0	2.0	23.0	2.068	10.2	7.3	17.7	1.947	27.35	27.61	7.55E-10	1.571
71.9	10.0	2.0	23.0	2.068	10.1	5.2	20.1	1.998	16.51	15.11	6.79E-10	1.676
75.0	10.1	5.2	20.1	1.998	10.2	8.8	16.7	1.918	18.58	17.71	7.12E-10	1.796
79.7	10.0	2.0	23.0	2.068	10.1	7.4	17.9	1.948	27.86	26.57	6.88E-10	1.977
81.9	10.1	7.4	17.9	1.948	10.1	9.8	15.6	1.894	12.38	11.98	6.91E-10	2.057
88.8	10.0	2.0	23.0	2.068	10.1	10.2	15.1	1.884	42.31	41.16	7.21E-10	2.334
88.9	10.0	2.0	23.0	2.068	10.0	2.1	22.9	2.066	0.52	0.52	9.33E-10	2.337
89.6	9.6	1.8	22.9	2.069	9.7	2.9	22.0	2.046	5.68	4.69	7.96E-10	2.371
94.1	10.2	3.2	22.0	2.043	10.3	8.5	16.7	1.921	27.35	27.61	7.36E-10	2.553
99.9	10.0	2.0	23.0	2.068	10.1	8.8	16.1	1.911	35.09	35.95	7.31E-10	2.789
105.1	10.0	2.0	23.0	2.068	10.1	8.1	16.8	1.927	31.48	32.30	7.36E-10	3.000
111.6	10.0	2.0	23.0	2.068	10.1	9.9	15.1	1.887	40.76	41.16	7.49E-10	3.271

Chemical Equilibrium Analysis (Specimen 3g)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.2 M $CaCl_2$	0.272	33.9	3.98	0.12	493.45	458.96	1293.65	6.16%
	0.600		6.28	0.19	1188.55	439.16	1738.45	5.90%
	0.833		10.60	0.31	1457.18	1021.56	3069.50	13.71%
	1.077	33.7	15.57	0.46	1346.78	2194.15	4989.52	29.46%
	1.390		21.5	0.64	1085.63	3785.12	7122.36	50.82%
	1.571		24.9	0.74	881.14	4937.88	8821.54	66.29%
	1.796	33.1	29.3	0.89	606.49	5719.56	10191.33	76.79%
	2.057		31.2	0.94	431.34	6412.15	13620.23	86.08%
	2.334		34.5	1.04	293.28	6597.99	11884.31	88.58%
	2.553	36.6	35.5	0.97	235.72	6891.80	12339.17	92.52%
	2.789		35.3	0.96	261.70	8102.93	13919.37	108.78%
	3.000		35.7	0.98	228.69	7988.75	13855.95	107.25%
	3.271	36.2	34.3	0.95	210.76	8011.97	13805.16	107.56%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.2 M $CaCl_2$: 155.34 ppm Na^+, 7448.77 ppm Ca^{2+}, 13547.08 ppm Cl^-

Specimen 3h
4.6 % SW101 Backfill
0.5 M $CaCl_2$

Phase Diagram (Specimen 3h)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	141.70	112.74
Mass Solids (g)	351.63	356.47
Total Mass (g)	493.33	469.21
Volume Air (cm^3)	8.12	0.00
Volume Water (cm^3)	141.70	112.74
Volume Solids (cm^3)	131.69	133.51
Total Volume (cm^3)	281.52	246.80
Water Content (%)	40.30%	31.63%
Volume Voids (cm^3)	149.82	112.74
Void Ratio	1.14	0.84
Porosity	0.53	0.46
Saturation (%)	94.58%	100%

Flexible Wall Test Results (Specimen 3h)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.9	10.0	2.0	23.0	2.068	10.3	2.4	24.4	2.080	2.06	-7.29	0.0E+00	0.014
8.8	10.3	2.4	23.0	2.063	10.4	3.4	22.2	2.043	5.16	4.17	9.28E-11	0.045
12.7	10.4	3.4	22.2	2.043	10.5	4.2	21.4	2.025	4.13	4.17	1.22E-10	0.073
19.7	10.5	4.2	21.4	2.025	10.6	6.3	19.6	1.980	10.84	9.38	1.72E-10	0.140
24.0	10.6	6.3	19.6	1.980	10.7	8.2	17.8	1.937	9.80	9.38	2.72E-10	0.204
28.6	10.7	8.2	17.8	1.937	10.7	11.0	15.3	1.877	14.45	13.03	3.73E-10	0.296
38.6	10.0	2.0	23.0	2.068	10.1	12.1	13.4	1.842	52.12	50.02	6.21E-10	0.637
44.9	10.0	2.0	23.0	2.068	10.1	9.4	16.1	1.904	38.18	35.95	7.01E-10	0.884
50.7	10.0	2.0	23.0	2.068	10.1	8.9	16.6	1.916	35.60	33.34	7.11E-10	1.114
57.6	10.0	2.0	23.0	2.068	10.1	9.9	15.6	1.893	40.76	38.55	6.89E-10	1.379
65.5	10.0	2.0	23.0	2.068	10.1	11.2	14.4	1.864	47.47	44.81	7.02E-10	1.687
70.5	10.0	2.0	23.0	2.068	10.0	7.9	17.5	1.937	30.44	28.66	7.10E-10	1.884
72.5	10.0	2.0	23.0	2.068	10.0	4.4	20.8	2.015	12.38	11.46	6.65E-10	1.964
75.6	10.0	4.4	20.8	2.015	10.1	7.7	17.6	1.941	17.03	16.67	6.53E-10	2.076
80.3	10.0	2.0	23.0	2.068	10.1	7.7	17.8	1.943	29.41	27.09	7.17E-10	2.265
82.5	10.1	7.7	17.8	1.943	10.1	10.0	15.7	1.893	11.87	10.94	6.45E-10	2.341
89.5	10.0	2.0	23.0	2.068	10.0	10.3	15.3	1.885	42.83	40.12	7.14E-10	2.618
94.8	10.0	2.0	23.0	2.068	10.0	8.2	17.1	1.929	31.99	30.74	7.05E-10	2.827
100.6	10.0	2.0	23.0	2.068	10.0	9.0	16.4	1.912	36.12	34.39	7.27E-10	3.062
106.3	10.0	2.0	23.0	2.068	10.0	8.8	16.7	1.918	35.09	32.82	7.09E-10	3.289
113.3	10.0	2.0	23.0	2.068	10.1	10.1	15.5	1.889	41.80	39.08	6.95E-10	3.559
120.2	10.0	2.0	23.0	2.068	10.1	10.0	15.6	1.892	41.28	38.55	6.88E-10	3.825
125.3	10.0	2.0	23.0	2.068	10.0	8.1	17.3	1.933	31.48	29.70	7.25E-10	4.029
131.7	10.0	2.0	23.0	2.068	10.0	9.6	16.0	1.901	39.22	36.47	7.07E-10	4.282
136.2	10.0	2.0	23.0	2.068	10.0	7.5	17.8	1.945	28.38	27.09	7.22E-10	4.467
143.3	10.0	2.0	23.0	2.068	10.0	10.4	15.2	1.882	43.34	40.64	7.16E-10	4.747

Chemical Equilibrium Analysis (Specimen 3h)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.5 M $CaCl_2$	0.296	76.3	5.63	0.07	940.29	575.62	2294.65	3.11%
	0.637		15.41	0.20	2012.37	1633.64	5178.90	8.82%
	0.884		29.9	0.39	1808.75	5048.85	11009.63	27.25%
	1.114	75.2	45.0	0.60	1419.50	9418.83	19507.23	50.84%
	1.379		55.5	0.74	1023.70	12616.21	25154.79	68.10%
	1.687	75.4	64.6	0.86	936.96	15286.16	30120.80	82.51%
	1.884		68.3	0.91	769.77	16595.94	32439.95	89.58%
	2.076		74.5	0.99	653.15	17268.23	30521.22	93.21%
	2.341	78.7	75.7	0.96	476.50	17979.79	37328.24	97.05%
	2.618		81.1	1.03	391.04	17074.32	30143.74	92.16%
	2.827		81.9	1.04	389.11	17487.80	31039.66	94.40%
	3.062	82.5	80.4	0.97	449.49	20407.29	34537.58	110.16%
	3.289		78.9	0.96	444.47	20474.47	34577.44	110.52%
	3.559		74.5	0.90	445.90	20788.94	34829.27	112.22%
	3.825	75.3	74.4	0.99	440.16	20844.22	35328.53	112.51%
	4.029		78.7	1.05	428.69	20492.90	34207.42	110.62%
	4.282		79.0	1.05	432.27	20714.63	34694.39	111.81%
	4.467	77.6	78.2	1.01	416.49	20067.86	33573.92	108.32%
	4.747		78.5	1.01	522.67	18890.23	34701.78	101.97%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.5 M $CaCl_2$: 402.73 ppm Na^+, 18525.87 ppm Ca^{2+}, 34377.04 ppm Cl^-

Specimen 3i
4.6 % SW101 Backfill
1.0 M $CaCl_2$

Phase Diagram (Specimen 3i)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	127.90	103.34
Mass Solids (g)	317.38	327.53
Total Mass (g)	445.28	430.87
Volume Air (cm^3)	32.76	0.00
Volume Water (cm^3)	127.90	103.34
Volume Solids (cm^3)	118.87	122.67
Total Volume (cm^3)	279.53	228.96
Water Content (%)	40.30%	31.55%
Volume Voids (cm^3)	160.66	103.34
Void Ratio	1.35	0.84
Porosity	0.57	0.45
Saturation (%)	79.61%	100%

Flexible Wall Test Results (Specimen 3i)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
3.7	10.0	2.0	23.0	2.068	10.4	2.5	22.5	2.057	2.58	2.61	8.04E-11	0.016
8.8	10.4	2.5	22.5	2.057	10.5	3.2	21.9	2.042	3.61	3.13	7.75E-11	0.037
12.7	10.5	3.2	21.9	2.042	10.5	4.2	21.1	2.021	5.16	4.17	1.38E-10	0.066
19.7	10.5	4.2	21.1	2.021	10.7	7.6	18.1	1.948	17.54	15.63	2.85E-10	0.168
24.0	10.7	7.6	18.1	1.948	10.8	11.5	14.5	1.862	20.12	18.76	5.69E-10	0.288
28.6	10.0	2.0	23.0	2.068	10.1	7.9	17.5	1.937	30.44	28.66	7.52E-10	0.471
38.5	10.0	2.0	23.0	2.068	10.1	13.8	12.1	1.808	60.89	56.79	7.27E-10	0.835
44.9	10.1	2.0	22.9	2.067	10.3	10.1	15.4	1.888	41.80	39.08	7.65E-10	1.084
50.7	10.0	2.0	23.0	2.068	10.1	9.4	16.1	1.904	38.18	35.95	7.67E-10	1.314
57.6	10.0	2.0	23.0	2.068	10.1	10.6	15.0	1.878	44.38	41.68	7.50E-10	1.580
65.5	10.0	2.0	23.0	2.068	10.1	11.9	13.9	1.850	51.08	47.41	7.54E-10	1.884
70.5	10.0	2.0	23.0	2.068	10.1	8.4	17.1	1.927	33.02	30.74	7.67E-10	2.081
72.6	10.0	2.0	23.0	2.068	10.1	4.6	20.6	2.011	13.42	12.50	7.27E-10	2.161
76.3	10.1	4.6	20.6	2.011	10.1	9.1	16.4	1.911	23.22	21.88	7.27E-10	2.300

Chemical Equilibrium Analysis (Specimen 3i)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
1.0 M $CaCl_2$	0.288	132.3	7.25	0.05	1171.12	730.22	2674.14	1.99%
	0.471		21.3	0.16	2444.29	3037.65	7940.69	8.29%
	0.835		66.6	0.50	1870.50	14469.40	26594.78	39.50%
	1.084	132.8	92.6	0.70	1556.11	23011.88	39713.90	62.83%
	1.314		108.9	0.82	1324.62	28694.28	49460.96	78.34%
	1.580		118.6	0.89	1215.62	31568.91	54755.67	86.19%
	1.884	131.4	124.6	0.95	1135.30	34591.63	60266.50	94.44%
	2.081		127.3	0.97	1084.49	35762.84	62744.98	97.64%
	2.300		131.7	1.00	1046.35	37565.79	64508.74	102.56%

* EC ratio = $EC_{effluent}/EC_{influent}$
** Influent ion concentrations for 1.0 M $CaCl_2$: 784.28 ppm Na^+, 36627.68 ppm Ca^{2+}, 67999.17 ppm Cl^-

Specimen 4a
5.7 % NG Backfill
Tap Water followed by 0.01 M $CaCl_2$

Phase Diagram (Specimen 4a)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	133.10	107.80
Mass Solids (g)	320.72	318.80
Total Mass (g)	453.82	426.60
Volume Air (cm^3)	28.30	0.00
Volume Water (cm^3)	133.10	107.80
Volume Solids (cm^3)	120.12	119.40
Total Volume (cm^3)	281.52	237.26
Water Content (%)	41.50%	33.81%
Volume Voids (cm^3)	161.39	107.80
Void Ratio	1.34	0.90
Porosity	0.57	0.45
Saturation (%)	82.47%	100%

Flexible Wall Test Results (Specimen 4a)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.37

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.1	10.0	2.0	23.0	2.068	10.5	3.0	21.9	2.044	5.16	5.73	3.05E-10	0.034
4.8	10.5	3.0	21.9	2.044	10.8	4.1	20.8	2.019	5.68	5.73	2.40E-10	0.069
8.8	10.8	4.1	20.8	2.019	11.1	5.8	20.2	1.992	8.77	3.13	1.78E-10	0.106
20.9	11.1	5.8	20.2	1.992	11.9	10.6	18.2	1.915	24.77	10.42	1.78E-10	0.215
26.2	11.9	10.6	18.2	1.915	12.1	12.6	17.2	1.880	10.32	5.21	1.84E-10	0.263
30.9	12.1	12.6	17.2	1.880	12.2	14.4	16.1	1.847	9.29	5.73	2.03E-10	0.310
36.3	10.0	2.0	23.0	2.068	10.1	4.3	21.4	2.023	11.87	8.34	2.19E-10	0.372
42.9	10.1	4.3	21.4	2.023	10.4	7.1	19.5	1.970	14.45	9.90	2.19E-10	0.448
50.2	10.4	7.1	19.5	1.970	10.5	10.0	17.9	1.918	14.96	8.34	1.95E-10	0.520
52.3	10.0	2.0	23.0	2.068	10.0	2.9	22.2	2.049	4.64	4.17	2.40E-10	0.547
54.6	10.0	2.9	22.2	2.049	10.1	3.9	21.7	2.031	5.16	2.61	1.99E-10	0.571
62.3	10.1	3.9	21.7	2.031	10.3	7.3	19.2	1.964	17.29	13.29	2.35E-10	0.666
64.3	10.3	7.3	19.2	1.964	10.3	8.1	18.4	1.945	4.39	3.91	2.49E-10	0.692
68.3	10.3	8.1	18.4	1.945	10.4	9.9	16.9	1.908	9.29	7.82	2.70E-10	0.745
70.5	10.4	9.9	16.9	1.908	10.5	11.0	15.9	1.884	5.42	5.21	2.90E-10	0.777
74.3	10.0	2.0	24.5	2.085	10.1	4.0	22.7	2.041	10.32	9.64	3.04E-10	0.839
77.2	10.1	4.0	22.7	2.041	10.1	5.5	21.3	2.008	7.74	7.03	3.01E-10	0.885
81.3	10.1	5.5	21.3	2.008	10.2	7.5	19.4	1.964	10.32	9.90	2.96E-10	0.948
85.5	10.2	7.5	19.4	1.964	10.2	9.7	17.4	1.916	11.35	10.42	3.18E-10	1.015
88.3	10.1	2.0	24.5	2.085	10.1	3.6	23.0	2.050	8.26	7.82	3.30E-10	1.065
90.2	10.1	3.6	23.0	2.050	10.1	4.7	22.0	2.026	5.68	5.21	3.23E-10	1.099
95.3	10.1	4.7	22.0	2.026	10.2	7.4	19.6	1.967	13.93	12.50	3.13E-10	1.181
97.2	10.2	7.4	19.6	1.967	10.2	8.4	18.6	1.944	5.16	5.21	3.25E-10	1.213

98.4	10.2	8.4	18.6	1.944	10.2	9.1	18.0	1.929	3.61	3.13	3.35E-10	1.234
103.2	10.1	2.0	23.0	2.068	10.2	4.4	20.6	2.013	12.38	12.50	3.04E-10	1.311
104.5	10.2	4.4	20.6	2.013	10.2	5.0	20.0	1.999	3.10	3.13	2.95E-10	1.330
106.2	10.2	5.0	20.0	1.999	10.2	5.9	19.1	1.979	4.64	4.69	3.17E-10	1.359
109.2	10.2	5.9	19.1	1.979	10.3	7.4	17.6	1.944	7.74	7.82	3.18E-10	1.407
112.2	10.3	7.4	17.6	1.944	10.3	8.9	16.1	1.910	7.74	7.82	3.14E-10	1.455
CHANGED PERMEANT FROM TAP WATER TO 0.01 M $CaCl_2$												
116.1	10.0	2.1	23.1	2.068	10.1	4.4	20.9	2.016	11.87	11.46	3.49E-10	1.528
118.1	10.1	4.4	20.9	2.016	10.2	5.4	19.8	1.992	5.16	5.47	3.13E-10	1.560
120.2	10.2	5.4	19.8	1.992	10.2	6.5	18.7	1.967	5.68	5.73	3.25E-10	1.596
123.2	10.2	6.5	18.7	1.967	10.2	8.1	17.2	1.932	8.26	7.82	3.35E-10	1.646
125.1	10.2	8.1	17.2	1.932	10.2	9.2	16.2	1.907	5.68	5.47	3.51E-10	1.680
126.1	10.2	9.2	16.2	1.907	10.2	9.8	15.6	1.894	3.10	2.87	3.72E-10	1.699
129.3	10.0	2.0	23.0	2.068	10.1	4.1	21.0	2.021	10.84	10.68	3.93E-10	1.765
131.3	10.1	4.1	21.0	2.021	10.2	5.3	19.8	1.994	6.19	5.99	3.72E-10	1.803
133.3	10.2	5.3	19.8	1.994	10.5	6.7	18.3	1.960	6.97	8.08	4.49E-10	1.850
136.3	10.5	6.7	18.3	1.960	10.5	8.6	16.4	1.917	10.06	9.64	3.99E-10	1.911
138.6	10.5	8.6	16.4	1.917	10.6	10.1	15.0	1.884	7.74	7.29	4.04E-10	1.957
143.4	10.0	2.0	23.0	2.068	10.1	5.5	19.6	1.989	18.06	17.71	4.37E-10	2.068
150.3	10.1	5.5	19.6	1.989	10.2	10.6	14.8	1.876	26.32	25.01	4.60E-10	2.227
157.6	10.0	2.0	23.0	2.068	10.2	7.7	17.6	1.941	29.41	28.13	4.65E-10	2.405
159.4	10.2	7.7	17.6	1.941	10.2	9.0	16.3	1.911	6.71	6.77	4.53E-10	2.447
164.4	10.0	2.0	23.0	2.068	10.1	6.1	19.1	1.976	21.16	20.32	4.91E-10	2.576
167.5	10.1	6.1	19.1	1.976	10.1	8.5	16.8	1.923	12.38	11.98	4.84E-10	2.651
170.4	10.1	8.5	16.8	1.923	10.1	10.8	14.7	1.872	11.87	10.94	4.85E-10	2.722
174.6	10.0	2.0	23.0	2.068	10.0	5.4	19.7	1.991	17.54	17.19	4.91E-10	2.829
178.4	10.0	5.4	19.7	1.991	10.0	10.3	15.0	1.881	25.28	24.49	7.84E-10	2.983
180.4	10.0	2.0	23.0	2.068	10.1	4.8	20.4	2.006	14.45	13.55	8.34E-10	3.070
181.6	10.1	4.8	20.4	2.006	10.1	6.3	18.9	1.972	7.74	7.82	7.78E-10	3.118
187.3	10.1	6.3	18.9	1.972	10.2	13.2	12.3	1.817	35.60	34.39	7.64E-10	3.335
191.4	10.0	2.0	23.0	2.068	10.0	7.3	17.9	1.949	27.35	26.57	7.93E-10	3.502
200.1	10.0	2.0	23.0	2.068	10.1	13.0	12.5	1.822	56.76	54.71	7.78E-10	3.848

Chemical Equilibrium Analysis (Specimen 4a)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
Tap Water	0.310	0.208	1.5	7.21	704.62	0.00	62.60	0%
	0.520		---	---	765.91	73.46	62.28	370.91%
	0.777		2.57	12.36	582.98	67.27	47.82	339.69%
	1.015		2.02	9.71	441.05	49.20	37.47	248.43%
	1.234		1.565	7.52	320.26	36.27	24.67	183.15%
	1.455	0.221	1.415	6.40	259.95	45.92	30.60	231.87%
0.01 M $CaCl_2$	0.243	2.36	1.712	0.73	---	---	---	---
	0.502		1.951	0.83	332.57	92.78	153.13	24.33%
	0.772		2.29	0.97	300.31	149.72	326.36	39.27%
	0.992	2.37	2.48	1.05	254.49	193.72	434.80	50.80%
	1.266		2.58	1.09	---	---	---	---
	1.528		2.90	1.22	---	---	---	---
	1.880	2.53	2.83	1.12	---	---	---	---
	2.047		2.80	1.11	---	---	---	---
	2.392		2.75	1.09	---	---	---	---

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for tap water: 9.29 ppm Na^+, 19.80 ppm Ca^{2+}, 51.29 ppm Cl^-

Influent ion concentrations for 0.01 M $CaCl_2$: 8.20 ppm Na^+, 381.31 ppm Ca^{2+}, 645.62 ppm Cl^-

Specimen 4b
5.7 % NG Backfill
Tap Water followed by 0.05 M $CaCl_2$

Phase Diagram (Specimen 4b)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	141.06	111.50
Mass Solids (g)	319.13	317.50
Total Mass (g)	460.19	429.00
Volume Air (cm^3)	20.93	0.00
Volume Water (cm^3)	141.06	111.50
Volume Solids (cm^3)	119.53	118.91
Total Volume (cm^3)	281.52	202.62
Water Content (%)	44.20%	35.12%
Volume Voids (cm^3)	161.99	111.50
Void Ratio	1.36	0.94
Porosity	0.58	0.55
Saturation (%)	87.08%	100%

Flexible Wall Test Results (Specimen 4b)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
1.9	10.0	3.4	21.4	2.034	10.2	4.3	20.6	2.014	4.64	4.17	2.73E-10	0.027
5.9	10.2	4.3	20.6	2.014	10.3	5.9	19.0	1.978	8.26	8.34	2.49E-10	0.078
8.8	10.3	5.9	19.0	1.978	10.4	7.2	17.7	1.948	6.71	6.77	2.73E-10	0.120
11.8	10.4	7.2	17.7	1.948	10.5	8.4	16.6	1.921	6.19	5.73	2.46E-10	0.157
13.3	10.5	8.4	16.6	1.921	10.6	9.0	16.0	1.908	3.10	3.13	2.63E-10	0.176
15.8	10.6	9.0	16.0	1.908	10.6	10.0	14.9	1.884	5.16	5.73	2.73E-10	0.210
18.8	10.6	10.0	14.9	1.884	10.6	11.4	13.5	1.851	7.22	7.29	3.07E-10	0.254
20.1	10.6	11.4	13.5	1.851	10.8	11.9	13.0	1.840	2.58	2.61	2.58E-10	0.270
22.0	10.8	11.9	13.0	1.840	10.9	12.7	12.2	1.822	4.13	4.17	2.86E-10	0.296
26.2	9.3	2.0	23.0	2.068	9.4	3.7	21.3	2.029	8.77	8.86	2.40E-10	0.350
28.8	9.4	3.7	21.3	2.029	9.5	4.9	20.1	2.002	6.19	6.25	2.82E-10	0.389
CHANGED PERMEANT FROM TAP WATER TO 0.05 M $CaCl_2$												
31.3	10.0	2.0	23.0	2.068	10.1	3.2	22.5	2.049	6.19	2.61	2.10E-10	0.427
33.8	10.1	3.2	22.5	2.049	10.2	4.5	21.8	2.026	6.71	3.65	2.36E-10	0.469
35.8	10.2	4.5	21.8	2.026	10.2	5.5	21.4	2.010	5.16	2.08	2.17E-10	0.500
39.0	10.2	5.5	21.4	2.010	10.3	7.2	19.7	1.971	8.77	8.86	3.27E-10	0.555
41.1	10.3	7.2	19.7	1.971	10.4	8.4	18.5	1.943	6.19	6.25	3.57E-10	0.593
43.0	10.4	8.4	18.5	1.943	10.4	9.4	17.4	1.919	5.16	5.73	3.64E-10	0.627
43.8	10.4	9.4	17.4	1.919	10.5	9.9	16.9	1.908	2.58	2.61	3.69E-10	0.643
45.6	10.0	2.0	23.0	2.068	10.1	3.3	21.7	2.038	6.71	6.77	4.31E-10	0.684
48.3	10.1	3.3	21.7	2.038	10.2	5.1	19.8	1.996	9.29	9.90	4.23E-10	0.744
51.4	10.2	5.1	19.8	1.996	10.2	7.4	17.5	1.943	11.87	11.98	4.61E-10	0.817
53.3	10.2	7.4	17.5	1.943	10.3	8.8	16.1	1.911	7.22	7.29	4.71E-10	0.862

54.3	10.3	8.8	16.1	1.911	10.3	9.5	15.4	1.895	3.61	3.65	4.74E-10	0.884
56.5	10.0	2.0	23.0	2.068	10.1	3.9	21	2.023	9.80	10.42	5.28E-10	0.947
57.5	10.1	3.9	21.0	2.023	10.1	4.7	20.2	2.005	4.13	4.17	5.01E-10	0.973
61.4	10.1	4.7	20.2	2.005	10.2	8	16.9	1.929	17.03	17.19	5.25E-10	1.078
68.3	10.0	2.0	23.0	2.068	10.2	8.5	16.5	1.919	33.54	33.87	5.80E-10	1.286
70.5	10.2	8.5	16.5	1.919	10.3	10.5	14.5	1.873	10.32	10.42	6.05E-10	1.350
71.5	10.3	10.5	14.5	1.873	10.3	11.4	13.6	1.853	4.64	4.69	6.02E-10	1.379
74.7	10.0	2.0	23.0	2.068	10.1	5.4	19.5	1.989	17.54	18.24	6.57E-10	1.489
77.5	10.1	5.4	19.5	1.989	10.1	8.3	16.7	1.924	14.96	14.59	6.36E-10	1.581
78.8	10.1	8.3	16.7	1.924	10.1	9.6	15.4	1.894	6.71	6.77	6.40E-10	1.622
83.5	10.0	2.0	23.0	2.068	10.1	7.3	17.7	1.947	27.35	27.61	6.86E-10	1.792
87.7	10.1	7.3	17.7	1.947	10.1	11.6	13.5	1.849	22.19	21.88	6.65E-10	1.928
90.5	10.0	2.0	23.0	2.068	10	5.1	19.9	1.997	16.00	16.15	6.67E-10	2.027
95.5	10.0	5.1	19.9	1.997	10.1	10.3	14.7	1.878	26.83	27.09	6.65E-10	2.194
98.4	10.0	2.0	23.0	2.068	10	5.9	19.1	1.979	20.12	20.32	7.98E-10	2.318
101.4	10.0	5.9	19.1	1.979	10.1	8.9	16	1.909	15.48	16.15	6.50E-10	2.416
104.5	10.0	2.0	23.0	2.068	10	5.6	19.4	1.986	18.58	18.76	7.16E-10	2.531
108.6	10.0	5.6	19.4	1.986	10	10	14.9	1.884	22.70	23.45	6.77E-10	2.674
112.4	10.0	2.0	23.0	2.068	10	6.4	18.6	1.967	22.70	22.92	7.15E-10	2.815
113.4	10.0	6.4	18.6	1.967	10.1	7.5	17.6	1.943	5.68	5.21	6.57E-10	2.848
116.3	10.0	2.0	23.0	2.068	10	5.3	19.7	1.992	17.03	17.19	6.91E-10	2.954
117.0	10.0	5.3	19.7	1.992	10	6.1	18.9	1.974	4.13	4.17	7.08E-10	2.979
119.2	10.0	6.1	18.9	1.974	10	8.4	16.6	1.921	11.87	11.98	6.78E-10	3.053
121.3	10.0	8.4	16.6	1.921	10	10.6	14.4	1.871	11.35	11.46	6.80E-10	3.123

Chemical Equilibrium Analysis (Specimen 4b)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.05 M $CaCl_2$	0.254	9.58	2.33	0.24	722.54	286.86	2165.06	15.45%
	0.496		4.04	0.42	1045.04	370.25	2459.50	19.93%
	0.689		5.65	0.59	1155.45	435.58	2620.66	23.45%
	0.990	9.76	7.02	0.72	1015.12	762.18	3191.73	41.04%
	1.233		8.23	0.84	617.76	1094.17	2721.34	58.91%
	1.539		8.99	0.92	410.00	1523.88	2998.81	82.05%
	1.805	9.60	9.51	0.99	215.28	1490.75	4094.57	80.27%
	2.027		9.68	1.01	139.07	1647.26	4261.54	88.69%
	2.285		9.75	1.02	85.73	1691.46	4327.37	91.07%
	2.459	9.54	9.82	1.03	60.33	1795.07	4366.82	96.65%
	2.735		10.11	1.06	60.04	1925.40	3621.47	103.67%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.05 M $CaCl_2$: 41.20 ppm Na^+, 1857.27 ppm Ca^{2+}, 3387.45 ppm Cl^-

Specimen 4c
5.7 % NG Backfill
Tap Water followed by 0.2 M $CaCl_2$

Phase Diagram (Specimen 4c)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:

Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	153.56	122.00
Mass Solids (g)	355.47	355.89
Total Mass (g)	509.03	477.89
Volume Air (cm^3)	-5.18	0.00
Volume Water (cm^3)	153.56	122.00
Volume Solids (cm^3)	133.13	133.29
Total Volume (cm^3)	281.52	273.24
Water Content (%)	43.20%	34.28%
Volume Voids (cm^3)	148.38	122.00
Void Ratio	1.11	0.92
Porosity	0.53	0.45
Saturation (%)	103.5%	100%

Flexible Wall Test Results (Specimen 4c)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.26

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.5	8.7	1.9	23.7	2.077	8.9	2.8	22.7	2.055	4.64	5.21	2.28E-10	0.033
5.5	8.9	2.8	22.7	2.055	9.0	4.1	21.5	2.027	6.71	6.25	2.51E-10	0.077
8.7	9.0	4.1	21.5	2.027	9.3	5.3	20.4	2.000	6.19	5.73	2.21E-10	0.117
12.9	9.3	5.3	20.4	2.000	9.4	6.9	19.0	1.966	8.26	7.29	2.18E-10	0.169
15.5	9.4	6.9	19.0	1.966	9.5	7.9	18.1	1.944	5.16	4.69	2.33E-10	0.203
18.0	9.5	7.9	18.1	1.944	9.6	8.8	17.2	1.924	4.64	4.69	2.33E-10	0.234
20.5	9.6	8.8	17.2	1.924	9.7	9.7	16.4	1.904	4.64	4.17	2.16E-10	0.264
CHANGED PERMEANT FROM TAP WATER TO 0.2 M $CaCl_2$												
22.5	9.7	2.0	23.0	2.068	9.7	2.8	22.3	2.051	4.13	3.65	2.27E-10	0.290
25.7	9.7	2.8	22.3	2.051	9.8	4.1	21.0	2.021	6.71	6.77	2.45E-10	0.335
27.8	9.8	4.1	21.0	2.021	9.9	5.1	20.1	1.999	5.16	4.69	2.75E-10	0.369
29.7	9.9	5.1	20.1	1.999	9.9	6.0	19.2	1.979	4.64	4.69	3.03E-10	0.400
32.3	9.9	6.0	19.2	1.979	10.1	7.4	17.9	1.948	7.22	6.77	3.15E-10	0.447
35.0	10.1	7.4	17.9	1.948	10.2	8.8	16.5	1.916	7.22	7.29	3.35E-10	0.496
36.0	10.2	8.8	16.5	1.916	10.2	9.4	15.9	1.902	3.10	3.13	4.01E-10	0.517
38.1	10.0	2.0	23.0	2.068	10.1	3.4	21.6	2.036	7.22	7.29	3.92E-10	0.566
41.0	10.1	3.4	21.6	2.036	10.2	5.4	19.6	1.990	10.32	10.42	4.27E-10	0.636
43.2	10.2	5.4	19.6	1.990	10.3	7.0	18.0	1.953	8.26	8.34	4.50E-10	0.692
44.2	10.3	7.0	18.0	1.953	10.3	7.7	17.3	1.937	3.61	3.65	4.54E-10	0.716
48.0	10.3	7.7	17.3	1.937	10.4	10.5	14.7	1.876	14.45	13.55	4.59E-10	0.811
54.0	10.1	2.0	23.0	2.068	10.3	7.3	17.9	1.949	27.35	26.57	5.30E-10	0.992
56.2	10.3	7.3	17.9	1.949	10.4	9.6	15.6	1.896	11.87	11.98	6.67E-10	1.073
59.1	10.0	2.0	23.0	2.068	10.1	5.4	19.8	1.992	17.54	16.67	6.89E-10	1.188

64.2	10.1	5.4	19.8	1.992	10.2	10.7	14.6	1.872	27.35	27.09	6.59E-10	1.371
70.2	10.0	2.0	23.0	2.068	10.2	8.7	16.5	1.917	34.57	33.87	6.75E-10	1.602
71.3	10.2	8.7	16.5	1.917	10.2	9.8	15.5	1.893	5.68	5.21	6.34E-10	1.639
74.4	10.0	2.0	23.0	2.068	10.1	5.4	19.7	1.991	17.54	17.19	6.65E-10	1.756
77.0	10.1	5.4	19.7	1.991	10.1	8.2	17.1	1.929	14.45	13.55	6.47E-10	1.850
82.2	10.0	2.0	23.0	2.068	10.1	7.5	17.7	1.944	28.38	27.61	6.39E-10	2.039
85.2	10.1	7.5	17.7	1.944	10.2	10.4	14.8	1.878	14.96	15.11	6.28E-10	2.140
91.2	10.0	2.0	23.0	2.068	10.1	8.2	16.9	1.927	31.99	31.78	6.31E-10	2.355
95.4	10.0	2.0	23.0	2.068	10.1	6.4	18.8	1.970	22.70	21.88	6.24E-10	2.505
99.1	10.1	6.4	18.8	1.970	10.1	10.3	15	1.881	20.12	19.80	6.55E-10	2.640
103.0	10.0	2.0	23.0	2.068	10.1	6.6	18.5	1.964	23.74	23.45	7.14E-10	2.799
103.7	10.1	6.6	18.5	1.964	10.1	7.4	17.8	1.947	4.13	3.65	6.74E-10	2.825
105.9	10.1	7.4	17.8	1.947	10.1	9.7	15.5	1.894	11.87	11.98	6.85E-10	2.905

Chemical Equilibrium Analysis (Specimen 4c)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.2 M $CaCl_2$	0.253	33.6	2.52	0.08	726.99	315.66	2177.50	4.24%
	0.547		5.34	0.16	1179.57	445.29	2880.40	5.98%
	0.809		10.82	0.32	1416.98	1166.77	4478.18	15.66%
	1.108	34.1	18.03	0.53	1070.23	2876.54	5419.55	38.62%
	1.375		23.5	0.69	814.02	4439.91	7448.19	59.61%
	1.586		27.2	0.80	636.65	5572.20	8691.86	74.81%
	1.876	34.0	30.0	0.88	398.18	6171.48	12339.68	82.85%
	2.091		31.3	0.92	308.43	6712.73	13290.01	90.12%
	2.376		32.6	0.96	231.37	6903.29	13701.49	92.68%
	2.642	32.7	33.1	1.01	218.27	6805.29	13147.75	91.36%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.2 M $CaCl_2$: 155.34 ppm Na^+, 7448.77 ppm Ca^{2+}, 13547.08 ppm Cl^-

Specimen 4d
5.7 % NG Backfill
Tap Water followed by 0.5 M $CaCl_2$

Phase Diagram (Specimen 4d)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	131.84	105.20
Mass Solids (g)	328.77	332.80
Total Mass (g)	460.61	438.00
Volume Air (cm^3)	26.54	0.00
Volume Water (cm^3)	131.84	105.20
Volume Solids (cm^3)	123.14	124.64
Total Volume (cm^3)	281.52	235.57
Water Content (%)	40.10%	31.61%
Volume Voids (cm^3)	158.38	105.20
Void Ratio	1.29	0.84
Porosity	0.56	0.45
Saturation (%)	83.24%	100%

Flexible Wall Test Results (Specimen 4d)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.9	10.0	2.0	23.0	2.068	10.1	2.4	22.6	2.059	2.06	2.08	2.60E-10	0.013
4.0	10.1	2.4	22.6	2.059	10.4	3.8	21.3	2.028	7.22	6.77	2.64E-10	0.057
5.9	10.4	3.8	21.3	2.028	10.5	4.6	20.5	2.010	4.13	4.17	2.53E-10	0.083
11.0	10.5	4.6	20.5	2.010	10.8	6.8	18.4	1.960	11.35	10.94	2.64E-10	0.154
12.9	10.8	6.8	18.4	1.960	10.9	7.6	17.6	1.942	4.13	4.17	2.64E-10	0.180
18.9	10.9	7.6	17.6	1.942	11.1	10.2	15.2	1.885	13.16	12.76	2.67E-10	0.262
22.0	10.0	2.0	23.0	2.068	10.1	3.4	21.7	2.037	7.22	6.77	2.67E-10	0.306
24.9	10.1	3.4	21.7	2.037	10.2	4.8	20.4	2.007	6.97	6.77	2.74E-10	0.349
27.0	10.2	4.8	20.4	2.007	10.3	5.7	19.4	1.984	4.90	5.21	2.84E-10	0.381
29.2	10.3	5.7	19.4	1.984	10.4	6.7	18.5	1.963	5.16	4.69	2.77E-10	0.412
CHANGED PERMEANT FROM TAP WATER TO 0.5 M $CaCl_2$												
31.9	10.0	2.0	23.0	2.068	10.1	3.6	21.7	2.034	8.26	7.03	3.28E-10	0.461
33.9	10.1	3.6	21.7	2.034	10.2	4.9	20.5	2.006	6.71	6.25	3.78E-10	0.502
35.9	10.2	4.9	20.5	2.006	10.3	6.4	19.1	1.973	7.74	7.03	4.47E-10	0.548
38.9	10.3	6.4	19.1	1.973	10.4	9.0	16.5	1.913	13.42	13.55	5.49E-10	0.633
39.9	10.4	9.0	16.5	1.913	10.5	10.1	15.5	1.889	5.68	5.21	6.56E-10	0.668
41.9	10.0	2.0	23.0	2.068	10.1	4.5	20.7	2.014	12.64	11.98	7.30E-10	0.746
45.1	10.1	4.5	20.7	2.014	10.2	8.2	17.3	1.932	19.09	17.97	7.00E-10	0.863
46.3	10.2	8.2	17.3	1.932	10.3	9.6	15.9	1.900	7.48	7.03	7.22E-10	0.908
47.0	10.0	2.0	23.0	2.068	10.1	2.9	22.2	2.049	4.64	4.17	7.37E-10	0.936
49.0	10.1	2.9	22.2	2.049	10.1	5.3	20.0	1.996	12.13	11.46	6.89E-10	1.011
52.0	10.1	5.3	20.0	1.996	10.2	8.7	16.8	1.921	17.54	16.67	6.86E-10	1.119
53.1	10.2	8.7	16.8	1.921	10.2	9.8	15.7	1.895	5.93	5.73	6.87E-10	1.155

55.0	10.0	2.0	23.0	2.068	10.1	4.5	20.6	2.012	12.90	12.50	7.61E-10	1.236
59.2	10.1	4.5	20.6	2.012	10.2	9.3	16.2	1.906	24.77	22.92	6.92E-10	1.386
66.0	10.0	2.0	23.0	2.068	10.2	9.8	15.8	1.896	40.25	37.51	6.89E-10	1.632
73.3	10.0	2.0	23.0	2.068	10.3	10.1	15.6	1.890	41.80	38.55	6.58E-10	1.885
75.0	10.0	2.0	23.0	2.068	10.1	4.0	21.2	2.025	10.32	9.38	6.70E-10	1.948
80.1	10.1	4.0	21.2	2.025	10.1	9.4	16.1	1.904	27.86	26.83	6.50E-10	2.120
83.2	10.0	2.0	23.0	2.068	10.1	5.5	19.8	1.991	18.06	16.93	6.67E-10	2.231
86.1	10.1	5.5	19.8	1.991	10.2	8.7	16.8	1.920	16.51	15.37	6.59E-10	2.331
90.3	10.0	2.0	23.0	2.068	10.1	6.6	18.7	1.966	23.74	22.40	6.54E-10	2.477
94.2	10.1	6.6	18.7	1.966	10.1	11.3	14.3	1.862	24.25	22.92	7.48E-10	2.626

Chemical Equilibrium Analysis (Specimen 4d)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.5 M $CaCl_2$	0.255	82.2	5.63	0.07	854.32	719.22	1261.22	3.88%
	0.496		14.44	0.18	1526.80	1384.10	4206.87	7.47%
	0.743		33.0	0.40	1429.00	5903.16	11184.39	31.86%
	0.974	82.0	53.5	0.65	949.08	12373.24	21429.65	66.79%
	1.219		67.1	0.82	786.77	15585.18	26209.19	84.13%
	1.473		73.1	0.89	610.49	18507.22	30748.97	99.90%
	1.708	79.4	78.1	0.98	---	---	---	---
	1.919		79.2	1.00	---	---	---	---
	2.214		85.9	1.08	---	---	---	---

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.5 M $CaCl_2$: 402.73 ppm Na^+, 18525.87 ppm Ca^{2+}, 34377.04 ppm Cl^-

Specimen 4e
5.7 % NG Backfill
Tap Water followed by 1.0 M $CaCl_2$

Phase Diagram (Specimen 4e)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	140.45	107.58
Mass Solids (g)	334.42	345.40
Total Mass (g)	474.87	452.98
Volume Air (cm^3)	15.81	0.00
Volume Water (cm^3)	140.45	107.58
Volume Solids (cm^3)	125.25	129.36
Total Volume (cm^3)	281.52	224.44
Water Content (%)	42.00%	31.15%
Volume Voids (cm^3)	156.27	107.58
Void Ratio	1.25	0.83
Porosity	0.56	0.48
Saturation (%)	89.88%	100%

Flexible Wall Test Results (Specimen 4e)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
1.9	10.0	3.0	22.0	2.045	10.1	3.8	21.2	2.027	4.13	4.17	2.54E-10	0.027
3.9	10.1	3.8	21.2	2.027	10.2	4.6	20.4	2.008	4.13	4.17	2.41E-10	0.053
6.1	10.2	4.6	20.4	2.008	10.3	5.4	19.7	1.991	4.13	3.65	2.18E-10	0.078
7.9	10.3	5.4	19.7	1.991	10.4	6.3	18.9	1.972	4.64	4.17	2.88E-10	0.106
10.6	10.4	6.3	18.9	1.972	10.4	7.3	17.9	1.949	5.16	5.21	2.34E-10	0.139
13.2	10.4	7.3	17.9	1.949	10.5	8.4	17.1	1.927	5.68	4.17	2.27E-10	0.171
16.4	10.5	8.4	17.1	1.927	10.6	9.5	16.0	1.902	5.68	5.73	2.27E-10	0.207
19.2	10.6	9.5	16.0	1.902	10.6	10.6	15.1	1.879	5.68	4.69	2.25E-10	0.241
21.3	10.0	2.0	23.0	2.068	10.1	2.8	22.2	2.050	4.13	4.17	2.38E-10	0.267
26.4	10.1	2.8	22.2	2.050	10.1	4.9	20.3	2.004	10.84	9.90	2.35E-10	0.333
CHANGED PERMEANT FROM TAP WATER TO 1.0 M $CaCl_2$												
32.2	10.0	2.1	23.0	2.067	10.2	5.4	20.2	1.997	17.03	14.59	3.19E-10	0.435
33.3	10.2	5.4	20.2	1.997	10.3	7.1	18.5	1.958	8.77	8.86	9.95E-10	0.491
35.4	10.3	7.1	18.5	1.958	10.4	9.7	16.1	1.901	13.42	12.50	7.44E-10	0.574
36.2	10.4	9.7	16.1	1.901	10.4	10.6	15.2	1.880	4.64	4.69	7.27E-10	0.604
37.3	10.0	2.0	23.0	2.068	10.1	3.6	21.5	2.033	8.26	7.82	8.38E-10	0.655
42.4	10.1	3.6	21.5	2.033	10.2	9.9	15.4	1.890	32.51	31.78	7.66E-10	0.861
48.5	10.0	2.0	23.0	2.068	10.1	9.6	16.0	1.901	39.22	36.47	7.50E-10	1.103
49.5	10.1	9.6	16.0	1.901	10.2	10.8	14.8	1.873	6.19	6.25	7.23E-10	1.143
52.6	10.0	2.1	23.0	2.067	10.1	5.9	19.4	1.982	19.61	18.76	7.40E-10	1.266
55.4	10.1	5.9	19.4	1.982	10.1	9.2	16.3	1.909	17.03	16.15	7.14E-10	1.372
60.4	10.0	2.0	23.0	2.068	10.1	8.0	17.4	1.935	30.96	29.18	7.18E-10	1.564
63.4	10.1	8.0	17.4	1.935	10.1	11.3	14.3	1.862	17.03	16.15	6.92E-10	1.670

69.4	10.0	2.0	23.0	2.068	10.1	9.2	16.2	1.908	37.15	35.43	7.23E-10	1.903
73.6	10.0	2.1	23.0	2.067	10	7.1	18.3	1.956	25.80	24.49	7.09E-10	2.064
77.4	10.0	7.1	18.3	1.956	10.1	11.3	14.2	1.861	21.67	21.36	7.08E-10	2.201
81.3	10.0	2.0	23.0	2.068	10.1	6.7	18.6	1.964	24.25	22.92	7.16E-10	2.352
82.0	10.0	2.0	23.0	2.068	10	2.9	22.1	2.047	4.64	4.69	7.69E-10	2.382
84.1	10.0	2.9	22.1	2.047	10	5.5	19.7	1.990	13.42	12.50	7.05E-10	2.465
86.2	10.0	5.5	19.7	1.990	10	7.9	17.4	1.936	12.38	11.98	7.05E-10	2.543
88.3	10.0	7.9	17.4	1.936	10	10.1	15.3	1.887	11.35	10.94	6.76E-10	2.614

Chemical Equilibrium Analysis (Specimen 4e)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^{+}	Ca^{2+}	Cl^{-}	
1.0 M $CaCl_2$	0.270	133.6	5.29	0.04	1112.62	639.42	2407.72	1.75%
	0.527		17.87	0.13	1491.49	2518.69	4928.04	6.88%
	0.809		50.2	0.38	1537.48	10583.55	22742.24	28.89%
	1.038	131.0	81.6	0.62	1232.00	20018.35	30543.54	54.65%
	1.337		104.8	0.80	1059.50	27539.77	42630.03	75.19%
	1.569		116.0	0.89	928.25	31434.33	55840.29	85.82%
	1.868	130.4	124.1	0.952	882.53	34331.16	60385.37	93.73%
	2.019		110.7	0.85	882.53	36473.72	57110.31	99.58%
	2.281		128.9	0.99	883.86	36422.99	72465.52	99.44%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 1.0 M $CaCl_2$: 784.28 ppm Na^{+}, 36627.68 ppm Ca^{2+}, 67999.17 ppm Cl^{-}

Specimen 4f
5.7 % NG Backfill
0.05 M $CaCl_2$

Phase Diagram (Specimen 4f)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	137.90	106.90
Mass Solids (g)	332.28	330.86
Total Mass (g)	470.18	437.76
Volume Air (cm^3)	19.17	0.00
Volume Water (cm^3)	137.90	106.90
Volume Solids (cm^3)	124.45	123.92
Total Volume (cm^3)	281.52	261.75
Water Content (%)	41.50%	32.31%
Volume Voids (cm^3)	157.06	106.90
Void Ratio	1.26	0.86
Porosity	0.56	0.41
Saturation (%)	87.80%	100%

Flexible Wall Test Results (Specimen 4f)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
1.0	10.0	2.0	23.0	2.068	10.2	2.5	22.6	2.058	2.58	2.08	2.75E-10	0.015
2.2	10.2	2.5	22.6	2.058	10.3	3.0	22.1	2.046	2.58	2.61	2.48E-10	0.031
8.2	10.3	3.0	22.1	2.046	10.7	5.6	19.9	1.991	13.42	11.46	2.43E-10	0.111
11.0	10.7	5.6	19.9	1.991	10.8	6.8	18.8	1.965	6.19	5.73	2.54E-10	0.149
17.4	10.8	6.8	18.8	1.965	10.9	9.6	16.4	1.905	14.45	12.50	2.58E-10	0.234
18.2	10.9	9.6	16.4	1.905	10.9	9.9	16.1	1.898	1.55	1.56	2.67E-10	0.244
20.5	10.0	2.0	23.0	2.068	10.0	3.2	21.9	2.042	6.19	5.73	3.02E-10	0.282
22.7	10.0	3.2	21.9	2.042	10.1	4.6	20.7	2.012	7.22	6.25	3.48E-10	0.325
29.5	10.1	4.6	20.7	2.012	10.4	8.9	16.8	1.917	22.19	20.58	3.83E-10	0.461
30.5	10.4	8.9	16.8	1.917	10.4	9.4	16.2	1.905	2.58	2.87	3.41E-10	0.479
32.5	10.0	2.0	23.0	2.068	10.1	3.5	21.6	2.035	7.74	7.29	4.29E-10	0.526
36.4	10.1	3.5	21.6	2.035	10.2	6.4	18.9	1.971	14.96	14.07	4.41E-10	0.619
38.7	10.2	6.4	18.9	1.971	10.3	8.2	17.2	1.931	9.29	8.86	4.82E-10	0.677
42.5	10.3	8.2	17.2	1.931	10.4	11.4	14.2	1.860	16.25	15.89	5.34E-10	0.779
44.6	10.0	2.1	23.0	2.068	10.0	4.2	21.0	2.020	11.09	10.42	6.00E-10	0.847
46.3	10.0	4.2	21.0	2.020	10.1	6.0	19.3	1.980	9.03	8.86	5.91E-10	0.904
49.4	10.1	6.0	19.3	1.980	10.2	9.0	16.3	1.911	15.74	15.63	6.23E-10	1.004
52.4	10.0	2.0	23.0	2.068	10.1	5.3	19.9	1.995	17.03	16.15	6.58E-10	1.110
56.4	10.1	5.3	19.9	1.995	10.2	9.5	15.9	1.901	21.67	20.84	6.39E-10	1.245
58.4	10.0	2.0	23.0	2.068	10.1	4.2	21.0	2.020	11.35	10.42	6.59E-10	1.314
59.4	10.1	4.2	21.0	2.020	10.1	5.2	19.9	1.996	5.16	5.73	6.43E-10	1.349
63.4	10.1	5.2	19.9	1.996	10.2	9.5	15.9	1.901	22.19	20.84	6.47E-10	1.486
65.3	10.0	2.0	23.0	2.068	10.0	4.3	20.8	2.017	11.87	11.46	7.16E-10	1.560

71.4	10.0	4.3	20.8	2.017	10.1	11	14.4	1.866	34.57	33.34	6.84E-10	1.777
74.4	10.0	2.0	23.0	2.068	10.1	5.55	19.6	1.988	18.32	17.71	7.07E-10	1.891
77.3	10.1	5.6	19.6	1.988	10.15	8.9	16.4	1.913	17.29	16.67	6.96E-10	1.999
79.4	10.2	8.9	16.4	1.913	10.2	11.1	14.2	1.863	11.35	11.46	6.88E-10	2.072
81.5	10.0	2.0	23.0	2.068	10.1	4.45	20.65	2.013	12.64	12.24	7.13E-10	2.151
84.3	10.1	4.5	20.7	2.013	10.15	7.6	17.65	1.943	16.25	15.63	6.73E-10	2.253
86.3	10.0	2.0	23.0	2.068	10	4.45	20.7	2.014	12.64	11.98	7.24E-10	2.331
88.4	10.0	4.5	20.7	2.014	10.1	6.8	18.4	1.960	12.13	11.98	6.84E-10	2.408
91.3	10.1	6.8	18.4	1.960	10.1	10.1	15.2	1.886	17.03	16.67	7.09E-10	2.515

Chemical Equilibrium Analysis (Specimen 4f)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.05 M $CaCl_2$	0.244	10.25	3.51	0.34	702.69	148.15	334.91	7.98%
	0.479		4.73	0.46	955.26	143.21	559.65	7.71%
	0.779		6.13	0.60	1163.01	184.66	1132.64	9.94%
	1.004	10.07	7.70	0.76	1141.01	386.55	1732.05	20.81%
	1.245		8.90	0.88	950.83	769.36	2318.69	41.42%
	1.486		9.86	0.98	700.10	1096.62	2618.12	59.04%
	1.777	10.57	10.56	1.00	471.85	1419.09	2928.98	76.41%
	2.072		10.89	1.03	299.11	1628.80	3091.52	87.70%
	2.253		10.71	1.01	205.55	1774.21	3209.48	95.53%
	2.515	10.26	11.17	1.09	151.93	1737.45	3296.72	93.55%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.05 M $CaCl_2$: 41.20 ppm Na^+, 1857.27 ppm Ca^{2+}, 3387.45 ppm Cl^-

Specimen 4g
5.7 % NG Backfill
0.2 M $CaCl_2$

Phase Diagram (Specimen 4g)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	133.79	109.06
Mass Solids (g)	322.39	322.86
Total Mass (g)	456.18	431.92
Volume Air (cm^3)	26.98	0.00
Volume Water (cm^3)	133.79	109.06
Volume Solids (cm^3)	120.74	120.92
Total Volume (cm^3)	281.52	232.64
Water Content (%)	41.50%	33.78%
Volume Voids (cm^3)	160.77	109.06
Void Ratio	1.33	0.90
Porosity	0.57	0.47
Saturation (%)	83.22%	100%

Flexible Wall Test Results (Specimen 4g)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.32

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.0	10.0	2.0	23.0	2.068	10.5	2.8	22.1	2.049	4.13	4.69	2.49E-10	0.027
4.8	10.5	2.8	22.1	2.049	10.9	3.9	21.1	2.025	5.68	5.21	2.28E-10	0.061
8.8	10.9	3.9	21.1	2.025	11.3	5.7	19.3	1.983	9.29	9.38	2.79E-10	0.119
16.2	11.3	5.7	19.3	1.983	11.8	9.6	15.3	1.893	20.12	20.84	3.38E-10	0.247
20.8	10.0	2.0	23.0	2.068	10.3	5.5	19.4	1.987	18.06	18.76	4.67E-10	0.361
21.8	10.3	5.5	19.4	1.987	10.3	6.3	18.5	1.967	4.13	4.69	5.31E-10	0.389
25.8	10.3	6.3	18.5	1.967	10.5	9.9	14.9	1.885	18.58	18.76	5.80E-10	0.505
33.0	10.0	2.0	23.0	2.068	10.3	9.6	15.3	1.893	39.22	40.12	6.59E-10	0.751
34.8	10.0	2.0	23.0	2.068	10.0	4.0	21.0	2.022	10.32	10.42	6.82E-10	0.816
40.0	10.0	4.0	21.0	2.022	10.2	9.5	15.4	1.895	28.38	29.18	6.68E-10	0.995
42.8	10.0	2.0	23.0	2.068	10.1	5.2	19.8	1.995	16.51	16.67	6.88E-10	1.098
49.2	10.1	5.2	19.8	1.995	10.2	11.2	13.7	1.856	30.96	31.78	6.08E-10	1.293
52.3	10.0	2.0	23.0	2.068	10.0	5.3	19.8	1.994	16.77	16.93	6.46E-10	1.398
54.5	10.1	5.3	19.8	1.994	10.1	7.6	17.4	1.940	12.13	12.24	6.47E-10	1.474
61.3	10.1	0.7	22.9	2.082	10.4	7.7	15.9	1.921	36.12	36.47	6.40E-10	1.700
64.3	10.1	2.0	23.0	2.068	10.1	5.4	19.5	1.989	17.54	18.24	6.89E-10	1.811
68.2	10.1	5.4	19.5	1.989	10.2	9.6	15.3	1.893	21.67	21.88	6.85E-10	1.946
70.5	10.0	2.0	23.0	2.068	10.0	4.7	20.3	2.006	13.93	14.07	7.17E-10	2.033
74.3	10.0	4.7	20.3	2.006	10.1	8.9	16.1	1.910	21.67	21.88	6.97E-10	2.169
75.5	10.1	8.9	16.1	1.910	10.1	10.2	14.8	1.880	6.71	6.77	6.88E-10	2.211
77.2	10.0	2.0	23.0	2.068	10.1	4.0	21.0	2.022	10.32	10.42	7.24E-10	2.275
81.2	10.1	4.0	21.0	2.022	10.1	8.6	16.4	1.917	23.48	24.23	7.04E-10	2.424
82.5	10.1	8.6	16.4	1.917	10.2	9.9	15.0	1.886	6.97	7.03	7.02E-10	2.467

84.2	10.0	2.0	23.0	2.068	10.1	4.1	20.9	2.020	10.84	10.94	7.50E-10	2.535
88.2	10.1	4.1	20.9	2.020	10.1	8.9	16.0	1.909	24.77	25.53	7.50E-10	2.691
89.2	10.1	8.9	16.0	1.909	10.1	10.0	14.9	1.884	5.68	5.73	7.29E-10	2.727
91.2	10.0	2.1	23.0	2.068	10.1	4.5	20.6	2.012	12.38	12.50	7.49E-10	2.804
95.2	10.1	4.5	20.6	2.012	10.1	9.2	15.8	1.902	24.51	25.27	7.41E-10	2.959
97.1	10.0	2.0	23.0	2.068	10.0	4.4	20.6	2.012	12.38	12.76	7.79E-10	3.037
103.2	10.0	4.4	20.6	2.012	10.1	11.2	13.7	1.856	35.09	35.69	7.19E-10	3.257
106.2	10.0	2.0	23.0	2.068	10.1	5.8	19.2	1.981	19.61	19.80	7.68E-10	3.380
109.1	10.1	5.8	19.2	1.981	10.1	9.2	15.7	1.902	17.54	18.24	7.44E-10	3.491
111.2	10.0	2.1	23.0	2.068	10.1	4.9	20.1	2.002	14.45	15.11	8.23E-10	3.583
112.1	10.1	4.9	20.1	2.002	10.1	5.9	19.1	1.978	5.42	5.47	7.40E-10	3.617
113.3	10.1	5.9	19.1	1.978	10.1	7.5	17.5	1.943	8.00	8.08	7.82E-10	3.667
116.1	10.0	2.0	23.0	2.068	10.1	5.4	19.6	1.990	17.54	17.71	7.54E-10	3.777
117.1	10.1	5.4	19.6	1.990	10.1	6.6	18.3	1.962	6.19	6.77	7.53E-10	3.817
118.1	10.1	6.6	18.3	1.962	10.1	7.7	17.2	1.936	5.68	5.73	7.09E-10	3.852
119.1	10.1	7.7	17.2	1.936	10.1	8.9	16.1	1.909	6.19	5.99	7.25E-10	3.890
120.1	10.1	8.9	16.1	1.909	10.1	10.0	15.0	1.885	5.68	5.47	7.39E-10	3.925

Chemical Equilibrium Analysis (Specimen 4g)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.2 M $CaCl_2$	0.247	34.6	3.24	0.09	625.32	144.36	264.63	1.94%
	0.505		7.43	0.21	1312.28	263.05	1660.19	3.53%
	0.751		14.69	0.42	1430.59	1697.62	4322.62	22.79%
	0.995	34.3	22.6	0.66	1097.74	3612.51	7462.77	48.50%
	1.293		26.8	0.78	684.24	5430.45	9902.39	72.90%
	1.474	32.3	31.3	0.97	551.51	6036.18	11386.87	81.04%
	1.700		32.5	1.01	482.56	6799.11	12759.08	91.28%
	1.946		33.5	1.04	276.04	7186.18	12208.15	96.47%
	2.211	34.1	34.7	1.02	217.57	7405.83	12472.63	99.42%
	2.467		36.0	1.06	184.21	7563.07	12698.07	101.53%
	2.727		36.2	1.06	161.50	7703.81	13218.00	103.42%
	2.959	36.9	36.3	0.98	172.51	7555.63	12697.62	101.43%
	3.257		36.7	0.99	167.04	7605.75	12697.94	102.11%
	3.491		37.0	1.00	171.59	7596.26	13256.51	101.98%
	3.667	37.2	37.1	1.00	172.13	7542.96	13062.71	101.26%
	3.925		36.2	0.97	177.59	7636.43	13045.57	102.52%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.2 M $CaCl_2$: 155.34 ppm Na^+, 7448.77 ppm Ca^{2+}, 13547.08 ppm Cl^-

Specimen 4h
5.7 % NG Backfill
0.5 M $CaCl_2$

Phase Diagram (Specimen 4h)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	132.42	106.50
Mass Solids (g)	319.10	323.33
Total Mass (g)	451.52	429.83
Volume Air (cm^3)	29.58	0.00
Volume Water (cm^3)	132.42	106.50
Volume Solids (cm^3)	119.51	121.10
Total Volume (cm^3)	281.52	269.39
Water Content (%)	41.50%	32.94%
Volume Voids (cm^3)	162.00	106.50
Void Ratio	1.36	0.88
Porosity	0.58	0.40
Saturation (%)	81.74%	100%

Flexible Wall Test Results (Specimen 4h)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.35

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
2.0	10.0	2.0	23.0	2.068	10.3	2.9	22.1	2.047	4.64	4.69	2.71E-10	0.029
4.8	10.3	2.9	22.1	2.047	10.4	4.3	20.9	2.018	7.22	6.25	2.83E-10	0.070
8.7	10.4	4.3	20.9	2.018	10.6	6.6	18.7	1.966	11.87	11.46	3.50E-10	0.142
13.8	10.6	6.6	18.7	1.966	10.8	10.5	15.1	1.880	20.12	18.76	4.78E-10	0.262
20.8	10.0	2.0	23.0	2.068	10.2	9.2	16.1	1.906	37.15	35.95	6.23E-10	0.488
25.7	10.0	2.0	23.0	2.068	10.1	7.6	17.7	1.943	28.90	27.61	6.74E-10	0.662
27.7	10.1	7.6	17.7	1.943	10.1	9.8	15.6	1.894	11.35	10.94	6.95E-10	0.731
34.7	10.0	2.0	23.0	2.068	10.1	10.3	15.1	1.882	42.83	41.16	7.25E-10	0.990
41.9	10.0	2.0	23.0	2.068	10.2	10.4	15.0	1.880	43.34	41.68	7.11E-10	1.253
49.1	10.0	2.0	23.0	2.068	10.1	9.8	15.6	1.894	40.25	38.55	6.53E-10	1.496
52.2	10.0	2.0	23.0	2.068	10.0	5.5	19.6	1.989	18.06	17.71	6.91E-10	1.606
54.4	10.0	5.5	19.6	1.989	10.1	8.2	16.7	1.925	13.93	15.11	7.80E-10	1.696
59.3	10.1	0.6	23.0	2.084	10.2	6.5	17.3	1.951	30.44	29.70	7.21E-10	1.882
61.2	10.2	6.5	17.3	1.951	10.3	8.6	15.4	1.905	10.84	9.90	6.99E-10	1.946
64.2	10.0	2.0	23.0	2.068	10.0	5.6	19.6	1.987	18.58	17.97	7.08E-10	2.059
68.4	10.0	5.6	19.6	1.987	10.1	10.2	15.2	1.885	23.74	22.66	6.78E-10	2.202
70.4	10.0	2.0	23.0	2.068	10.1	4.6	20.5	2.010	13.42	13.03	7.84E-10	2.283
74.1	10.1	4.6	20.5	2.010	10.1	9.1	16.3	1.911	22.96	21.88	7.17E-10	2.422
75.4	10.1	9.1	16.3	1.911	10.1	10.4	15.1	1.881	6.97	6.51	6.82E-10	2.463
77.0	10.0	2.0	23.0	2.068	10.1	4.1	21.1	2.023	10.58	9.90	7.19E-10	2.527
81.1	10.1	4.1	21.1	2.023	10.1	8.9	16.5	1.915	25.03	23.97	7.23E-10	2.678
83.2	10.1	8.9	16.5	1.915	10.2	11.2	14.3	1.863	11.87	11.46	7.08E-10	2.750

Chemical Equilibrium Analysis (Specimen 4h)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm) Na^+	Ca^{2+}	Cl^-	% Ca^{2+} of influent**
0.5 M $CaCl_2$	0.262	76.6	3.95	0.05	743.08	339.02	732.99	1.83%
	0.488		11.54	0.15	1698.94	783.72	3159.75	4.23%
	0.731		30.4	0.40	1722.76	5243.22	10696.88	28.30%
	0.990	77.0	51.2	0.66	1148.35	11011.15	19666.64	59.44%
	1.253		65.1	0.85	783.08	15419.20	26222.30	83.23%
	1.496		68.0	0.88	570.73	17650.20	29808.49	95.27%
	1.696	74.6	75.6	1.01	687.49	18163.46	32923.76	98.04%
	1.946		76.5	1.03	640.87	18646.28	33909.11	100.65%
	2.202		78.9	1.06	402.86	19331.33	32713.66	104.35%
	2.463	80.1	79.3	0.99	394.97	19588.73	33271.95	105.74%
	2.750		81.6	1.02	440.87	19405.26	33392.57	104.75%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.5 M $CaCl_2$: 402.73 ppm Na^+, 18525.87 ppm Ca^{2+}, 34377.04 ppm Cl^-

Specimen 5a
5.6 % MSB Backfill
Tap Water followed by 0.01 M $CaCl_2$

Phase Diagram (Specimen 5a)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	148.89	125.09
Mass Solids (g)	374.11	371.37
Total Mass (g)	523.00	496.46
Volume Air (cm^3)	12.33	0.00
Volume Water (cm^3)	148.89	125.09
Volume Solids (cm^3)	140.11	139.09
Total Volume (cm^3)	301.34	299.14
Water Content (%)	39.80%	33.68%
Volume Voids (cm^3)	161.23	125.09
Void Ratio	1.15	0.90
Porosity	0.54	0.42
Saturation (%)	92.35%	100%

Flexible Wall Test Results (Specimen 5a)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.60
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 27.21

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.7	10.0	2.0	23.0	2.068	10.4	2.2	22.7	2.062	1.03	1.56	2.13E-10	0.008
3.8	10.4	2.2	22.7	2.062	11.0	2.9	22.0	2.046	3.61	3.65	1.50E-10	0.031
14.9	11.0	2.9	22.0	2.046	11.6	5.5	19.7	1.990	13.42	11.98	1.44E-10	0.109
22.8	11.6	5.5	19.7	1.990	11.8	7.4	18.1	1.950	9.80	8.34	1.47E-10	0.166
32.8	11.8	7.4	18.1	1.950	11.9	9.6	16.1	1.902	11.35	10.42	1.44E-10	0.233
38.9	11.9	9.6	16.1	1.902	12.0	10.9	15.0	1.874	6.71	5.73	1.37E-10	0.272
43.8	10.0	2.0	23.0	2.068	10.1	3.2	21.8	2.041	6.19	6.25	1.57E-10	0.310
56.7	10.1	3.2	21.8	2.041	10.2	6.5	18.9	1.970	17.03	15.11	1.58E-10	0.410
69.9	10.2	6.5	18.9	1.970	10.4	9.6	16.1	1.902	16.00	14.59	1.53E-10	0.505
89.8	10.0	2.0	23.0	2.068	10.3	7.3	18.3	1.953	27.35	24.49	1.65E-10	0.666
95.1	10.3	7.3	18.3	1.953	10.3	8.6	17.0	1.924	6.71	6.77	1.67E-10	0.707
99.8	10.3	8.6	17.0	1.924	10.4	9.8	16.0	1.898	6.19	5.21	1.60E-10	0.743
105.2	10.0	2.0	23.0	2.068	10.1	3.5	21.6	2.035	7.74	7.29	1.74E-10	0.789
111.8	10.1	3.5	21.6	2.035	10.2	5.3	20.0	1.996	9.29	8.34	1.68E-10	0.844
118.2	10.2	5.3	20.0	1.996	10.3	6.8	18.6	1.963	7.74	7.29	1.52E-10	0.891
121.2	10.3	6.8	18.6	1.963	10.3	7.6	17.9	1.945	4.13	3.65	1.65E-10	0.915
123.5	10.3	7.6	17.9	1.945	10.4	8.2	17.4	1.933	2.84	2.87	1.66E-10	0.932
130.2	10.4	8.2	17.4	1.933	10.5	9.9	15.8	1.895	9.03	8.08	1.69E-10	0.985
133.3	10.0	2.0	23.0	2.068	10.1	2.9	22.2	2.049	4.64	4.17	1.78E-10	1.013
137.1	10.1	2.9	22.2	2.049	10.1	4.0	21.1	2.023	5.68	5.73	1.84E-10	1.048
143.2	10.1	4.0	21.1	2.023	10.2	5.8	19.5	1.984	9.29	8.34	1.84E-10	1.103
146.1	10.2	5.8	19.5	1.984	10.2	6.6	18.7	1.966	4.13	4.17	1.84E-10	1.129
151.3	10.2	6.6	18.7	1.966	10.3	8.1	17.3	1.933	7.74	7.29	1.90E-10	1.175
153.2	10.3	8.1	17.3	1.933	10.4	8.8	16.8	1.920	3.35	2.61	2.11E-10	1.194

157.2	10.4	8.8	16.8	1.920	10.4	10.0	15.7	1.893	6.45	5.73	2.00E-10	1.231
159.2	10.4	10.0	15.7	1.893	10.5	10.6	15.2	1.880	3.10	2.87	2.03E-10	1.250
164.2	10.0	2.0	23.0	2.068	10.1	3.7	21.5	2.031	8.77	7.82	2.07E-10	1.301
166.2	10.1	3.7	21.5	2.031	10.1	4.3	20.9	2.018	3.10	3.13	1.98E-10	1.321
172.2	10.1	4.3	20.9	2.018	10.2	6.3	19.2	1.976	10.06	8.86	2.00E-10	1.379
175.2	10.2	6.3	19.2	1.976	10.2	7.2	18.3	1.954	4.90	4.95	2.14E-10	1.410
178.2	10.2	7.2	18.3	1.954	10.3	8.3	17.3	1.931	5.42	4.95	2.26E-10	1.442
181.4	10.3	8.3	17.3	1.931	10.3	9.3	16.3	1.908	5.42	5.21	2.18E-10	1.475
CHANGED PERMEANT FROM TAP WATER TO 0.01 M $CaCl_2$												
185.1	10.0	2.1	23.0	2.068	10.1	3.6	21.8	2.037	7.74	6.25	2.34E-10	1.518
187.1	10.1	3.6	21.8	2.037	10.2	4.3	21.2	2.021	3.87	3.13	2.22E-10	1.540
189.2	10.2	4.3	21.2	2.021	10.2	5.1	20.5	2.004	3.87	3.65	2.25E-10	1.563
192.1	10.2	5.1	20.5	2.004	10.2	6.2	19.5	1.980	5.68	5.21	2.35E-10	1.597
194.1	10.2	6.2	19.5	1.980	10.2	6.9	18.9	1.964	3.87	3.39	2.44E-10	1.620
198.3	10.2	6.9	18.9	1.964	10.3	8.5	17.4	1.929	8.26	7.55	2.45E-10	1.669
200.2	10.3	8.5	17.4	1.929	10.3	9.3	16.8	1.913	4.13	3.13	2.49E-10	1.691
202.2	10.3	9.3	16.8	1.913	10.4	10.1	16.0	1.895	4.13	4.17	2.72E-10	1.717
205.2	10.0	2.0	23.0	2.068	10.0	3.4	21.8	2.038	7.22	6.25	2.79E-10	1.759
208.3	10.0	3.4	21.8	2.038	10.1	4.7	20.6	2.010	6.71	6.25	2.70E-10	1.799
212.4	10.1	4.7	20.6	2.010	10.1	6.5	19.0	1.971	9.29	8.34	2.74E-10	1.854
219.3	10.1	6.5	19.0	1.971	10.2	9.6	16.3	1.904	16.00	14.07	2.86E-10	1.947
226.6	10.0	2.0	23.0	2.068	10.2	5.5	19.9	1.992	18.06	16.15	2.93E-10	2.053
228.4	10.2	5.5	19.9	1.992	10.2	6.3	19.2	1.975	4.13	3.65	2.71E-10	2.077
233.4	10.2	6.3	19.2	1.975	10.2	8.6	17.1	1.925	11.61	10.94	2.95E-10	2.147
236.4	10.2	8.6	17.1	1.925	10.2	9.9	15.8	1.895	6.97	6.77	2.99E-10	2.190
239.4	10.0	2.0	23.0	2.068	10.0	3.6	21.6	2.034	8.00	7.29	3.23E-10	2.237
243.5	10.0	3.6	21.6	2.034	10.0	5.6	19.8	1.990	10.58	9.38	3.05E-10	2.299
247.4	10.0	5.6	19.8	1.990	10.0	10.0	15.5	1.890	22.70	22.40	7.59E-10	2.439
249.4	10.0	10.0	15.5	1.890	10.1	11.5	14.1	1.857	7.74	7.29	5.17E-10	2.485
250.6	10.0	2.0	23.0	2.068	10.1	3.1	22.0	2.044	5.68	5.21	5.67E-10	2.519
256.3	10.1	3.1	22.0	2.044	10.1	7.8	17.7	1.941	24.25	22.40	5.19E-10	2.664
260.3	10.1	7.8	17.7	1.941	10.1	10.8	14.8	1.873	15.48	15.11	5.08E-10	2.759
269.1	10.1	2.0	23.0	2.068	10.1	8.9	16.4	1.913	35.60	34.65	5.11E-10	2.977
271.5	10.1	8.9	16.4	1.913	10.1	10.5	14.8	1.876	8.26	8.34	4.57E-10	3.028
272.1	10.1	10.5	14.8	1.876	10.1	10.9	14.3	1.866	2.06	2.34	5.14E-10	3.042

Chemical Equilibrium Analysis (Specimen 5a)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
Tap Water	0.272	0.1705	2.62	15.37	622.36	127.61	108.06	644.36%
	0.505		2.99	17.54	653.56	126.39	98.97	638.19%
	0.743		2.77	16.25	550.47	118.74	61.53	599.55%
	0.985		2.39	14.02	466.10	109.26	55.49	551.72%
	1.250		2.19	12.84	422.16	111.08	46.37	560.89%
	1.475	0.203	2.13	10.49	334.73	115.90	57.41	585.21%
0.01 M $CaCl_2$	0.242	2.51	2.07	0.82	---	---	---	---
	0.472		2.55	1.02	326.82	290.72	170.91	76.24%
	0.715		3.19	1.27	---	---	---	---
	1.010	2.43	3.79	1.56	---	---	---	---
	1.284		3.86	1.59	---	---	---	---
	1.567		3.65	1.50	---	---	---	---

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for tap water: 9.29 ppm Na^+, 19.80 ppm Ca^{2+}, 51.29 ppm Cl^-

Influent ion concentrations for 0.01 M $CaCl_2$: 8.20 ppm Na^+, 381.31 ppm Ca^{2+}, 645.62 ppm Cl^-

Specimen 5b
5.6 % MSB Backfill
Tap Water followed by 0.05 M $CaCl_2$

Phase Diagram (Specimen 5b)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	137.92	110.79
Mass Solids (g)	344.79	340.38
Total Mass (g)	482.71	451.17
Volume Air (cm^3)	14.46	0.00
Volume Water (cm^3)	137.92	110.79
Volume Solids (cm^3)	129.14	127.48
Total Volume (cm^3)	281.52	238.27
Water Content (%)	40.00%	32.55%
Volume Voids (cm^3)	152.38	110.79
Void Ratio	1.18	0.87
Porosity	0.54	0.46
Saturation (%)	90.51%	100%

Flexible Wall Test Results (Specimen 5b)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 44.8
Head Pressure (psi): 41.1
Tail Pressure (psi): 38.5
Max Gradient: 29.29

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
1.0	6.9	3.1	21.9	2.043	6.9	3.4	21.6	2.036	1.55	1.56	1.79E-10	0.010
1.9	6.9	3.4	21.6	2.036	6.9	3.8	21.3	2.028	2.06	1.56	2.53E-10	0.022
2.9	6.9	3.8	21.3	2.028	6.9	4.1	21.0	2.021	1.55	1.56	1.77E-10	0.032
3.8	6.9	4.1	21.0	2.021	6.9	4.4	20.7	2.014	1.55	1.56	1.93E-10	0.043
4.9	6.9	4.4	20.7	2.014	7.0	4.8	20.4	2.006	2.06	1.56	2.11E-10	0.054
6.8	7.0	4.8	20.4	2.006	7.0	5.6	19.8	1.990	4.13	3.13	2.17E-10	0.078
8.9	7.0	5.6	19.8	1.990	7.1	6.3	19.1	1.974	3.61	3.65	2.10E-10	0.102
10.5	7.1	6.3	19.1	1.974	7.1	6.9	18.6	1.962	3.10	2.61	2.15E-10	0.121
12.7	7.1	6.9	18.6	1.962	7.1	7.8	17.9	1.943	4.64	3.65	2.28E-10	0.148
14.6	7.1	7.8	17.9	1.943	7.1	8.4	17.3	1.929	3.10	3.13	2.05E-10	0.168
16.6	7.1	8.4	17.3	1.929	7.2	9.2	16.7	1.913	4.13	3.13	2.23E-10	0.192
18.5	7.7	1.5	23.5	2.080	7.7	2.2	22.9	2.065	3.61	3.13	2.18E-10	0.214
CHANGED PERMEANT FROM TAP WATER TO 0.05 M $CaCl_2$												
19.5	5.2	1.6	23.1	2.074	5.2	2.0	22.8	2.066	2.06	1.56	2.93E-10	0.226
21.6	5.2	2.0	22.8	2.066	5.2	2.9	22.1	2.047	4.64	3.65	2.25E-10	0.253
23.5	5.2	2.9	22.1	2.047	5.2	3.8	21.5	2.030	4.64	3.13	2.42E-10	0.279
25.5	5.2	3.8	21.5	2.030	5.2	4.6	20.7	2.012	4.13	4.17	2.35E-10	0.306
26.5	5.2	4.6	20.7	2.012	5.2	5.1	20.4	2.003	2.58	1.56	2.60E-10	0.320
28.9	5.2	5.1	20.4	2.003	5.2	6.1	19.5	1.981	5.16	4.69	2.42E-10	0.352
30.8	5.2	6.1	19.5	1.981	5.2	6.9	18.8	1.964	4.13	3.65	2.48E-10	0.378
32.8	5.2	6.9	18.8	1.964	5.2	7.8	18.0	1.944	4.64	4.17	2.64E-10	0.406
34.8	5.2	7.8	18.0	1.944	5.3	8.7	17.3	1.926	4.64	3.65	2.53E-10	0.434
35.8	5.3	8.7	17.3	1.926	5.3	9.2	16.9	1.916	2.58	2.08	3.18E-10	0.449

38.9	5.4	2.4	22.6	2.059	5.4	4.0	21.2	2.025	8.26	7.29	2.90E-10	0.500
40.8	5.4	4.0	21.2	2.025	5.4	5	20.3	2.003	5.16	4.69	3.00E-10	0.532
42.5	5.4	5.0	20.3	2.003	5.4	5.9	19.6	1.984	4.64	3.65	2.91E-10	0.560
45.9	5.4	5.9	19.6	1.984	5.4	7.7	18.0	1.945	9.29	8.34	3.20E-10	0.617
48.9	5.4	7.7	18.0	1.945	5.5	9.3	16.7	1.912	8.26	6.77	3.05E-10	0.667
51.5	5.5	9.3	16.7	1.912	5.5	10.8	15.5	1.881	7.74	6.25	3.34E-10	0.713
53.9	5.5	10.8	15.5	1.881	5.5	12.1	14.4	1.854	6.71	5.73	3.38E-10	0.753
55.9	5.5	2.1	23.1	2.068	5.6	3.4	21.9	2.039	6.71	6.25	3.58E-10	0.796
57.8	5.6	3.4	21.9	2.039	5.6	4.6	20.9	2.014	6.19	5.21	3.56E-10	0.833
59.6	5.6	4.6	20.9	2.014	5.6	5.7	20.0	1.991	5.68	4.69	3.46E-10	0.867
62.5	5.6	5.7	20.0	1.991	5.6	7.5	18.5	1.953	9.29	7.82	3.56E-10	0.923
65.8	5.6	7.5	18.5	1.953	5.7	9.5	16.8	1.911	10.32	8.86	3.57E-10	0.986
67.7	5.7	9.5	16.8	1.911	5.7	10.7	15.8	1.886	6.19	5.21	3.72E-10	1.024
70.0	5.7	10.7	15.8	1.886	5.7	12.1	14.7	1.857	7.22	5.73	3.65E-10	1.066
72.8	5.7	12.1	14.7	1.857	5.7	13.7	13.3	1.823	8.26	7.29	3.55E-10	1.117
73.8	5.7	13.7	13.3	1.823	5.7	14.2	12.8	1.811	2.58	2.61	3.60E-10	1.134
76.1	4.8	1.6	23.2	2.075	4.8	3.3	21.6	2.037	8.77	8.34	4.36E-10	1.190
77.6	4.8	3.3	21.6	2.037	4.9	4.4	20.7	2.014	5.68	4.69	3.96E-10	1.224
80.5	4.9	4.4	20.7	2.014	4.9	6.3	19.1	1.974	9.80	8.34	3.71E-10	1.284
83.5	4.9	6.3	19.1	1.974	4.9	8.3	17.4	1.932	10.32	8.86	3.86E-10	1.347
85.8	4.9	8.3	17.4	1.932	4.9	9.7	16.1	1.901	7.22	6.77	3.83E-10	1.393
87.8	4.9	9.7	16.1	1.901	4.9	11	15.1	1.874	6.71	5.21	3.72E-10	1.432
91.0	4.9	1.5	23.5	2.080	4.9	3.8	21.5	2.030	11.87	10.42	4.09E-10	1.505
92.8	4.9	3.8	21.5	2.030	4.9	5.1	20.4	2.003	6.71	5.73	3.89E-10	1.546
94.5	4.9	5.1	20.4	2.003	4.9	6.2	19.5	1.980	5.68	4.69	3.75E-10	1.580
97.5	4.9	6.2	19.5	1.980	5	8.2	17.8	1.937	10.32	8.86	3.83E-10	1.643
99.7	5.0	8.2	17.8	1.937	5	9.6	16.6	1.908	7.22	6.25	3.76E-10	1.687
102.9	5.0	1.5	23.5	2.080	5	3.6	21.6	2.034	10.84	9.90	3.85E-10	1.755
105.5	5.0	3.6	21.6	2.034	5.1	5.4	20.1	1.996	9.29	7.82	3.90E-10	1.811
107.8	5.1	5.4	20.1	1.996	5.1	7	18.7	1.962	8.26	7.29	3.91E-10	1.862
109.9	5.1	7.0	18.7	1.962	5.1	8.3	17.6	1.934	6.71	5.73	3.67E-10	1.903
112.0	5.1	8.3	17.6	1.934	5.1	9.7	16.4	1.904	7.22	6.25	3.90E-10	1.947
113.7	5.1	9.7	16.4	1.904	5.1	10.8	15.6	1.882	5.68	4.17	3.72E-10	1.980
116.4	5.2	2.0	23.0	2.068	5.2	4.3	21	2.019	11.87	10.42	4.83E-10	2.053
118.4	5.2	4.3	21.0	2.019	5.2	6	19.6	1.983	8.77	7.29	4.73E-10	2.105

121.5	5.2	6.0	19.6	1.983	5.2	8.3	17.6	1.934	11.87	10.42	4.41E-10	2.179
123.8	5.2	8.3	17.6	1.934	5.2	10.1	16.1	1.896	9.29	7.82	4.52E-10	2.235
125.7	5.2	10.1	16.1	1.896	5.2	11.4	15	1.869	6.71	5.73	4.18E-10	2.275
129.5	5.2	2.0	23.0	2.068	5.2	5	20.4	2.004	15.48	13.55	4.49E-10	2.371
131.6	5.2	5.0	20.4	2.004	5.2	6.6	19	1.970	8.26	7.29	4.33E-10	2.422
133.6	5.2	6.6	19.0	1.970	5.3	8.1	17.8	1.939	7.74	6.25	4.21E-10	2.468
137.6	5.3	8.1	17.8	1.939	5.3	10.9	15.4	1.879	14.45	12.50	4.22E-10	2.556
140.4	5.3	10.9	15.4	1.879	5.3	12.8	13.8	1.839	9.80	8.34	4.12E-10	2.616

Chemical Equilibrium Analysis (Specimen 5b)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.05 M $CaCl_2$	0.235	3.8	1.016	0.27	---	---	---	---
	0.539		3.17	0.83	---	---	---	---
	0.920	9.28	5.45	0.59	---	---	---	---
	1.218		6.94	0.75	---	---	---	---
	1.473		7.69	0.83	---	---	---	---
	1.765		8.61	0.93	---	---	---	---
	2.061	9.42	9.15	0.97	---	---	---	---
	2.401		9.48	1.01	0.00	1068.50	6019.61	57.53%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.05 M $CaCl_2$: 41.20 ppm Na^+, 1857.27 ppm Ca^{2+}, 3387.45 ppm Cl^-

Specimen 5c
5.6 % MSB Backfill
Tap Water followed by 0.2 M $CaCl_2$

Phase Diagram (Specimen 5c)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	141.15	114.49
Mass Solids (g)	352.89	347.27
Total Mass (g)	494.04	461.76
Volume Air (cm^3)	8.19	0.00
Volume Water (cm^3)	141.15	114.49
Volume Solids (cm^3)	132.17	130.06
Total Volume (cm^3)	281.52	244.55
Water Content (%)	40.00%	32.97%
Volume Voids (cm^3)	149.35	114.49
Void Ratio	1.13	0.88
Porosity	0.53	0.47
Saturation (%)	94.51%	100%

Flexible Wall Test Results (Specimen 5c)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 44.8
Head Pressure (psi): 41.1
Tail Pressure (psi): 38.5
Max Gradient: 29.31

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
1.0	4.9	3.0	22.2	2.047	4.9	3.3	21.8	2.039	1.55	2.08	2.08E-10	0.012
1.9	4.9	3.3	21.8	2.039	5.0	3.5	21.6	2.035	1.03	1.04	1.44E-10	0.019
2.9	5.0	3.5	21.6	2.035	5.0	3.8	21.2	2.027	1.55	2.08	2.05E-10	0.031
3.8	5.0	3.8	21.2	2.027	5.0	4.1	20.9	2.020	1.55	1.56	1.92E-10	0.042
4.9	5.0	4.1	20.9	2.020	5.1	4.4	20.6	2.013	1.55	1.56	1.80E-10	0.052
6.8	5.1	4.4	20.6	2.013	5.2	5.0	19.9	1.998	3.10	3.65	2.01E-10	0.075
8.9	5.2	5.0	19.9	1.998	5.2	5.7	19.3	1.983	3.61	3.13	1.94E-10	0.097
10.5	5.2	5.7	19.3	1.983	5.3	6.2	18.8	1.972	2.58	2.61	1.94E-10	0.115
12.7	5.3	6.2	18.8	1.972	5.3	6.8	18.0	1.956	3.10	4.17	1.98E-10	0.139
14.6	5.3	6.8	18.0	1.956	5.4	7.4	17.4	1.942	3.10	3.13	2.03E-10	0.160
16.6	5.4	7.4	17.4	1.942	5.4	8.0	16.7	1.927	3.10	3.65	2.06E-10	0.182
18.5	5.8	1.6	23.5	2.078	6.0	2.1	22.8	2.065	2.58	3.65	1.98E-10	0.203
CHANGED PERMEANT FROM TAP WATER TO 0.2 M $CaCl_2$												
19.5	6.0	1.6	23.5	2.078	6.0	1.9	23.6	2.076	1.55	-0.52	8.97E-11	0.207
21.6	6.0	1.9	23.6	2.076	6.1	2.6	23.4	2.066	3.61	1.04	1.26E-10	0.222
23.5	6.1	2.6	23.4	2.066	6.2	3.3	23.0	2.053	3.61	2.08	1.76E-10	0.241
25.6	6.2	3.3	23.0	2.053	6.3	4.2	22.3	2.035	4.64	3.65	2.33E-10	0.269
26.5	6.3	4.2	22.3	2.035	6.3	4.6	22.0	2.027	2.06	1.56	2.27E-10	0.281
28.9	6.3	4.6	22.0	2.027	6.4	5.6	21.0	2.004	5.16	5.21	2.52E-10	0.316
30.8	6.4	5.6	21.0	2.004	6.5	6.4	20.3	1.987	4.13	3.65	2.45E-10	0.342
32.8	6.5	6.4	20.3	1.987	6.5	7.4	19.4	1.965	5.16	4.69	2.92E-10	0.375
34.8	6.5	7.4	19.4	1.965	6.6	8.6	18.0	1.935	6.19	7.29	4.07E-10	0.420
35.8	6.6	8.6	18.0	1.935	6.7	9.1	17.5	1.924	2.58	2.61	3.48E-10	0.437

38.9	6.7	2.3	22.7	2.061	6.7	4.0	20.9	2.021	8.77	9.38	3.39E-10	0.498
40.8	6.7	4.0	20.9	2.021	6.8	5.1	19.9	1.997	5.68	5.21	3.32E-10	0.535
42.5	6.8	5.1	19.9	1.997	6.8	6.1	19.1	1.976	5.16	4.17	3.28E-10	0.566
45.9	6.8	6.1	19.1	1.976	6.9	8.1	17.8	1.939	10.32	6.77	3.12E-10	0.623
48.9	6.9	8.1	17.8	1.939	7.0	9.9	16.7	1.905	9.29	5.73	3.06E-10	0.673
51.5	7.0	9.9	16.7	1.905	7.0	11.4	15.6	1.876	7.74	5.73	3.23E-10	0.718
53.8	7.0	11.4	15.6	1.876	7.1	12.8	14.7	1.849	7.22	4.69	3.26E-10	0.758
56.0	7.1	3.1	21.8	2.042	7.1	4.4	20.6	2.013	6.71	6.25	3.62E-10	0.802
57.8	7.1	4.4	20.6	2.013	7.2	5.6	19.7	1.989	6.19	4.69	3.44E-10	0.838
59.6	7.2	5.6	19.7	1.989	7.2	6.7	18.9	1.967	5.68	4.17	3.33E-10	0.871
62.5	7.2	6.7	18.9	1.967	7.2	8.6	17.5	1.929	9.80	7.29	3.60E-10	0.928
65.8	7.2	8.6	17.5	1.929	7.3	10.8	16.3	1.890	11.35	6.25	3.32E-10	0.987
67.7	7.3	10.8	16.3	1.890	7.3	11.8	15.5	1.870	5.16	4.17	3.07E-10	1.018
70.0	7.3	11.8	15.5	1.870	7.4	12.5	15.3	1.860	3.61	1.04	1.32E-10	1.034
72.8	7.4	12.5	15.3	1.860	7.5	12.5	15.8	1.865	0.00	-2.61	---	---
73.8	5.6	1.5	23.3	2.077	5.6	2.3	22.8	2.062	4.13	2.61	4.00E-10	1.048
76.1	5.6	2.5	23.6	2.069	5.6	4.1	22.1	2.034	8.26	7.82	4.13E-10	1.102
77.6	5.6	4.1	22.1	2.034	5.6	5.2	20.9	2.007	5.68	6.25	4.56E-10	1.142
80.5	5.6	5.2	20.9	2.007	5.7	7.4	18.6	1.956	11.35	11.98	4.80E-10	1.220
83.5	5.7	7.4	18.6	1.956	5.7	9.4	16.6	1.910	10.32	10.42	4.22E-10	1.289
85.8	5.7	9.4	16.6	1.910	5.8	10.7	15.2	1.879	6.71	7.29	3.89E-10	1.336
87.8	5.8	1.4	23.5	2.081	5.8	2.9	21.8	2.044	7.74	8.86	4.73E-10	1.392
91.0	5.8	2.9	21.8	2.044	5.9	4.9	19.8	1.998	10.32	10.42	3.86E-10	1.461
92.9	5.9	4.9	19.8	1.998	5.9	6.1	18.6	1.971	6.19	6.25	3.95E-10	1.503
94.5	5.9	6.1	18.6	1.971	5.9	7.1	17.5	1.947	5.16	5.73	4.00E-10	1.539
97.5	5.9	7.1	17.5	1.947	6.0	9.2	15.2	1.896	10.84	11.98	4.64E-10	1.616
99.7	6.0	1.4	22.0	2.063	6.1	3.0	20.5	2.028	8.26	7.82	4.24E-10	1.669
102.9	6.1	3.0	20.5	2.028	6.1	5.0	18.6	1.983	10.32	9.90	3.83E-10	1.737
105.5	6.1	5.0	18.6	1.983	6.2	6.7	16.9	1.944	8.77	8.86	4.12E-10	1.796
106.7	6.2	6.7	16.9	1.944	6.2	7.5	16.1	1.926	4.13	4.17	3.97E-10	1.824
112.0	6.2	2.0	23.0	2.068	6.3	5.6	19.4	1.986	18.58	18.76	4.14E-10	1.949
113.7	6.3	5.6	19.4	1.986	6.3	6.7	18.4	1.962	5.68	5.21	3.94E-10	1.985
116.4	6.3	6.7	18.4	1.962	6.3	8.5	16.6	1.920	9.29	9.38	4.14E-10	2.048
118.5	6.3	8.5	16.6	1.920	6.4	9.9	15.3	1.889	7.22	6.77	4.34E-10	2.095
121.5	6.4	2.0	23.0	2.068	6.4	4.2	20.8	2.018	11.35	11.46	4.33E-10	2.171

123.9	6.4	4.2	20.8	2.018	6.4	5.8	19.3	1.982	8.26	7.82	4.07E-10	2.225
125.7	6.4	5.8	19.3	1.982	6.5	7.0	18.0	1.953	6.19	6.77	4.16E-10	2.268
129.5	6.5	7.0	18.0	1.953	6.5	9.5	15.6	1.897	12.90	12.50	4.17E-10	2.353

Chemical Equilibrium Analysis (Specimen 5c)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.2 M $CaCl_2$	0.231	14.1	2.03	0.14	---	---	---	---
	0.552		7.11	0.50	---	---	---	---
	0.841	33.6	16.03	0.48	---	---	---	---
	1.129		23.5	0.70	---	---	---	---
	1.409		27.1	0.81	---	---	---	---
	1.617		29.6	0.88	---	---	---	---
	1.888	33.6	31.5	0.94	---	---	---	---
	2.147		32.6	0.97	185.54	6631.11	15047.35	89.02%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.2 M $CaCl_2$: 155.34 ppm Na^+, 7448.77 ppm Ca^{2+}, 13547.08 ppm Cl^-

Specimen 5d
5.6 % MSB Backfill
Tap Water followed by 0.5 M $CaCl_2$

Phase Diagram (Specimen 5d)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	133.03	106.62
Mass Solids (g)	332.59	335.23
Total Mass (g)	465.62	441.85
Volume Air (cm^3)	23.92	0.00
Volume Water (cm^3)	133.03	106.62
Volume Solids (cm^3)	124.56	125.55
Total Volume (cm^3)	281.52	232.17
Water Content (%)	40.00%	31.81%
Volume Voids (cm^3)	156.95	106.62
Void Ratio	1.26	0.85
Porosity	0.56	0.46
Saturation (%)	84.76%	100%

Flexible Wall Test Results (Specimen 5d)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.5	5.0	2.0	23.0	2.068	5.0	6.9	22.5	2.006	25.28	2.61	3.61E-09	0.017
0.7	5.0	6.9	22.5	2.006	5.0	9.0	22.1	1.978	10.84	2.08	3.40E-09	0.030
1.6	5.0	9.0	22.1	1.978	5.1	16.3	20.8	1.879	37.67	6.77	2.83E-09	0.073
3.0	5.1	4.0	20.8	2.020	5.1	12.9	18.7	1.894	45.92	10.94	2.60E-09	0.143
3.5	10.0	5.1	20.0	1.998	10.1	5.3	19.8	1.994	1.03	1.04	2.40E-10	0.149
4.4	10.1	5.3	19.8	1.994	10.1	5.7	19.5	1.986	2.06	1.56	2.48E-10	0.161
6.4	10.1	5.7	19.5	1.986	10.2	6.6	18.6	1.965	4.64	4.69	2.73E-10	0.191
9.5	10.2	6.6	18.6	1.965	10.2	8.0	17.3	1.934	7.22	6.77	2.78E-10	0.235
11.8	10.2	8.0	17.3	1.934	10.3	9.2	16.3	1.909	6.19	5.21	3.00E-10	0.272
13.7	10.3	9.2	16.3	1.909	10.3	10.0	15.5	1.890	4.13	4.17	2.75E-10	0.298
17.5	10.3	10.0	15.5	1.890	10.4	11.8	13.8	1.850	9.29	8.86	3.06E-10	0.356
19.6	10.4	11.8	13.8	1.850	10.4	12.8	12.9	1.829	5.16	4.69	2.96E-10	0.387
21.7	10.4	12.8	12.9	1.829	10.5	13.7	12.1	1.809	4.64	4.17	2.85E-10	0.415
24.6	10.5	13.7	12.1	1.809	10.5	15.4	10.4	1.770	8.77	8.86	3.96E-10	0.471
28.5	10.5	15.4	10.4	1.770	10.6	17.2	8.8	1.731	9.29	8.34	3.10E-10	0.528
31.4	10.6	17.2	8.8	1.731	10.6	18.5	7.5	1.701	6.71	6.77	3.14E-10	0.570
38.4	10.6	18.5	7.5	1.701	10.9	24.0	2.4	1.580	28.38	26.57	5.68E-10	0.746
40.1	7.5	2.0	23.0	2.068	7.7	3.1	22.1	2.045	5.68	4.69	3.54E-10	0.779
40.3	7.7	3.1	22.1	2.045	7.7	3.2	22.0	2.043	0.52	0.52	3.32E-10	0.782
41.3	7.7	3.2	22.0	2.043	7.8	3.7	21.5	2.031	2.58	2.61	3.06E-10	0.798
43.3	7.8	3.7	21.5	2.031	7.8	4.8	20.5	2.007	5.68	5.21	3.21E-10	0.833
45.4	7.8	4.8	20.5	2.007	7.9	5.9	19.5	1.983	5.68	5.21	3.05E-10	0.868
47.3	7.9	5.9	19.5	1.983	7.9	6.9	18.5	1.960	5.16	5.21	3.31E-10	0.901

50.5	7.9	6.9	18.5	1.960	8.0	8.4	17.0	1.926	7.74	7.82	3.01E-10	0.950
52.5	8.0	8.4	17.0	1.926	8.0	9.5	16.0	1.902	5.68	5.21	3.35E-10	0.985
54.4	8.0	9.5	16.0	1.902	8.1	10.4	15.2	1.882	4.64	4.17	2.92E-10	1.013
58.4	8.1	10.4	15.2	1.882	8.1	12.4	13.3	1.838	10.32	9.90	3.25E-10	1.077
60.4	8.1	12.4	13.3	1.838	8.2	13.4	12.4	1.816	5.16	4.69	3.21E-10	1.109
61.3	8.2	2.3	23.0	2.065	8.2	2.8	22.5	2.053	2.58	2.61	3.05E-10	1.125
64.3	8.2	2.8	22.5	2.053	8.3	4.4	20.9	2.017	8.26	8.34	3.25E-10	1.178
65.3	8.3	4.4	20.9	2.017	8.3	4.9	20.4	2.005	2.58	2.61	3.03E-10	1.195
CHANGED PERMEANT FROM TAP WATER TO 0.5 M $CaCl_2$												
67.2	8.7	2.1	23.1	2.068	8.7	3.5	22.0	2.039	7.22	5.73	3.91E-10	1.236
69.4	8.7	3.5	22.0	2.039	8.6	5.3	20.3	1.999	9.29	8.86	4.88E-10	1.294
71.2	8.6	5.3	20.3	1.999	8.6	7.1	18.7	1.960	9.29	8.34	5.86E-10	1.350
73.2	8.6	7.1	18.7	1.960	8.8	9.0	17.1	1.920	9.80	8.34	5.59E-10	1.408
74.5	8.8	9.0	17.1	1.920	8.8	10.1	16.1	1.896	5.68	5.21	5.44E-10	1.442
78.7	9.0	2.0	23.0	2.068	9.1	6.0	19.3	1.980	20.64	19.28	5.57E-10	1.570
81.3	9.1	6.0	19.3	1.980	9.2	8.3	17.3	1.931	11.87	10.42	5.17E-10	1.641
83.2	9.2	8.3	17.3	1.931	9.2	9.9	15.8	1.895	8.26	7.82	5.34E-10	1.692
85.4	9.2	2.0	23.0	2.068	9.3	4.1	21.0	2.021	10.84	10.42	5.49E-10	1.760
87.3	9.3	4.1	21.0	2.021	9.3	5.8	19.4	1.983	8.77	8.34	5.41E-10	1.814
89.4	9.3	5.8	19.4	1.983	9.3	7.7	17.7	1.942	9.80	8.86	5.33E-10	1.873
91.4	9.3	7.7	17.7	1.942	9.4	9.4	16.1	1.904	8.77	8.34	5.17E-10	1.928
93.5	10.1	2.0	23.0	2.068	10.1	4.1	21.0	2.021	10.84	10.42	5.90E-10	1.996
95.4	10.1	4.1	21.0	2.021	10.1	5.8	19.5	1.984	8.77	7.82	5.37E-10	2.049
98.1	10.1	5.8	19.5	1.984	10.2	8.1	17.3	1.933	11.87	11.46	5.28E-10	2.123
99.8	10.2	8.2	17.3	1.932	10.2	9.7	15.9	1.898	7.74	7.29	5.48E-10	2.171
100.7	10.2	9.7	15.9	1.898	10.2	10.5	15.1	1.880	4.13	4.17	5.57E-10	2.197
103.8	9.7	2.0	23.0	2.068	9.8	5.0	20.2	2.002	15.48	14.59	5.60E-10	2.293
107.0	9.8	5.0	20.2	2.002	9.8	7.8	17.6	1.940	14.45	13.55	5.32E-10	2.382
108.7	10.0	2.0	23.0	2.068	10.1	3.6	21.5	2.033	8.26	7.82	5.40E-10	2.433
109.9	10.1	3.6	21.5	2.033	10.1	4.7	20.5	2.008	5.68	5.21	5.56E-10	2.468
113.9	10.1	4.7	20.5	2.008	10.1	8.1	17.3	1.933	17.54	16.67	5.17E-10	2.577
121.1	10.0	2.0	23.0	2.068	10.1	9.2	16.4	1.910	37.15	34.39	5.92E-10	2.805
122.9	10.1	9.2	16.4	1.910	10.2	10.9	14.8	1.872	8.77	8.34	5.90E-10	2.859
124.8	10.2	10.9	14.8	1.872	10.2	12.6	13.2	1.834	8.77	8.34	5.68E-10	2.914
131.2	10.0	2.0	23.0	2.068	10.1	8.5	17.0	1.925	33.54	31.26	6.05E-10	3.120

133.1	10.1	8.5	17.0	1.925	10.1	10.2	15.4	1.887	8.77	8.34	5.75E-10	3.175
135.9	10.1	2.0	23.0	2.068	10.1	5.0	20.2	2.002	15.48	14.59	6.09E-10	3.271
140.7	10.1	5.0	20.2	2.002	10.2	9.4	16.1	1.904	22.70	21.36	5.67E-10	3.411
142.7	10.2	9.4	16.1	1.904	10.2	11.2	14.4	1.864	9.29	8.86	5.72E-10	3.469
147.9	10.0	2.0	23.0	2.068	10.1	7.3	18.1	1.951	27.35	25.53	6.01E-10	3.637
150.9	10.1	7.3	18.1	1.951	10.1	10.0	15.5	1.890	13.93	13.55	5.63E-10	3.725

Chemical Equilibrium Analysis (Specimen 5d)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.5 M $CaCl_2$	0.248	77.8	2.22	0.03	116.34	182.39	4136.86	0.98%
	0.497		13.07	0.17	237.60	2347.69	7492.68	12.67%
	0.733		32.4	0.42	304.61	6707.65	15232.28	36.21%
	1.002	74.2	50.3	0.68	572.87	12068.02	23127.53	65.14%
	1.187		61.5	0.83	572.87	14984.32	28528.81	80.88%
	1.382		68.1	0.92	616.00	16693.13	31222.15	90.11%
	1.719	76.9	71.0	0.92	616.91	18003.40	33344.29	97.18%
	1.980		74.8	0.97	447.77	17891.95	32839.50	96.58%
	2.274		75.6	0.98	452.70	18215.95	33902.58	98.33%
	2.530	76.1	76.1	1.00	408.34	18678.28	29537.79	100.82%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.5 M $CaCl_2$: 402.73 ppm Na^+, 18525.87 ppm Ca^{2+}, 34377.04 ppm Cl^-

Specimen 5e
5.6 % MSB Backfill
Tap Water followed by 1.0 M $CaCl_2$

Phase Diagram (Specimen 5e)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Additional Assumptions: Water Content (before permeation – used target values)
Known values:
Before Permeation: Void Ratio, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	135.43	107.34
Mass Solids (g)	338.58	345.45
Total Mass (g)	474.01	452.79
Volume Air (cm^3)	19.27	0.00
Volume Water (cm^3)	135.43	107.34
Volume Solids (cm^3)	126.81	129.38
Total Volume (cm^3)	281.52	236.72
Water Content (%)	40.00%	31.07%
Volume Voids (cm^3)	154.71	107.34
Void Ratio	1.22	0.83
Porosity	0.55	0.45
Saturation (%)	87.54%	100%

Flexible Wall Test Results (Specimen 5e)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
1.7	5.0	2.0	23.0	2.068	5.1	2.7	22.3	2.052	3.61	3.65	2.53E-10	0.023
4.4	5.1	2.7	22.3	2.052	5.2	3.7	21.4	2.030	5.16	4.69	2.10E-10	0.055
6.4	5.2	3.7	21.4	2.030	5.3	4.4	20.7	2.014	3.61	3.65	2.08E-10	0.079
9.5	5.3	4.4	20.7	2.014	5.4	5.5	19.7	1.990	5.68	5.21	2.11E-10	0.114
11.8	5.4	5.5	19.7	1.990	5.4	6.3	18.9	1.972	4.13	4.17	2.12E-10	0.141
13.7	5.4	6.3	18.9	1.972	5.5	7.0	18.3	1.957	3.61	3.13	2.16E-10	0.163
17.5	5.5	7.0	18.3	1.957	5.6	8.3	17.0	1.927	6.71	6.77	2.19E-10	0.206
19.6	5.6	8.3	17.0	1.927	5.6	9.1	16.3	1.910	4.13	3.65	2.24E-10	0.231
21.7	5.6	9.1	16.3	1.910	5.7	9.7	15.7	1.896	3.10	3.13	1.92E-10	0.251
24.6	5.7	9.7	15.7	1.896	5.7	10.7	14.7	1.873	5.16	5.21	2.21E-10	0.285
28.5	5.7	10.7	14.7	1.873	5.8	12.0	13.5	1.845	6.71	6.25	2.14E-10	0.327
34.0	5.8	12.0	13.5	1.845	5.9	13.7	11.8	1.806	8.77	8.86	2.09E-10	0.384
46.7	5.9	13.7	11.8	1.806	6.2	18.2	7.6	1.706	23.22	21.88	2.40E-10	0.529
52.7	6.2	18.2	7.6	1.706	6.3	20.1	5.8	1.664	9.80	9.38	2.24E-10	0.591
54.4	7.5	2.1	23.1	2.068	7.7	2.9	22.4	2.051	4.13	3.65	2.64E-10	0.617
54.6	7.7	2.9	22.4	2.051	7.7	2.9	22.3	2.050	0.00	0.52	1.68E-10	0.618
55.6	7.7	2.9	22.3	2.050	7.7	3.4	21.9	2.039	2.58	2.08	2.74E-10	0.633
57.6	7.7	3.4	21.9	2.039	7.7	4.2	21.2	2.022	4.13	3.65	2.28E-10	0.658
59.7	7.7	4.2	21.2	2.022	7.8	5.1	20.3	2.002	4.64	4.69	2.59E-10	0.689
61.6	7.8	5.1	20.3	2.002	7.8	5.8	19.6	1.986	3.61	3.65	2.29E-10	0.712
64.7	7.8	5.8	19.6	1.986	7.8	7.1	18.4	1.957	6.71	6.25	2.47E-10	0.754
66.7	7.8	7.1	18.4	1.957	7.8	7.9	17.7	1.940	4.13	3.65	2.35E-10	0.779
68.6	7.8	7.9	17.7	1.940	7.9	8.6	17.0	1.924	3.61	3.65	2.35E-10	0.803

74.6	7.9	8.6	17.0	1.924	7.9	10.9	14.3	1.866	11.87	14.07	2.72E-10	0.886
78.6	7.9	2.1	23.1	2.068	7.9	3.8	21.6	2.031	8.77	7.82	2.43E-10	0.940
80.0	7.9	3.8	21.6	2.031	8.0	4.4	21.0	2.018	3.10	3.13	2.48E-10	0.960
82.6	8.0	4.4	21.0	2.018	8.0	5.5	20.0	1.994	5.68	5.21	2.54E-10	0.995
CHANGED PERMEANT FROM TAP WATER TO 1.0 M $CaCl_2$												
85.5	8.1	2.0	22.9	2.067	8.0	3.8	21.4	2.029	9.29	7.82	3.38E-10	1.051
86.8	8.0	3.8	21.4	2.029	8.1	4.7	20.8	2.012	4.64	3.13	3.58E-10	1.076
88.7	8.1	4.7	20.8	2.012	8.2	5.9	19.7	1.986	6.19	5.73	3.63E-10	1.114
93.0	8.2	5.9	19.7	1.986	8.2	8.7	17.1	1.924	14.45	13.55	4.03E-10	1.205
94.8	8.2	8.7	17.1	1.924	8.3	10.0	15.9	1.895	6.71	6.25	4.37E-10	1.247
98.0	8.3	2.0	23.0	2.068	8.4	4.5	20.7	2.013	12.90	11.98	4.56E-10	1.327
99.7	8.4	4.5	20.7	2.013	8.4	5.7	19.6	1.987	6.19	5.73	4.12E-10	1.366
101.6	8.4	5.7	19.6	1.987	8.4	7.0	18.4	1.958	6.71	6.25	4.16E-10	1.407
103.7	8.4	7.0	18.4	1.958	8.4	8.4	17.1	1.927	7.22	6.77	4.04E-10	1.453
105.7	8.4	8.4	17.1	1.927	8.4	9.7	15.9	1.898	6.71	6.25	3.96E-10	1.495
107.8	10.1	2.0	23.0	2.068	10.1	3.4	21.8	2.038	7.22	6.25	3.70E-10	1.538
109.7	10.1	3.4	21.8	2.038	10.1	4.5	20.7	2.013	5.68	5.73	3.65E-10	1.575
112.4	10.1	4.5	20.7	2.013	10.2	6.1	19.4	1.980	8.26	6.77	3.34E-10	1.624
115.0	10.2	6.1	19.4	1.980	10.2	7.6	18.0	1.947	7.74	7.29	3.43E-10	1.672
118.1	10.2	7.6	18.0	1.947	10.3	9.3	16.5	1.910	8.77	7.82	3.26E-10	1.726
121.0	10.0	2.0	23.0	2.068	10.1	4.1	21.0	2.021	10.84	10.42	4.29E-10	1.794
123.0	10.1	4.1	21.0	2.021	10.1	5.4	19.8	1.992	6.71	6.25	3.83E-10	1.836
124.2	10.1	5.4	19.8	1.992	10.1	6.1	19.1	1.976	3.61	3.65	3.78E-10	1.860
128.1	10.1	6.1	19.1	1.976	10.2	8.6	16.8	1.921	12.90	11.98	3.82E-10	1.940
135.4	10.0	2.0	23.0	2.068	10.1	6.9	18.4	1.959	25.28	23.97	4.02E-10	2.099
139.1	10.1	6.9	18.4	1.959	10.2	9.3	16.2	1.906	12.38	11.46	3.89E-10	2.176
140.4	10.2	9.3	16.2	1.906	10.2	10.0	15.4	1.889	3.61	4.17	3.98E-10	2.202
142.4	10.2	10.0	15.4	1.889	10.2	11.3	14.3	1.862	6.71	5.73	3.80E-10	2.242
145.5	10.0	2.0	23.0	2.068	10.1	4.1	21.0	2.021	10.84	10.42	4.02E-10	2.310
150.3	10.1	4.1	21.0	2.021	10.2	6.9	18.4	1.959	14.45	13.55	3.52E-10	2.401
155.0	10.2	6.9	18.4	1.959	10.5	9.5	15.7	1.898	13.42	14.07	3.57E-10	2.490
157.2	10.0	2.0	23.0	2.068	10.1	3.7	21.4	2.030	8.77	8.34	4.49E-10	2.545
162.2	10.1	3.7	21.4	2.030	10.2	6.9	18.2	1.957	16.51	16.67	3.97E-10	2.652
165.2	10.2	6.9	18.2	1.957	10.4	8.9	16.3	1.912	10.32	9.90	4.13E-10	2.718
171.2	10.0	2.0	23.0	2.068	10.2	6.1	18.9	1.974	21.16	21.36	4.16E-10	2.855

175.4	10.2	6.1	18.9	1.974	10.3	8.7	16.5	1.917	13.42	12.50	3.78E-10	2.939
177.2	10.3	8.7	16.5	1.917	10.3	9.8	15.4	1.892	5.68	5.73	3.97E-10	2.976
179.2	10.0	2.0	23.0	2.068	10.0	3.3	21.7	2.038	6.71	6.77	3.92E-10	3.019
183.7	10.0	3.3	21.7	2.038	10.2	6.1	19.1	1.976	14.45	13.55	3.62E-10	3.110
185.9	10.2	6.1	19.1	1.976	10.2	7.3	17.9	1.949	6.19	6.25	3.48E-10	3.150
188.0	10.2	7.3	17.9	1.949	10.2	8.4	16.8	1.924	5.68	5.73	3.34E-10	3.187
190.1	10.2	8.4	16.8	1.924	10.3	9.6	15.7	1.897	6.19	5.73	3.60E-10	3.225

Chemical Equilibrium Analysis (Specimen 5e)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
1.0 M $CaCl_2$	0.251	137.4	1.532	0.01	165.80	27.43	3998.14	0.07%
	0.499		15.88	0.12	480.12	2772.29	8593.83	7.57%
	0.730		45.0	0.33	772.43	10470.77	20705.67	28.59%
	0.945	129.5	73.2	0.57	894.84	18269.78	34924.61	49.88%
	1.246		98.1	0.76	953.16	26088.94	44385.89	71.23%
	1.494		107.2	0.83	798.42	29144.35	45430.27	79.57%
	1.722	129.6	115.1	0.89	769.91	31681.41	50490.65	86.50%
	1.980		122.5	0.95	803.78	33850.05	60040.77	92.42%
	2.230		126.0	0.97	835.62	35371.34	62930.97	96.57%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 1.0 M $CaCl_2$: 784.28 ppm Na^+, 36627.68 ppm Ca^{2+}, 67999.17 ppm Cl^-

Specimen 5f
5.6 % MSB Backfill
0.05 M $CaCl_2$

Phase Diagram (Specimen 5f)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:
Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	131.61	109.45
Mass Solids (g)	330.69	326.98
Total Mass (g)	462.30	436.43
Volume Air (cm^3)	26.05	0.00
Volume Water (cm^3)	131.61	109.45
Volume Solids (cm^3)	123.85	122.46
Total Volume (cm^3)	281.52	246.91
Water Content (%)	39.80%	33.47%
Volume Voids (cm^3)	157.66	109.45
Void Ratio	1.27	0.89
Porosity	0.56	0.44
Saturation (%)	83.48%	100%

Flexible Wall Test Results (Specimen 5f)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.7	10.1	2.1	23.0	2.067	10.5	2.4	22.6	2.059	1.55	2.08	2.81E-10	0.012
3.7	10.5	2.4	22.6	2.059	10.8	3.2	21.6	2.038	4.13	5.21	1.80E-10	0.041
14.8	10.8	3.2	21.6	2.038	11.0	6.4	18.4	1.965	16.51	16.67	1.77E-10	0.146
22.8	11.0	6.4	18.4	1.965	11.1	9.1	16.0	1.906	13.93	12.50	2.03E-10	0.230
31.7	10.0	2.0	23.0	2.068	10.1	5.9	19.4	1.982	20.12	18.76	2.56E-10	0.354
39.8	10.1	5.9	19.4	1.982	10.2	9.5	16.0	1.902	18.58	17.71	2.75E-10	0.469
51.2	10.0	2.0	23.0	2.068	10.4	8.3	16.7	1.924	32.51	32.82	3.42E-10	0.676
54.0	10.4	8.3	16.7	1.924	10.4	9.9	15.1	1.887	8.26	8.34	3.63E-10	0.728
64.0	10.0	2.0	23.0	2.068	10.2	8.4	16.8	1.924	33.02	32.30	3.90E-10	0.936
66.9	10.2	8.4	16.8	1.924	10.3	10.1	15.2	1.886	8.77	8.34	3.68E-10	0.990
80.8	10.0	2.0	23.0	2.068	10.2	10.8	14.4	1.869	45.41	44.81	3.93E-10	1.276
89.7	10.0	2.0	23.0	2.068	10.2	8.0	17.3	1.934	30.96	29.70	4.01E-10	1.468
93.0	10.2	8.0	17.3	1.934	10.2	10.0	15.3	1.888	10.32	10.42	3.97E-10	1.534
95.0	10.0	2.0	23.0	2.068	10.0	3.5	21.5	2.034	7.74	7.82	4.46E-10	1.583
104.7	10.0	3.5	21.5	2.034	10.1	10.2	15.2	1.885	34.57	32.82	4.24E-10	1.797
112.7	10.0	2.0	23.0	2.068	10.2	7.5	17.8	1.945	28.38	27.09	4.10E-10	1.973
118.1	10.2	7.5	17.8	1.945	10.3	10.8	14.7	1.872	17.03	16.15	3.78E-10	2.078
121.1	10.0	2.0	23.0	2.068	10.0	4.2	20.8	2.018	11.35	11.46	4.42E-10	2.151
123.4	10.0	4.2	20.8	2.018	10.0	5.9	19.2	1.980	8.77	8.34	4.48E-10	2.205
128.4	10.0	5.9	19.2	1.980	10.2	9.4	15.9	1.902	18.06	17.19	4.34E-10	2.317
131.2	10.0	2.0	23.0	2.068	10.1	4.0	21.1	2.023	10.32	9.90	4.24E-10	2.381
133.2	10.1	4.0	21.1	2.023	10.1	5.4	19.7	1.991	7.22	7.29	4.23E-10	2.427
137.1	10.1	5.4	19.7	1.991	10.2	8.0	17.3	1.933	13.42	12.76	4.06E-10	2.510

138.1	10.2	8.0	17.3	1.933	10.2	8.7	16.6	1.918	3.61	3.39	4.16E-10	2.532
143.2	10.0	2.0	23.0	2.068	10.1	5.6	19.6	1.988	18.58	17.71	4.22E-10	2.647
145.2	10.1	5.6	19.6	1.988	10.1	7.0	18.3	1.957	7.22	6.77	4.06E-10	2.692
147.1	10.1	7.0	18.3	1.957	10.1	8.2	17.1	1.929	6.19	6.51	4.30E-10	2.732
150.1	10.0	2.0	23.0	2.068	10.1	4.4	20.7	2.014	12.38	11.98	4.62E-10	2.809
153.1	10.1	4.4	20.7	2.014	10.1	6.6	18.7	1.966	11.35	10.68	4.47E-10	2.879
157.1	10.1	6.6	18.7	1.966	10.1	9.5	15.9	1.900	14.96	14.59	4.46E-10	2.973
159.1	10.0	2.0	23.0	2.068	10.0	3.5	21.6	2.035	7.74	7.29	4.48E-10	3.020
164.1	10.0	3.5	21.6	2.035	10.1	7.1	18.1	1.953	18.58	18.24	4.37E-10	3.137
166.1	10.1	7.1	18.1	1.953	10.1	8.5	16.8	1.923	7.22	6.77	4.34E-10	3.181
167.3	10.1	8.5	16.8	1.923	10.1	9.3	16.0	1.904	4.13	4.17	4.35E-10	3.208
172.1	10.0	2.0	23.0	2.068	10.1	5.5	19.7	1.990	18.06	17.19	4.27E-10	3.320
175.1	10.1	5.5	19.7	1.990	10.1	7.6	17.6	1.942	10.84	10.94	4.41E-10	3.389
178.1	10.1	7.6	17.6	1.942	10.1	9.7	15.6	1.895	10.84	10.42	4.40E-10	3.456
180.1	10.0	2.0	23.0	2.068	10.1	3.7	21.4	2.030	8.77	8.34	4.80E-10	3.510
182.2	10.1	3.7	21.4	2.030	10.1	5.3	20.0	1.996	8.26	7.29	4.53E-10	3.560
185.0	10.1	5.3	20.0	1.996	10.2	7.3	18.0	1.950	10.32	10.42	4.36E-10	3.625
187.0	10.2	7.3	18.0	1.950	10.2	8.7	16.7	1.919	7.22	6.77	4.35E-10	3.670
189.0	10.2	8.7	16.7	1.919	10.2	10.0	15.4	1.889	6.71	6.77	4.23E-10	3.713
192.1	10.0	2.0	23.0	2.068	10.0	4.3	20.8	2.017	11.87	11.46	4.42E-10	3.787
194.0	10.0	4.3	20.8	2.017	10.0	5.7	19.5	1.986	7.22	6.77	4.33E-10	3.831
198.2	10.0	5.7	19.5	1.986	10.0	8.7	16.5	1.917	15.48	15.63	4.50E-10	3.930
200.1	10.0	8.7	16.5	1.917	10.1	10.1	15.3	1.887	7.22	6.25	4.33E-10	3.972
202.1	10.0	2.0	23.0	2.068	10.0	3.5	21.6	2.035	7.74	7.29	4.49E-10	4.020
205.1	10.0	3.5	21.6	2.035	10.1	5.7	19.5	1.986	11.35	10.94	4.39E-10	4.091
206.2	10.1	5.7	19.5	1.986	10.1	6.5	18.8	1.968	4.13	3.65	4.29E-10	4.115

Chemical Equilibrium Analysis (Specimen 5f)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.05 M $CaCl_2$	0.230	9.91	2.74	0.28	550.38	148.23	260.08	7.98%
	0.469		4.06	0.41	871.38	71.92	668.70	3.87%
	0.728		5.69	0.57	853.42	313.74	1199.15	16.89%
	0.990	10.25	7.21	0.70	719.32	714.69	1774.40	38.48%
	1.276		8.37	0.82	541.73	1092.49	2774.23	58.82%
	1.534		9.20	0.90	386.03	1377.96	3019.65	74.19%
	1.797	10.13	9.78	0.97	288.84	1630.60	3056.81	87.80%
	2.078		9.76	0.96	214.62	1730.47	3366.42	93.17%
	2.317	9.66	10.68	1.11	159.04	1930.42	3497.90	103.94%
	2.532		10.83	1.12	115.55	2089.84	3370.11	112.52%
	2.732		11.17	1.16	92.24	2105.59	3266.88	113.37%
	2.973	10.33	11.43	1.11	81.74	2202.82	3457.69	118.61%
	3.208		11.47	1.11	73.94	2183.13	3331.99	117.55%
	3.456		11.64	1.13	63.11	2181.96	3435.78	117.48%
	3.713	10.53	11.18	1.06	60.08	2188.95	3312.24	117.86%
	3.972		11.57	1.10	66.71	2130.64	3372.49	114.72%
	4.115		11.45	1.09	61.06	2235.49	3320.19	120.36%

* EC ratio = $EC_{effluent}/EC_{influent}$
** Influent ion concentrations for 0.05 M $CaCl_2$: 41.20 ppm Na^+, 1857.27 ppm Ca^{2+}, 3387.45 ppm Cl^-

Specimen 5g
5.6 % MSB Backfill
0.2 M $CaCl_2$

Phase Diagram (Specimen 5g)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:

Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	138.19	118.40
Mass Solids (g)	347.21	347.60
Total Mass (g)	485.40	466.00
Volume Air (cm^3)	13.28	0.00
Volume Water (cm^3)	138.19	118.40
Volume Solids (cm^3)	130.04	130.19
Total Volume (cm^3)	281.52	301.29
Water Content (%)	39.80%	34.06%
Volume Voids (cm^3)	151.47	118.40
Void Ratio	1.16	0.91
Porosity	0.54	0.39
Saturation (%)	91.23%	100%

Flexible Wall Test Results (Specimen 5g)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
0.7	10.0	2.1	23.0	2.067	10.2	2.4	22.8	2.061	1.55	1.04	2.04E-10	0.009
3.7	10.2	2.4	22.8	2.061	10.4	3.3	22.0	2.042	4.64	4.17	1.70E-10	0.038
14.8	10.4	3.3	22.0	2.042	10.9	7.3	18.5	1.956	20.64	18.24	2.08E-10	0.166
21.0	10.9	7.3	18.5	1.956	11.1	9.8	16.3	1.902	12.90	11.46	2.42E-10	0.246
35.8	10.0	2.0	23.0	2.068	10.4	10.1	15.9	1.894	41.80	36.99	3.21E-10	0.506
49.8	10.0	2.0	23.0	2.068	10.2	10.0	15.8	1.894	41.28	37.51	3.36E-10	0.767
62.0	10.0	2.1	23.0	2.067	10.2	10.0	15.9	1.895	40.76	36.99	3.81E-10	1.023
73.7	10.0	2.0	23.0	2.068	10.2	9.5	16.3	1.905	38.70	34.91	3.78E-10	1.266
86.9	10.0	2.0	23.0	2.068	10.2	9.9	16.0	1.897	40.76	36.47	3.51E-10	1.521
89.7	10.0	2.0	23.0	2.068	10.0	4.0	21.2	2.025	10.32	9.38	4.05E-10	1.586
95.0	10.0	4.0	21.2	2.025	10.1	7.5	18.1	1.949	18.06	16.15	3.87E-10	1.699
98.1	10.1	7.5	18.1	1.949	10.1	9.4	16.3	1.906	9.80	9.38	3.85E-10	1.762
105.1	10.0	2.0	23.0	2.068	10.1	6.9	18.6	1.962	25.28	22.92	4.05E-10	1.921
109.7	10.1	6.9	18.6	1.962	10.2	9.8	16.0	1.898	14.96	13.55	3.82E-10	2.016
119.0	10.0	2.0	23.0	2.068	10.1	7.5	18.0	1.948	28.38	26.05	3.45E-10	2.195
121.1	10.0	2.0	23.0	2.068	10.0	3.4	21.7	2.037	7.22	6.77	3.85E-10	2.241
123.4	10.0	3.4	21.7	2.037	10.1	5.0	20.3	2.003	8.26	7.29	4.03E-10	2.293
129.3	10.1	5.0	20.3	2.003	10.2	8.9	16.8	1.918	20.12	18.24	3.92E-10	2.419
131.1	10.2	8.9	16.8	1.918	10.2	10.0	15.8	1.894	5.68	5.21	3.91E-10	2.455
133.2	10.0	2.0	23.0	2.068	10.0	3.5	21.6	2.035	7.74	7.29	4.13E-10	2.505
137.1	10.0	3.5	21.6	2.035	10.1	6.2	19.2	1.976	13.93	12.50	4.01E-10	2.592
139.4	10.1	6.2	19.2	1.976	10.1	7.7	17.9	1.944	7.74	7.03	3.90E-10	2.641
143.2	10.1	7.7	17.9	1.944	10.2	10.1	15.7	1.892	12.38	11.20	3.82E-10	2.719

146.0	10.0	2.0	23.0	2.068	10.0	3.9	21.3	2.027	9.80	8.86	3.82E-10	2.780
150.1	10.0	3.9	21.3	2.027	10.1	6.5	19.0	1.971	13.42	11.98	3.69E-10	2.864
153.1	10.1	6.5	19.0	1.971	10.1	8.4	17.3	1.929	9.80	8.86	3.86E-10	2.926
154.3	10.1	8.4	17.3	1.929	10.1	9.2	16.6	1.912	4.13	3.65	3.81E-10	2.952
157.1	10.0	2.0	23.0	2.068	10.0	4.2	21.1	2.021	11.35	10.16	4.51E-10	3.023
159.1	10.0	4.2	21.1	2.021	10.1	5.7	19.7	1.988	7.74	7.03	4.46E-10	3.071
164.1	10.1	5.7	19.7	1.988	10.1	9.3	16.5	1.910	18.58	16.67	4.28E-10	3.188
166.1	10.1	9.3	16.5	1.910	10.1	10.7	15.3	1.880	7.22	6.51	4.32E-10	3.233
172.1	10.0	2.0	23.0	2.068	10.1	6.5	19.0	1.971	23.22	20.84	4.32E-10	3.378
175.1	10.1	6.5	19.0	1.971	10.1	8.6	17.1	1.925	10.84	9.90	4.24E-10	3.447
178.0	10.1	8.6	17.1	1.925	10.1	10.5	15.4	1.884	9.80	8.86	3.91E-10	3.509

Chemical Equilibrium Analysis (Specimen 5g)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^+	Ca^{2+}	Cl^-	
0.2 M $CaCl_2$	0.246	35.1	2.71	0.08	561.28	102.50	251.27	1.38%
	0.506		6.85	0.20	1131.77	434.27	1835.02	5.83%
	0.767		14.13	0.40	1053.72	2066.17	4582.71	27.74%
	1.023	35.6	19.72	0.55	890.22	3428.98	6400.64	46.03%
	1.266		24.5	0.69	712.07	4647.61	8075.62	62.39%
	1.521		28.1	0.79	564.93	5600.09	12532.73	75.18%
	1.762	33.8	32.2	0.95	439.87	6678.05	11546.77	89.65%
	2.016		33.1	0.98	350.50	7121.51	12187.92	95.61%
	2.195		32.1	0.95	382.84	7155.43	13172.29	96.06%
	2.455	32.3	34.0	1.05	342.68	7465.85	13620.99	100.23%
	2.719		34.9	1.08	211.12	7554.74	12861.52	101.42%
	2.952		36.0	1.11	203.36	7607.13	12917.72	102.13%
	3.233	36.4	36.2	0.99	186.43	7679.24	12786.37	103.09%
	3.509		36.6	1.01	178.74	7667.46	13418.27	102.94%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.2 M $CaCl_2$: 155.34 ppm Na^+, 7448.77 ppm Ca^{2+}, 13547.08 ppm Cl^-

Specimen 5h
5.6 % MSB Backfill
0.5 M $CaCl_2$

Phase Diagram (Specimen 5h)

Common Assumptions: G_s of SB backfill = 2.67, Mass Air = 0 g, Volume Air (after permeation) = 0 g
Known values:

Before Permeation: Water Content, Total Mass, Total Volume
After Permeation: Water Content, Total Mass

Property	Before permeation	After permeation
Mass Air (g)	0.00	0.00
Mass Water (g)	137.17	109.92
Mass Solids (g)	343.78	347.61
Total Mass (g)	480.95	457.53
Volume Air (cm^3)	15.59	0.00
Volume Water (cm^3)	137.17	109.92
Volume Solids (cm^3)	128.76	130.19
Total Volume (cm^3)	281.52	246.95
Water Content (%)	39.90%	31.62%
Volume Voids (cm^3)	152.76	109.92
Void Ratio	1.19	0.84
Porosity	0.54	0.45
Saturation (%)	89.79%	100%

Flexible Wall Test Results (Specimen 5h)

Average Tube Area (cm^2): 5.185
Sample Length (cm): 7.10
Sample Diameter (cm): 7.10
Sample Cross-Sectional Area (cm^2): 39.65

Cell Pressure (psi): 45.0
Head Pressure (psi): 41.3
Tail Pressure (psi): 38.7
Max Gradient: 29.13

Total elapsed time (days)	Initial Readings				Final Readings				Q_{in} (cm^3)	Q_{out} (cm^3)	*k* (m/s)	Total PVF
	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen	Cell Burette	Head Burette	Tail Burette	Head loss across Specimen				
1.0	3.1	2.0	23.0	2.068	3.3	2.6	22.6	2.057	3.10	2.08	3.02E-10	0.017
2.2	3.3	2.6	22.6	2.057	3.3	3.1	22.2	2.046	2.58	2.08	2.23E-10	0.032
8.2	3.3	3.1	22.2	2.046	3.6	5.3	20.0	1.996	11.35	11.46	2.22E-10	0.107
11.0	3.6	5.3	20.0	1.996	3.7	6.4	18.8	1.970	5.68	6.25	2.54E-10	0.146
17.4	3.7	6.4	18.8	1.970	3.9	9.2	15.7	1.902	14.45	16.15	2.93E-10	0.246
20.5	5.0	2.0	23.0	2.068	5.0	3.7	21.2	2.028	8.77	9.38	3.49E-10	0.305
22.7	5.0	3.7	21.2	2.028	5.1	5.2	19.6	1.992	7.74	8.34	4.19E-10	0.358
27.7	5.1	5.2	19.6	1.992	5.3	8.4	15.9	1.913	16.51	19.28	4.41E-10	0.475
30.5	5.0	2.0	23.0	2.068	5.1	3.9	21.0	2.023	9.80	10.42	4.18E-10	0.541
32.5	5.1	3.9	21.0	2.023	5.1	5.2	19.5	1.991	6.71	7.82	4.24E-10	0.589
36.4	5.1	5.2	19.5	1.991	5.2	7.7	16.8	1.932	12.90	14.07	4.18E-10	0.677
38.7	5.2	7.7	16.8	1.932	5.3	9.1	15.3	1.898	7.22	7.82	4.10E-10	0.726
42.5	5.0	2.0	23.0	2.068	5.1	4.6	20.2	2.006	13.42	14.59	4.33E-10	0.818
44.6	5.1	4.6	20.2	2.006	5.1	6.0	18.7	1.974	6.97	7.82	4.19E-10	0.867
46.4	5.1	6.0	18.7	1.974	5.1	7.1	17.5	1.947	5.93	6.25	4.11E-10	0.906
50.4	5.1	7.1	17.5	1.947	5.2	9.7	14.7	1.885	13.42	14.59	4.31E-10	0.998
52.4	5.0	2.0	23.0	2.068	5.1	3.5	21.4	2.033	7.74	8.34	4.66E-10	1.051
56.4	5.1	3.5	21.4	2.033	5.1	6.3	18.3	1.965	14.45	16.15	4.48E-10	1.151
58.4	5.1	6.3	18.3	1.965	5.2	7.6	16.9	1.934	6.71	7.29	4.41E-10	1.197
59.6	5.2	7.6	16.9	1.934	5.2	8.4	16.0	1.915	4.13	4.69	4.28E-10	1.226
63.4	5.1	2.0	23.0	2.068	5.1	4.7	20.1	2.004	13.93	15.11	4.49E-10	1.321
65.3	5.1	4.7	20.1	2.004	5.1	6.0	18.6	1.972	6.71	7.82	4.53E-10	1.368
71.4	5.1	6.0	18.6	1.972	5.2	10.1	14.3	1.876	21.16	22.40	4.43E-10	1.511

74.4	5.0	2.0	23.0	2.068	5.1	4.3	20.5	2.013	11.87	13.03	4.84E-10	1.592
77.3	5.1	4.3	20.5	2.013	5.1	6.4	18.2	1.963	10.84	11.98	4.59E-10	1.667
79.4	5.1	6.4	18.2	1.963	5.2	7.9	16.6	1.927	7.74	8.34	4.69E-10	1.719
80.4	5.2	7.9	16.6	1.927	5.2	8.6	15.9	1.912	3.35	3.65	4.61E-10	1.742
84.3	5.0	2.0	23.0	2.068	5.1	4.9	19.9	1.999	14.96	16.15	4.64E-10	1.844
86.3	5.1	4.9	19.9	1.999	5.2	6.3	18.4	1.966	7.22	7.82	4.47E-10	1.893
88.4	5.2	6.3	18.4	1.966	5.2	7.7	16.8	1.932	7.22	8.34	4.50E-10	1.944
91.3	5.2	7.7	16.8	1.932	5.2	9.6	14.7	1.886	9.80	10.94	4.41E-10	2.012
93.3	5.1	2.0	23.0	2.068	5.1	3.5	21.4	2.033	7.74	8.34	4.78E-10	2.065
97.5	5.1	3.5	21.4	2.033	5.1	6.5	18.2	1.962	15.22	16.67	4.51E-10	2.169
99.4	5.1	6.5	18.2	1.962	5.2	7.8	16.8	1.931	6.97	7.29	4.50E-10	2.216
101.4	5.2	7.8	16.8	1.931	5.2	9.2	15.3	1.897	7.22	7.82	4.62E-10	2.265

Chemical Equilibrium Analysis (Specimen 5h)

Permeant	PVF of permeant	$EC_{influent}$ (mS/cm)	$EC_{effluent}$ (mS/cm)	EC ratio*	Effluent ion concentration (ppm)			% Ca^{2+} of influent**
					Na^{+}	Ca^{2+}	Cl^{-}	
0.5 M $CaCl_2$	0.246	79.0	2.38	0.03	483.14	0.00	320.08	0.00%
	0.475		8.15	0.10	1133.71	690.14	1978.45	3.73%
	0.726		23.0	0.29	1302.24	3839.40	7344.86	20.72%
	0.998	80.5	43.3	0.54	975.22	8841.33	15207.44	47.72%
	1.226		58.1	0.72	753.11	13227.01	22806.16	71.40%
	1.511		68.1	0.85	630.80	15748.87	26166.48	85.01%
	1.742	82.6	73.8	0.89	508.24	16518.79	28973.60	89.17%
	2.012		77.7	0.94	605.94	18177.84	31665.25	98.12%
	2.265		79.4	0.96	526.66	19238.30	32154.75	103.85%

* EC ratio = $EC_{effluent}/EC_{influent}$

** Influent ion concentrations for 0.5 M $CaCl_2$: 402.73 ppm Na^{+}, 18525.87 ppm Ca^{2+}, 34377.04 ppm Cl^{-}