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Effect of Bentonite Swelling on Hydraulic Conductivity of Sand-Bentonite Mixtures (SBMs)

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Effect of Bentonite Swelling on Hydraulic Conductivity of Sand-Bentonite Mixtures (SBMs)

by

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Dedication

This is dedicated to my mother Antoinette, father Robert, great-grandmother Louise, grandfather Joe, sisters Skylar and Essence, brothers Daunte, Robert, Clarence (Jasmine), Justin, Kaylin, and Jordan, nieces Dauntasia, Layleiona, and Ja'Layah, and the rest of my family and loved ones.

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Abstract

Effect of Bentonite Swelling on Hydraulic Conductivity of Sand-Bentonite Mixtures (SBMs)

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The University of Texas at Austin, 2014

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The hydraulic conductivity of sand-bentonite mixtures (SBMs) were measured to investigate the effects of mixing method, uniformity, and hydration of the mixtures on the final hydraulic conductivity. Triaxial tests were completed to determine the hydraulic conductivity of each specimen. Specimens using Ottawa sand and Wyoming bentonite, prepared with dry and suspension mixing conditions that altered the degree of hydration and swelling of bentonite, had varying bentonite content by percentage dry weight of sand. The conclusions of this experiment can be applied to the construction of cut off walls used in levees to mitigate groundwater seepage through underlying pervious layers.

Eleven sand-bentonite specimens were tested in this study: nine were prepared

using dry mixing and two were prepared using suspension mixing. The results do not show strong correlations between hydraulic conductivity and bentonite content, mixing method, clay void ratio, or time. Therefore, further investigation of the results was necessary. The bentonite void ratio (clay void ratio) assumes that bentonite is fully swelled for both blocked and partially blocked flow. Blocked flow occurs when the swelled bentonite blocks all the sand voids and forcing the water to flow within the bentonite voids. However, the results in this study shows that the concept of clay void ratio doesn't capture the performance of SBMs when the bentonite is partially swelled; therefore, a new concept of effective clay void ratio was introduce to account for bentonite partial swelling. The effective clay void ratio determines the volume of swelled clay as a function of the volume of fully swelled bentonite. This is useful when comparing results with literature or predicting hydraulic conductivity in cases where only partial swelling of bentonite is expected.

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Chapter 1: Introduction

1.1 Research Significance and Objectives

The construction of levees has evolved over time from farmer-driven earthworks with little engineering to a more modern design. A large percentage of levee failures over the past 100 years occurred due to under-seepage through a highly conductive layer underneath the levee and embedded below the topsoil. Recent designs (and retrofits of existing levees) feature a cutoff wall to serve as a hydraulic barrier for underseepage.

Soil layers underlying levees have diverse stratigraphy that can consists of sands, silts, clays and gravels at some depth within its thickness. This heterogeneity substantiates the use of specific treatments to problematic layers to ensure that the shortcomings of the soil do not render the levee unstable. When sand underlies the ground surface of a levee, measures are taken to prevent the water from flowing through the sand due to its high permeability. If this flow was not controlled, chances of piping, high volumes of seepage, and levee collapse could occur due to high hydraulic gradients. Stagnating the flow with a cutoff wall reduces the pore pressure within the levee and therefore, increasing its factor of safety. While various types of treatments can be used with the soil to create the cutoff wall, much research has gone into determining the properties of sand-bentonite mixtures (SBMs) and their use as hydraulic barriers.

The quality of a SBM will depend predominantly on its hydraulic conductivity and shear strength. These properties vary with the conditions of the construction and site environment: confining stress and location of water table, as well as with the mixing conditions: amount of bentonite, dry versus wet mixing, and properties of the water used. Determining the effect of the type of mixing, prehydration and swelling of bentonite on the hydraulic conductivity of a SBM would be beneficial to the construction of cutoff walls.

It will take years and up to 100,000 billion dollars to improve levees nationwide (National Levee Safety Program, 2013). In 2013 the American Society of Civil Engineers issued a report on infrastructure in America, and the state of levees was given a D-, which is on the precipice of failing. This is not just a problem for the United States Army Corps of Engineers and Federal Emergency Management Agency but also to all the communities served and protected by these levees. Cost-effective solutions that can meet the demands of levee requirements will save lives and inland infrastructure from severe flood damage; this would be a great return for a “small investment”. Reevaluating sand-bentonite mixtures used as cutoff walls is one way to consider the influence of underseepage on levees.

1.2 Research Objectives

The overall objective of this research is to investigate the effects of bentonite swelling and uniformity on the hydraulic conductivity of SBMs. Swelling of bentonite is relied on in the field to produce uniform, low flow hydraulic cutoff walls on site. This research will provide further information on the factors affecting the hydraulic conductivity of SBMs, which are increasingly being used for large-scale levee projects (Magnus Pacific, 2014). In order to properly execute the experimental objective, many tasks must be completed:

1. Practice proper sample preparation for triaxial specimens to determine the hydraulic conductivity of sand specimens.
2. Practice proper sample preparation, and mixing method, for triaxial specimens to determine hydraulic conductivity of sand-bentonite specimens.
3. Use triaxial testing programs to collect data on volume changes to ensure that they are minimal, as the skeletal void ratio of sand should not change much throughout this experiment. Also collect data on other parameters that are useful to this experiment.
4. Reproduce results; determine range of hydraulic conductivity values given the changes in time, bentonite content, clay void ratio, and mixing method.

The complimentary research objectives are:

1. To determine and evaluate proper sample preparation techniques for each mixing method.

2. To evaluate the efficiency of triaxial cells to determine the hydraulic conductivity of SBMs.
3. To quantify bentonite swelling upon hydration and its affect on the hydraulic conductivity of SBMs.
4. To obtain results of water content and bentonite content post-hydraulic conductivity testing to validate the properties of the specimen as compared to those calculated from the initial conditions.

1.3 Scope of Thesis

This thesis is composed of five chapters. After this introduction, Chapter 2 discusses different research studies conducted with an emphasis on obtaining the hydraulic conductivity of SBMs. Chapter 2 is divided into five parts: an introduction to SBMs, a discussion of underseepage, the limitations, uniformity, and environmental impact of SBMs, the swelling potential of bentonite and influence of exchangeable cations reacting with bentonite, the importance of field and lab tests for determining the hydraulic conductivity of SBMs.

Chapter 3 details the experimental methods of this study. It describes the materials and equipment used, preparation of specimen, the different mixing methods used for SBMs, the stages of sample preparation, procedures for hydraulic conductivity testing and bentonite content analysis.

Chapter 4 presents the results obtained in this study and the analyses used to explain the results in context of previous results. The specimen parameters of all specimens used in this study are described, the hydraulic conductivity of each specimen is tabulated, the effects of experimental factors are illustrated, and a comparison of results with those in the literature is provided.

Chapter 5 presents the conclusions and future work that will be necessary to provide more insight on the effects of swelling of bentonite in SBMs on their hydraulic conductivity.

Chapter 2: Literature Review

2.1 INTRODUCTION

The appeal for using sand-bentonite mixtures in the field is accredited to the inherent properties of bentonite and how its properties can be utilized to complement the use of sand in engineering applications. Bentonite is a type of clay that is composed mostly of montmorillonite. The observation of its high swelling abilities makes it a good candidate to fill the large voids of granular soil to form a low hydraulic conductivity mixture. Sand is a granular soil that has a high hydraulic conductivity thus it cannot be used as a hydraulic barrier on its own. Adding bentonite to sand is a way to create new applications where the sand-bentonite mixture becomes a feasible hydraulic barrier material. Sand-bentonite mixtures have wide use in geotechnical engineering applications. SBMs can be used construct liners in landfills, nuclear disposal burier facilities, and construct hydraulic cutoff walls.

With several levees in need of remediation within the United States, the use of soil-bentonite cutoff walls as cost-effective mitigation can be promising (ASCE, 2013). Soil-bentonite cutoff walls have been used in levees constructed as early as the 1970s (Duncan and Rice, 2010). Cutoff walls are created when sand and bentonite are mixed together in slurry form, creating a new material. Increasing technical knowledge regarding design and implementation of sand-bentonite cutoff walls has only provided further incentive for their use. The American Society of Civil Engineers (ASCE)

Sacramento Section has awarded two Outstanding Project of the Year awards to Magnus Pacific for their role in the Natomas Cross Canal Levee Improvement Program and the Upper Yuba Levee Improvement Project. Over one million square feet of soil-bentonite cutoff wall was constructed in response to levee seepage issues, bringing levees up to compliance for levees protecting urban areas. These projects were completed within budget because sand-bentonite mixtures suit projects that require a large quantity of materials at an affordable price. These projects were also completed on-time, illustrating that levees constructed using soil-bentonite cutoff walls are an effective solution to flood control (Magnus Pacific, 2014).

This chapter provides information on different aspects of sand-bentonite mixtures and conclusions made from prior research. Mechanisms of underseepage, performance of sand-bentonite mixtures, properties of bentonite, and methods to determine hydraulic conductivity of SBMs are presented in this literature review.

2.2 UNDERSEEPAGE

When water levels rise after intense rainstorms or in the event of a hurricane, water surges are expected to be the most dominant factor in the failure of a levee. What is often overlooked is the fact that any rises in water level that exceed the groundwater table level of the land on the "dry side" of the levee will induce underseepage. Underseepage is the process of water flowing from the shore side underneath the levee to the landside. This causes excess pressure landward and will often lead to heave, piping, and sand boils.

In some cases erosion of soil can lead to significant settlement and fail levees (Yoon, 2011). When the soil layer just underneath levees is sand, with a typical hydraulic conductivity of 10^{-3} cm/s, it does not take long for the excess water pressure to exceed the submerged unit weight of sand. Sand boils manifest and deposit eroded soils on the landside, leaving large channels for water to flow. Underseepage is a problem that needs to be mitigated for long-term stability of levees.

2.3 Sand-Bentonite Mixtures

This section covers research on sand-bentonite mixtures and their use in landfill liners, as well as sand-bentonite mixtures and their use as cutoff walls. Sand-bentonite mixtures can be used in landfill liners to mitigate leakage. Sand-bentonite mixtures are used to mitigate underseepage.

Based on Hwang (2010), the importance of controlling hydraulic conductivity of sand bentonite mixtures is the need to construct liners that will not allow leakage to infiltrate into surrounding soil. Liners produced with sand and bentonite have the advantage of being relatively more cost efficient than other hydraulic barrier alternatives such as compacted clay, geotextiles, and geomembranes. Mixing sand with bentonite has lowered its hydraulic conductivity to 10-9cm/s in some instances (Hwang, 2010). Parameters outlined in affecting hydraulic conductivity of SBMs include: clay void ratio, which is the ratio of volume of water to volume of bentonite, the amount of bentonite in the specimen, the type of bentonite, properties of sand, and time of hydration and consolidation. Hwang's report forms a basis for improving in situ hydraulic conductivity of soil liners based off of laboratory procedures and results.

Cutoff walls constructed out of bentonite slurry and sand backfill can be used to retard groundwater flow in levees. Impeding groundwater flow is significant as it could make a difference in flooding an urban area when water levels rise. Cutoff walls are hydraulic barriers that are installed through the permeable soil layer, extending some depth into the impermeable soil layer. Figure 2-1 shows a common case in which a cutoff wall is implemented. While this review will not fully detail the construction processes of cutoff walls, the information regarding SBMs will be relevant to its construction. This application was tested for its stability under high gradients; critical gradients in which washing out occurs were determined to be lower when higher percentages of bentonite content were used for permeated specimens (El Khattab, 2013). This is due to clay void ratios dominating hydraulic conductivity, causing higher water pressures to develop because of the greater difference in permeability between the barriers and surrounding soil (Duncan and Rice, 2010). When critical gradients occur, washing out will result in increases in hydraulic conductivity. This information shows that while cutoff walls are feasible hydraulic barriers, there must be limitations for design and construction of earth structures using when using bentonite with sand.

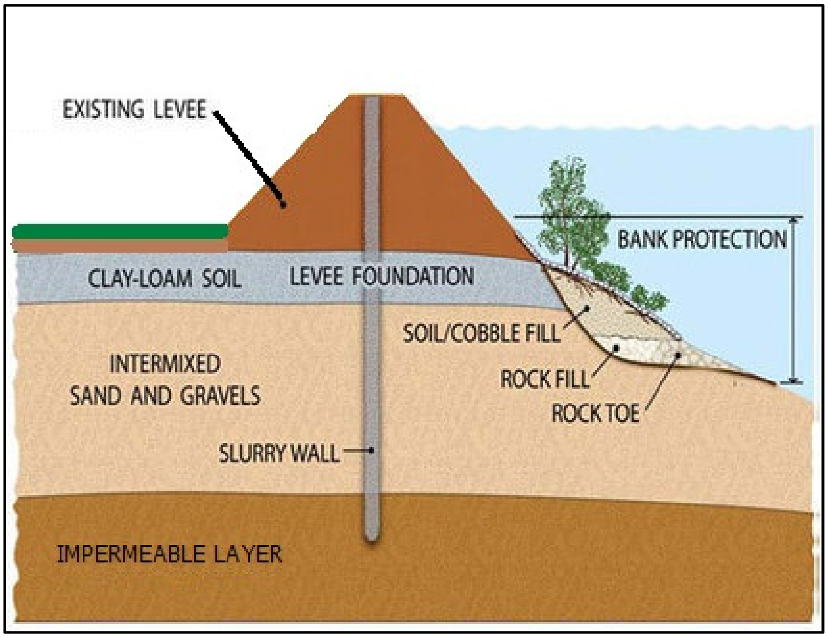

Figure 2-1 Levee with Cutoff Wall (adapted from Portland Cement Association)

2.3.1 Limitations

Constraints are necessary when adding bentonite to sand to create hydraulic barriers. Studies show that the density, water content, and percentage of bentonite in sand will affect hydraulic conductivity of the mixture (Abichou et. al, 2002, Arrykul and Chalermyanont, 2005, and Komine 2004). Emphasis is placed on bentonite content of the mixture while modifications of density and water content are case specific. The appropriate range of bentonite content should be considered when creating sand-bentonite mixtures because properties can vary greatly depending on the amount of bentonite used. Bentonite content is the ratio of the mass of dry bentonite to the mass of dry sand.

Experiments have investigated the effects of bentonite content on the specimen parameters such as soil classification, hydraulic conductivity, optimum water content, maximum dry unit weight, shear strength, and friction angle. Mixtures with bentonite content of 5-30% are able to maintain compaction characteristics of sandy soil (Komine, 2004). In Komine's experiments, hydraulic conductivity measurements were made once the specimen reached a constant vertical swelling pressure. Originally a range of 5-30% was used for bentonite content due to the mixture still behaving as a sandy soil rather than a clayey soil. Later it was observed that bentonite content between 5-20% experienced distinguished decreases in hydraulic conductivity while the difference in hydraulic conductivity for bentonite contents between 20-50% is smaller.

Arrykul and Chalermyanont (2005) investigated the variations of hydraulic conductivity, optimum water content, and maximum dry unit weight with different percentages of bentonite content. They concluded bentonite content ranging from 3-5% is ideal for sand bentonite mixtures because the swell percentage is high while maintaining a high friction angle and shear strength. In these cases, the maximum dry density decreases and the optimum water content increases with increasing bentonite content. When bentonite content ranges from 5-20%, bentonite swelling does not increase much under constant confining stresses of 17.17, 29.57, and 41.94 kPa but there are significant decreases in the friction angle and shear strength.

A closer look at the range of 0-10% bentonite content in specimens reveals that the differences in hydraulic conductivity of sand-bentonite mixtures can be separated into three regions as illustrated in Figure 2-2 (Abichou et. al, 2002).

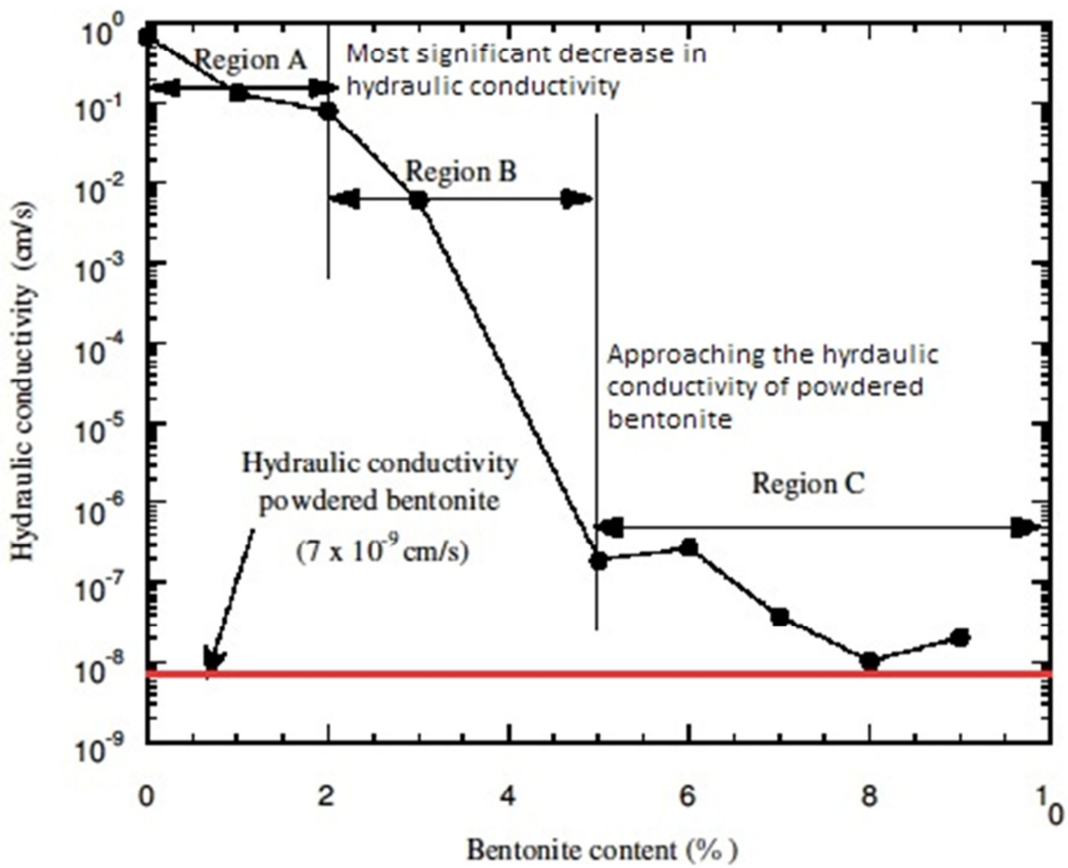

Figure 2-2: Three Regions of Hydraulic Conductivity for SBMs (Adapted from Abichou et. al 2002)

By using simulated sand-bentonite mixtures where glass beads represented the granular size of sand, Abichou et al. (2004), made observations of the microstructure of the mixture. Using scanning electron micrographs easily distinguished the behavior of bentonite particles. Region B was determined to be the range of bentonite content between 2-5% where the significant decrease in hydraulic conductivity occurs. This is due to the bentonite blocking the flow paths. When bentonite content exceeds 5%, the reduction in bentonite is not as significant because the void ratio of bentonite is being reduced, which has a smaller impact on the mixture than reducing the flow through the sand pores. This shows that target hydraulic conductivity can be achieved using 2-5% bentonite content with minor reductions in properties like friction angle, and shear strength.

The long-term impact of sand-bentonite mixtures on levees also places limitations on its design and construction. In a study that examined the long-term performance of over 30 hydraulic barriers used in dams and levees, it was determined that new failure mechanisms are introduced to the structure when these barriers are included (Duncan and Rice, 2010). Failure mechanisms resulting from the construction of any seepage barrier such as sheet piles, concrete core walls, and soil-bentonite barriers primarily stem from high pressure gradients and localized excess pore pressures. Fatigue caused by these mechanisms can lead to erosion and leaks, especially if defects are already present in the barrier. Figure 2-3 shows underseepage occurring through the foundation of a levee when the water level rises. It also emphasizes that any defects in the cutoff wall will be targets for increased flow through the cutoff wall, failing the wall and causing great threat to what lies on the other side of the levee.

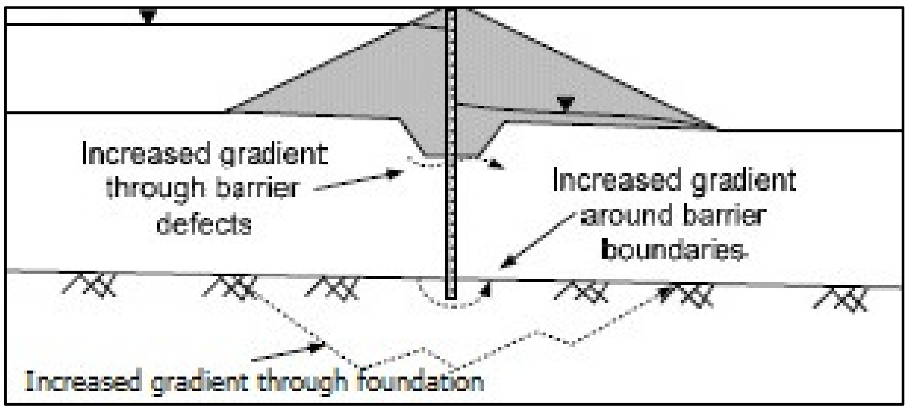

Figure 2-3 Underseepage with Cutoff Wall (Adapted from Rice et al. 2010)

Out of five soil-bentonite cutoff walls examined in this study, two of them showed leaks post construction and one required removal of the cutoff wall for remediation. Failure mechanisms detected in soil-bentonite walls were cracks and gaps from settlement of infill and backfill. In the case where the cutoff wall was removed, both failure mechanisms occurred following drawdown. Early detection of these problems is achieved by monitoring the construction and long-term performance, which will be discussed later in this chapter. While limits on bentonite content are likely to reduce the likelihood that new failure mechanisms will occur, uniformity of SBMs will also impact localized pore pressures and gradients throughout the system.

2.3.2 Uniformity

Achieving the proper bentonite content during initial mixing is not very difficult, while achieving the proper uniformity is a more meticulous process. Continuous mixtures are created when distributions of bentonite throughout mixtures are even. In cases where sections of mixtures have more bentonite than others, bentonite cannot fill all the sand voids in the mixture, creating areas where hydraulic conductivity will vary. Variance in hydraulic conductivity will create areas of higher gradients in the sand-bentonite cutoff walls, which can lead to undesired seepage. Cutoff walls lacking continuous hydraulic conductivity are poor hydraulic barriers. Mixing methods and hydration of bentonite controls uniformity in SBMs. Efficient mixing methods will thoroughly mix sand and bentonite in mixtures, creating a constant bentonite content in the mixture. Mixtures can be formed using wet mixing, dry mixing, and suspension mixing.

Wet mixing is the process of mixing dry amounts of sand and bentonite together, followed by spraying water over the mixture. The mixture is continuously mixed while spraying water until particular water content is obtained. Dry mixing is the process of mixing dry amounts of sand and bentonite together; no water is added to the mixture until it is already in place; the mixture is then flushed or inundated with water (less common in practice). Suspension mixing combines water and bentonite to create a slurry form before adding to the sand. Water and bentonite are mixed using a high shear mixer, causing bentonite to suspend in water. Sand is combined with water and bentonite to form the mixture. These mixing methods are modeled in the field. All mixing methods have high productivity such that large quantities can be produced if necessary. This advantage also makes it economical (Kirsch and Bell, 2013). Other benefits attributed to all mixing methods include causing minimal lateral or vertical stresses that could damage adjacent structures when preparing in the field, and the quality of mixture can be tested during construction (Kirsch and Bell, 2013). In some cases wet mixing may be more advantageous due to providing better uniformity because of longer mixing time, whereas dry mixing is less affected by low temperatures and allows for targeted treatment. Suspension mixing is likely to produce the most hydrated mixture (Hwang, 2010), however the amount of spoil after construction exceeds that of the other methods. While hydration affects uniformity of SBMs, proper mixing using any of the methods is also necessary for uniformity.

When water is added to a mixture, sand particles will only absorb a negligible amount in comparison to what bentonite will absorb. Hydration and swelling of bentonite are key to properly prepare the mixture for optimal hydraulic conductivity. When sections of mixtures do not have the desired bentonite content due to poor mixing methods, this defect is compounded by the fact that parts of the mixture will now be hydrated while others may not achieve hydration. In dry mixing, hydration does not occur until after the cutoff wall in the field, or specimen in the lab, is already constructed. This means that hydration is obtained by flushing water with the intent to saturate the specimen and hydrate the bentonite. In wet mixing and suspension mixing methods bentonite is hydrated prior to construction, hence these methods use prehydration to ensure bentonite will be hydrated at completion of construction, allowing the maximum decrease in hydraulic conductivity. Before mixing and construction, however, SBM cutoff walls' impact on the environment is important to consider in implementation.

2.3.3 Environmental Impact

Sand-bentonite mixtures are advantageous because it has a low impact on the environment. Over 70% of sodium bentonite in the world is found in Wyoming (World Mining Association, 2009). The abundance of bentonite makes it a sustainable product for various uses. Bentonite is extracted through mining. The mining process begins with exploration, then observation of the potential site and hazards, and finally mining is permitted under federal, state, and local mining regulations. When bentonite is used in cutoff walls to create hydraulic barriers it can be combined with other additives such as cement, fly ash, etc. Chemical changes occur when cement and groundwater interact which making it unideal for use in levees. Fly ash would also be problematic because it must be enhanced by cement to reach strength requirements. When bentonite is mixed with sand it does not undergo chemical changes since both naturally occurring materials. SBMs do not require an addition of cement for strength when the right percentages are added. Other properties of bentonite illustrate its ability to compliment sand.

2.4 BENTONITE

Bentonite has a significant presence in the United States as a product of multiple uses. Its first discovery in the United States was over 100 years ago. Today its uses include serving as an additive to bleaching and washing agents, cosmetics, drilling mud, pet litter, foundry sands, and several products for civil engineering application. The chemical and physical properties of bentonite make it a viable option for wide use.

Bentonite is predominantly composed of montmorillonite minerals but smaller percentages of other minerals such as quartz, gypsum, and pyrite may exist. Montmorillonite is a 2:1 clay mineral that has two tetrahedrally shaped bonds of Aluminum, Silicon, and Oxygen ions that are linked by an octahedrally shaped bond of Aluminum, Magnesium, and Oxygen ions. Between sheets of montmorillonite, water in the form of dipoles, hydrogen bonds, or ions interact with the outer tetrahedral bonds to adsorb to the surface. The crystalline structure of montmorillonite provides structural stability of the mineral and allows it to resist weathering. This structure can be formed through combinations of ions that combine in a solution and from magma as a result of cooling (Mitchell, 1993). The result is a porous, plate-like structure with a smooth surface. Figure 2-4 shows the atomic structure of montmorillonite with ions floating between layers.

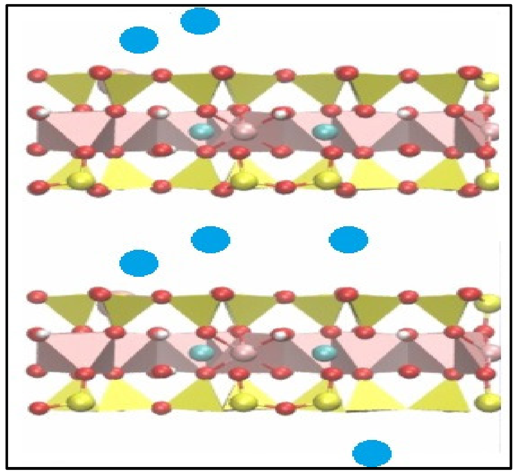

Figure 2-4 Structure of Montmorillonite with Floating Ions (Adapted from Walley et al. 2012)

Bentonite is usually found in drier regions such as Texas and Wyoming thus natural water content of dry bentonite is less than ten percent. The color of bentonite can vary with environment but often bentonite will have a grey color. Bentonite is distributed commercially as fine powder clay to allow precise quantities to be used since it is mostly used as small fractions of a larger mix. While granular forms exist, it usually yields higher bentonite content in SBMs due to decreased efficiency in fully hydrating the lumps of bentonite (Gleason et al. 1997). When water is added to bentonite, water is easily absorbed and bentonite can expand exceeding seven times its volume unless the volume is restricted. The swelling capacity of bentonite is predicted and monitored when determining its quality for use in civil engineering applications.

2.4.1 Swelling Potential and Influence of Exchangeable Cations

Bentonite has a propensity to swell greatly when in contact with cations in water. The swelling is a response to repulsive and attractive forces between the montmorillonite layers. When water is introduced to bentonite, the montmorillonite particles adsorbs the water and expands, exceeding the void space in the clay while volumes of other minerals remain constant (Komine and Ogata, 1994). The swelling capacity of bentonite will vary depending on the percentage of montmorillonite, available volume of water, and applied confining stresses. It is also affected by the type and amount of cations in solution, and is time dependent.

Montmorillonite is unique because it has a large specific surface area that can exceed 800 m2/g due to its large internal and external surface area when the lattices expand to adsorb water. As the percentage of montmorillonite increases, the amount of surface area to adsorb water increases. Dry bentonite can absorb water from the atmosphere even at low humidity (Mitchell, 1993). Bentonite has a net negative charge due to isomorphous substitution, which allows ions (aluminum, silicon, and magnesium) to be replaced by other ions (sodium, calcium, etc.) without changing the crystalline structure. These replacement ions are commonly referred to as exchangeable cations; the montmorillonite layer expands differently depending on the type of exchangeable cations in the diffused double layer.

The Gouy-Chapman diffuse double layer theory describes the relationship between charged surfaces of clay particles and surrounding ions attracted to these surfaces. The concentration of ions follows the Boltzmann distribution, which assumes that ions do not interact and forces at the surface obtain equilibrium. Uniform distribution of charge on clay surfaces is maintained through processes of diffusing ions continuously to maintain equilibrium. Electrical potential of the solution exponentially decays with distance from the surface of the particle. The center of gravity of the diffuse charge is located at a distance equal to the reciprocal of the decay constant; this distance is known as the diffuse double layer thickness. These concepts are expressed by Equation 2-1 and Equation 2-2, where ψ=electrical potential of the solution, $1/\kappa$= thickness of diffuse double layer, ε_0= permittivity of vacuum, D= dielectric constant of pore fluid; k= Boltzmann constant, T= temperature in ^{o}K, n_0= reference ion concentration; e= charge of one electron, and ν= ion valence. An increase in the double layer thickness represents swelling while a decrease represents shrinking.

$$\boldsymbol{\psi = \psi_0 \mathbf{exp}(-\kappa x)} \qquad \textbf{Equation 2-1}$$

$$\frac{\mathbf{1}}{\boldsymbol{\kappa}} = \sqrt{\frac{\boldsymbol{\varepsilon_0 DkT}}{\boldsymbol{2n_0 e^2 v^2}}} \qquad \textbf{Equation 2-2}$$

In the presence of water with a high ionic concentration, diffuse double layers may accept more cations to adsorb to the surface of the clay. Under low confining stresses, the volume of bentonite would increase when more cations are adsorbed to its surface. When confining stresses are high and approach the swelling pressure, the swelling of the clay is limited or shrinkage could occur. Exchangeable cations will also affect the amount of swelling bentonite experiences. Sodium cations replacing aluminum, silicon, or magnesium ions will yield sodium bentonite. Typically sodium bentonite is used throughout civil engineering application because of its higher swelling capacity when compared to other common bentonites such as calcium bentonite. This is because more of the water bonds to the clay surface in sodium bentonite rather than remaining as free water between particles; free water can be removed under a hydraulic gradient (Ahn and Jo, 2009). As common with clays, the swelling capacity of bentonite increases as time of hydration increases. Allowing bentonite the proper time to fully swell will optimize its use as a hydraulic barrier.

2.5 Field and Lab Tests

Hydraulic conductivity tests evaluate the performance of SBMs as hydraulic barriers. It is imperative to conduct in situ testing to observe the macrostructure effects of the mixture on the hydraulic conductivity and confirm that the in situ hydraulic conductivity is within an acceptable range (Olson and Daniel, 1981). However, it is more feasible to conduct laboratory measurements of hydraulic conductivity because of the controlled setting and lower costs. Correlating hydraulic conductivity tests in the lab to those in the field requires that lab conditions simulate the environment in the field.

2.5.1 Field Tests

In situ hydraulic conductivity tests are conducted using the piezocone, packer or self-boring permeameter (SBP) tests (Joshi et. al, 2010), and other equipment. Piezocone tests are synonymous with cone penetration tests (CPT). It consists of pushing a cone into soil and recording the pore pressure dissipation with time. When 50% of the pore pressure has dissipated, the time elapsed can be empirically correlated with hydraulic conductivity. Packer tests require boreholes to lower the device into the wall. Once the packer has reached the desired depth, membranes above and below the packer can be inflated under air pressure to seal off a water filled cavity created by the device. The surrounding wall can undergo a constant or falling head test. The SBP is ideal for eliminating faulty results from smearing of the wall during in situ hydraulic conductivity tests. The device bores itself downward into the wall and after reaching a specified depth; it begins to pump water at a constant rate into the cavity created after it retracted. The water pressure is measured and hydraulic conductivity can be determined under constant flow principles. While such in situ results can be very useful, it is common to get different results depending on the method used. Hydraulic conductivity tests in the lab are more consistent due to a more controlled environment.

2.5.2 Lab Tests

Hydraulic conductivity of SBMs using flexible wall permeameters and rigid wall permeameters are common standards of practice in the lab. A flexible wall permeameter is commonly used to test undisturbed soil samples while reducing the amount of sidewall leakage as compared to rigid wall permeameter (Daniel et al 1985). The flexible wall permeameter system provides a close simulation using lab samples to the in situ soils that typically experience in situ overburden pressure. It consists of a permeameter chamber (which can be represented by a triaxial cell) attached to a pressure source that delivers pressurized air and pore fluid through the specimen. The chamber secures the undisturbed sample between top and bottom platens. Porous stones and filter papers separate the top and bottom of the soil specimen from the platens for even distribution of the permeant. The platens, porous stones, filter paper, and soil specimen are placed inside of a latex membrane that allows the specimen to deform while isolating the specimen from the chamber fluid. The chamber surrounding the specimen is filled with water that is pressurized to create a confining stress. The burettes containing the influent and effluent have the same water levels when no hydraulic gradient is applied across the specimen. Water levels in the influent and effluent burette are monitored throughout the consolidation and are equal except during hydraulic conductivity measurements.

The hydraulic conductivity of the specimen is determined using the falling head/rising tail test according to ASTM 5084-10 standards. During the test, the hydraulic conductivity of the soil being permeated with a given fluid is measured. Draining the water in the effluent burette to levels less than that in the influent burette creates a hydraulic head; this adjustment is made with the specimen isolated from the burettes so that the gradient is not applied gradually across the specimen. The influent and effluent valves are then opened and the timer begins to record the travel time of the effluent to reach water levels sufficient to be read off of the burette. The elapsed time between the total hydraulic head applied initially and the total hydraulic head applied at a specified time interval is recorded. The saturated hydraulic conductivity is proportional to the natural log of the ratio of the hydraulic head applied at the start and finish of the testing interval. Other properties that affect flow rate include the specimen height, specimen cross-sectional area, cross-sectional area of the influent and effluent burettes, and elapsed time between the hydraulic gradients applied (Selvam and Barkdoll, 2005).

Rigid wall permeameters can also be used to measure the hydraulic conductivity. A rigid wall permeameter consists of a simpler set-up and tests samples according to ASTM 5856-95. It is low in cost and can test different permeants, whereas the flexible wall membrane would potentially degrade, ruining the specimen (unless specialized, more expensive membranes are used). When backpressure saturation is used to saturate the specimen, formations of channels and side flow could develop in rigid wall specimens (Edil and Erickson, 1985). Saturation cannot be verified in rigid wall setups. In recent studies, measurements from rigid wall permeameters were similar to flexible wall permeameters, therefore it is suggested that either can be used for testing (Daniel et. al 1985).

2.5.3 Impact of Testing Environment

The fact that many tests completed on SBMs with similar mixing properties, bentonite content, and other physical properties yield different results attests to the importance of the testing environment. Properties of the specimen such as confining stresses, hydraulic gradients, degree of saturation, and time are aspects of the testing environment that can affect results.

Confining stresses in situ or in the lab represent the surrounding pressures that SBMs experience. Confining stresses prior to complete swelling of bentonite could limit the ability of bentonite to fully swell to fill voids in sand; therefore the hydraulic conductivity may not decrease significantly. This would have a negative impact since the aim is to obtain the lowest possible hydraulic conductivity. On the other hand, after bentonite completely swells, confining pressures on SBMs increase its self-healing potential. If small cracks occur during swelling, they close up during confinement as the soil particles move closer together.

Hydraulic gradients describe changes in water head along the length of SBMs. Following Darcy's law; the hydraulic gradient is linearly proportional to the flow rate when flow is laminar. Laminar flow exists for hydraulic gradients that are low whereas higher gradients yield turbulent flows that contribute to washing out of fines (Yoon, 2011). While SBMs exhibit Darcian flow characteristics, it is necessary to examine critical gradients and transitional gradients of SBMs to understand flow mechanisms at different gradients. Recall that critical gradients trigger washing out. Transitional gradients are the upper bound of gradients that decrease flow rates and hydraulic conductivity as shown in Figure 2-5. Gradients lower than transitional gradients have lower hydraulic conductivity because certain flow paths in micro-pores are not conductive at such small gradients (Dixon et al. 1999).

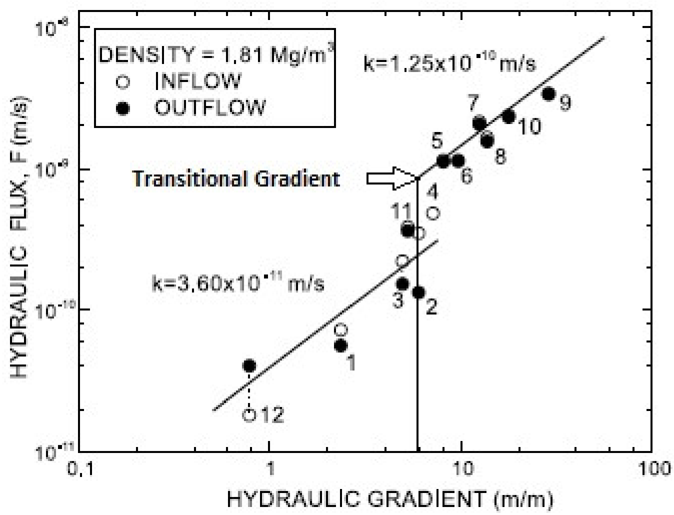

Figure 2-5: Hydraulic Flux versus Hydraulic Gradient (Adapted from Dixon et. al 1999)

The degree of saturation of SBMs indicates the volume of water within the volume of voids. In geotechnical practice, interest is placed on the hydraulic conductivity of fully saturated SBMs. When SBMs are not fully saturated hydraulic conductivity tests will result in misleading low values. This is because air blocks voids and limits flow paths for water to move through (Olson and Daniel, 1981).

Time elapsed for different procedures in hydraulic conductivity tests will also impact the results. If SBMs are not given enough time to fully swell then hydraulic conductivity measurements will be greater than the hydraulic conductivity of SBMs with fully swelled bentonite. If not enough time is given for influents and effluents to stabilize, then the hydraulic conductivity measurements will not be consistent and a representative hydraulic conductivity cannot be determined. In some instances, it could take up to two weeks to measure hydraulic conductivities representative of SBMs (Chalermoyant and Arrykul, 2005).

2.5.4 Comparison of Field and Lab Test Results

Results from field and lab tests will differ due to varying construction methods and testing environments. Considering field tests are on a larger scale and has a larger margin of error, hydraulic conductivity measurements are generally higher in the field than in the lab. While low gradients in the field are easy to obtain, ensuring that mixtures are uniform, saturated, and fully swelled are more difficult. For these reasons, practitioners use water contents and bentonite contents that are one order of magnitude less of what is used to yield the desired hydraulic conductivity in the lab.

2.5.5 Summary

This chapter illustrates that different aspects of sand-bentonite mixtures have been investigated to determine how SBMs can efficiently be used as hydraulic barriers. Understanding mechanisms of underseepage, the uses of sand-bentonite mixtures and mixing methods used to create them, properties of bentonite, and methods to determine hydraulic conductivity of SBMs are essential to developing a research program to appropriately identify how hydration and bentonite content affect hydraulic conductivity.

Chapter 3: Experimental Program

3.1 Introduction

In order to conduct hydraulic conductivity tests many procedures are used to prepare testing samples. SBMs are comprised of Ottawa sand, Wyoming bentonite, and deaired water. Procedures are completed to decrease the likelihood that testing conditions will lead to biased results. When using the triaxial cell as a flexible wall permeameter, the sample is prepared similar to specimen prepared for consolidated undrained (CU) tests. After the specimen is prepared, a data acquisition system was used in this study to collect data during each stage leading to determining the hydraulic conductivity. Finally, wet sieving tests were done to determine the water content and bentonite content of each specimen. This chapter describes the materials and equipment used along with the necessary steps to conduct this study. The experimental program is comprised of equipment calibration, preparation of specimens, back pressure saturation, consolidation, and hydraulic conductivity tests.

3.2 Materials

3.2.1 Sand

Ottawa sand used in this study is manufactured from U.S. Silica located in Ottawa, Illinois. It is taken from St. Peter Sandstone deposits (US Silica, 2014). Ottawa sand is approved for hydraulic testing and adheres to ASTM C-778. The grain diameter is greater than 0.075 mm but less than 2 mm and it is classified as poorly graded sand with a round shape and tan color. The grain size distribution curve for sand used in this experiment is provided in Figure 3-1. The sieving analysis and properties of sand such as its specific gravity, minimum and maximum void ratio, diameter of 10 percent passing and diameter of 50 percent passing, coefficient of uniformity and coefficient of curvature, and the Unified Soils Classification System symbol respectively are listed in Table 3-1.

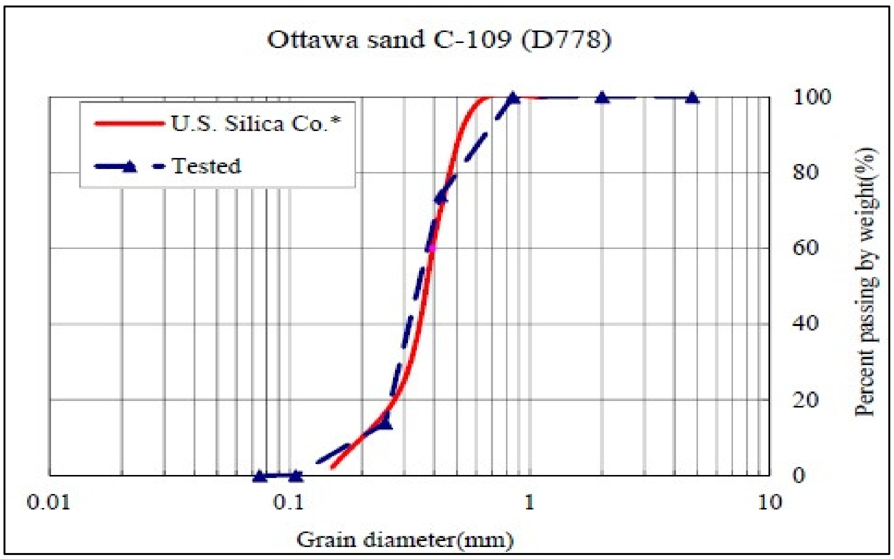

Figure 3-1: Grain Size Distribution (Hwang, 2010)

Table 3-1: Sieve Analysis and Sand Properties (Hwang, 2010)

Sieve Analysis			Sand Properties	
Sieve #	Size (mm)	Passing%	G_s	2.65
4	4.75	100.00	e_{min}	0.5
10	2	100.00	e_{max}	0.78
20	0.85	99.96	D_{10} (mm)	0.23
40	0.425	73.90	D_{50} (mm)	0.346
60	0.25	13.84	Cu	1.62
140	0.106	0.02	Cc	1.07
200	0.075	0.00	USCS	SP

3.2.2 Bentonite

Volclay manufactured Wyoming bentonite used in this study, where its commercial name is Volcay CP-200. Used as a soil sealant, it meets American Petroleum Institute (API) Specification 13A for Drilling Fluid Materials. The primary applications of Wyoming bentonite listed by the manufacturer are soil/bentonite liners and soil trenching. The minimum free swelling it provides is 8 ml per gram of water added (CETCO, 2009). For the purpose of this experiment, it was necessary to sieve bentonite through the #200 mesh to remove any impurities before testing. The moisture content of bentonite used in this experiment is 6.7%.

3.3 EQUIPMENT

Tests run for this experiment required the use of GEOTAC's TestNet system which acquired data and controlled testing for Sigma-1 CU automated load testing system for CU triaxial testing using GeoJac load frame. A pressure panel manufactured by Trautwein was used to deliver pore and cell pressure to specimens. The permeant used for hydraulic conductivity testing was deaired water provided by the nold deaerator manufactured by Geokon. Figure 3-2 shows the configuration of triaxial testing equipment.

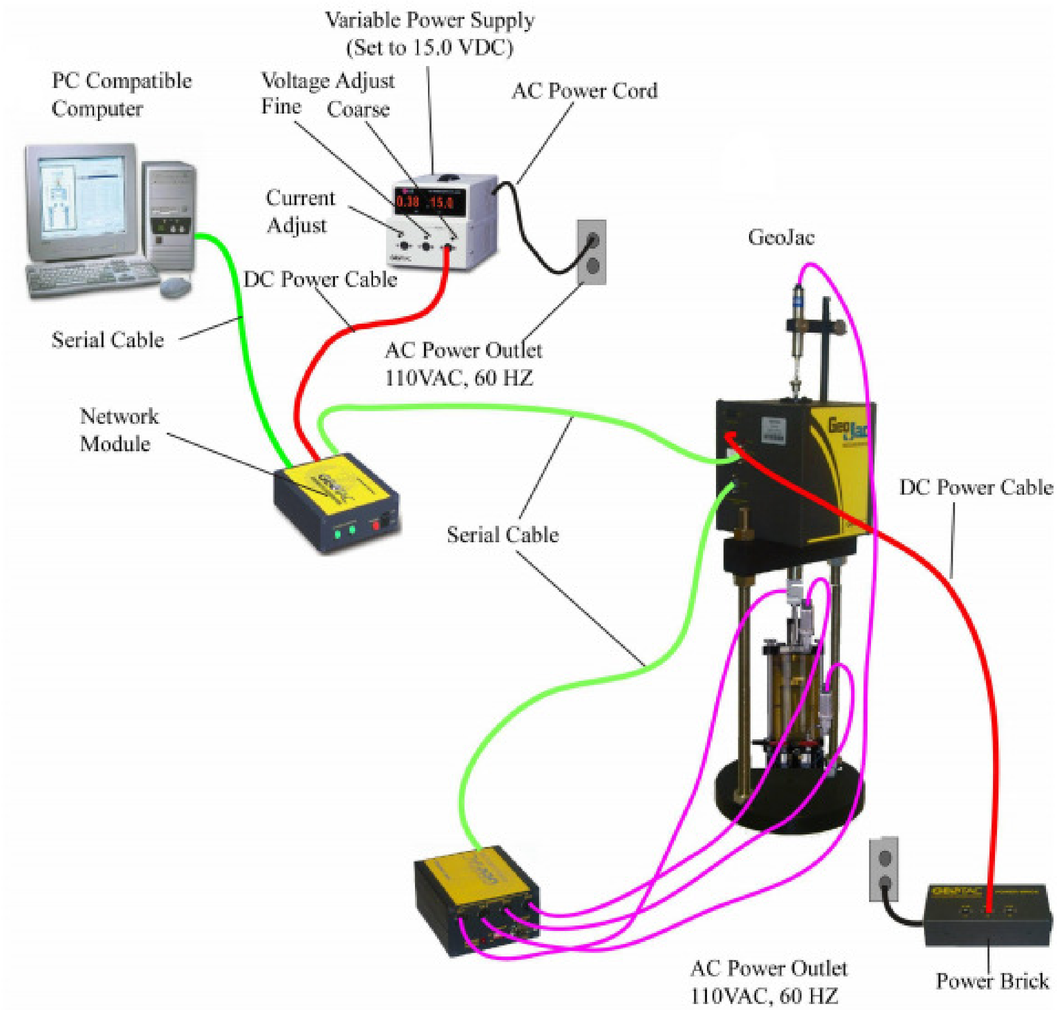

Figure 3-2: Configuration of Triaxial Testing Equipment (GEOTAC, 2003)

3.3.1 GEOTAC

GEOTAC is part of Trautwein Soil Testing Equipment Company. This combination of products, Sigma-1 and GeoJac automated systems, is designed to meet the needs of geotechnical laboratory testing. TestNet uses Distributed Data Acquisition and Control to collect data and convert analog signals into digital before transmission, which allows most information to be distributed from a sensor by a single cable connected to the sensor and the PC compatible computer. Sensors used in this experiment include a load cell, cell pressure and pore pressure transducers, and a deformation sensor. The user interface allows sensor measurements to be displayed at all times as illustrated in Figure 3-3. The test specimen shown in Figure 3-4 illustrates the typical set up for flushing, swelling, back pressure saturation, consolidation, and hydraulic conductivity tests. These tests take at least a week to complete so it is important to have a reliable data acquisition system to monitor the changes in the specimen efficiently until tests are complete.

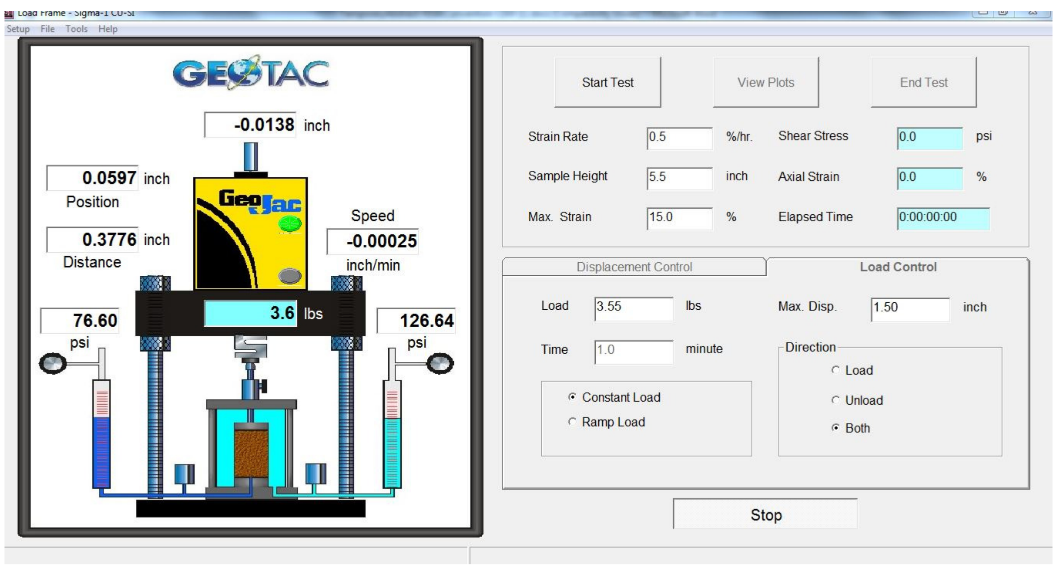

Figure 3-3: Sigma-1 CU Interface

Figure 3-4: Test Specimen

3.3.2 Pressure Panel

Many stages within testing required use of the Trautwein pressure panel. The panel received deaired water from Geoken nold dearator. Air pressure was used to deliver cell pressure to the specimen while water was used to fill the cell and deliver pore pressure to the specimen. Figure 3-5 and Figure 3-6 show the pressure panel and dearator respectively. Manual controls on the pressure panel and dearator were used to empty and fill the tank to supply annuli and pipets for cell pressure, influent, and effluent, to fill the triaxial cells, and clean the triaxial base of any leftover material in the pore pressure valves after removing specimens.

Figure 3-5: Trautwein Pressure Panel

Figure 3-6: Geoken Nold Dearator

3.3.3 Flexible Wall Permeameter: Triaxial Cell

A triaxial cell is commonly used in geotechnical testing for consolidating and shearing specimens. In this experiment the triaxial cell is used to consolidate specimen and determine hydraulic conductivity. This experiment will determine if triaxial cells can function as a proper flexible wall permeameter (typical flexible wall permeameter specimens have a H/D/ of 1 while standard triaxial specimens have a H/D of 2). If accurate hydraulic conductivity values can be measured using the triaxial cell, then multiple properties of soil (shear strength, cyclic strength, hydraulic conductivity, etc.) could be determined from a single specimen in a triaxial cell. The triaxial base has 4 valves that attach to a specimen on its base in order to regulate pore pressures and allow flow to go through the specimen. Two valves can deliver pore pressure from the bottom of the specimen and the other valves deliver pore pressure from the top of the specimen. In this experiment, the water was delivered to the specimen from the bottom of the specimen propagating upwards during the flushing and hydraulic conductivity measurement stages. The valve providing water into the specimen will be denoted by the term influent valve for the remainder of this chapter; the valve that expels flow from the specimen to the pressure panel will be denoted as effluent valve for the remainder of this chapter. Figure 3-7 shows a specimen on the triaxial base.

Figure 3-7: Specimen in Mold on Triaxial Base

3.3.4 Calibrating Sensors

The sensors used in this experiment were calibrated to represent units that were used in this study. The linear variable differential transducer (lvdt), external load cell, pore pressure transducer and cell pressure transducer voltage measurements were calibrated to inches, lbs, kPa, and kPa respectively. Three experiments were run simultaneously which required having three sets of sensors. Following are the calibration graphs used to determine calibration factors in this study.

Linear variable differential transducers are used to determine the amount of deformation specimens undergo while testing by measuring the axial displacement.

Figure 3-8 through Figure 3-10 show proper calibration factors used for each lvdt in this study. Axial displacements of specimens were within the range used for calibration.

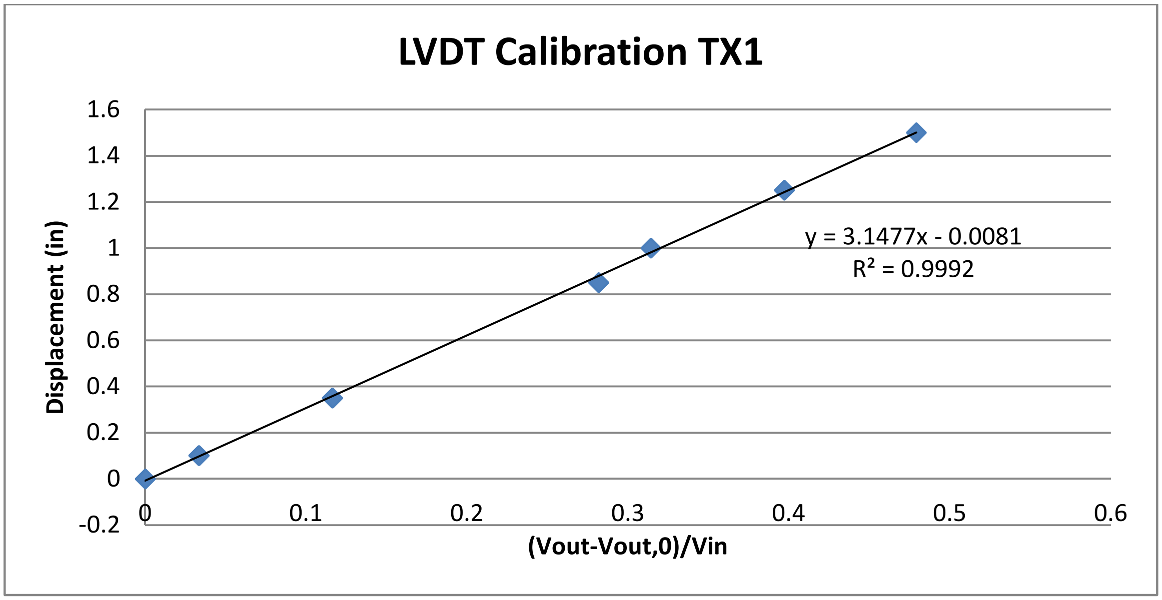

Figure 3-8: LVDT Calibration Triaxial Station 1

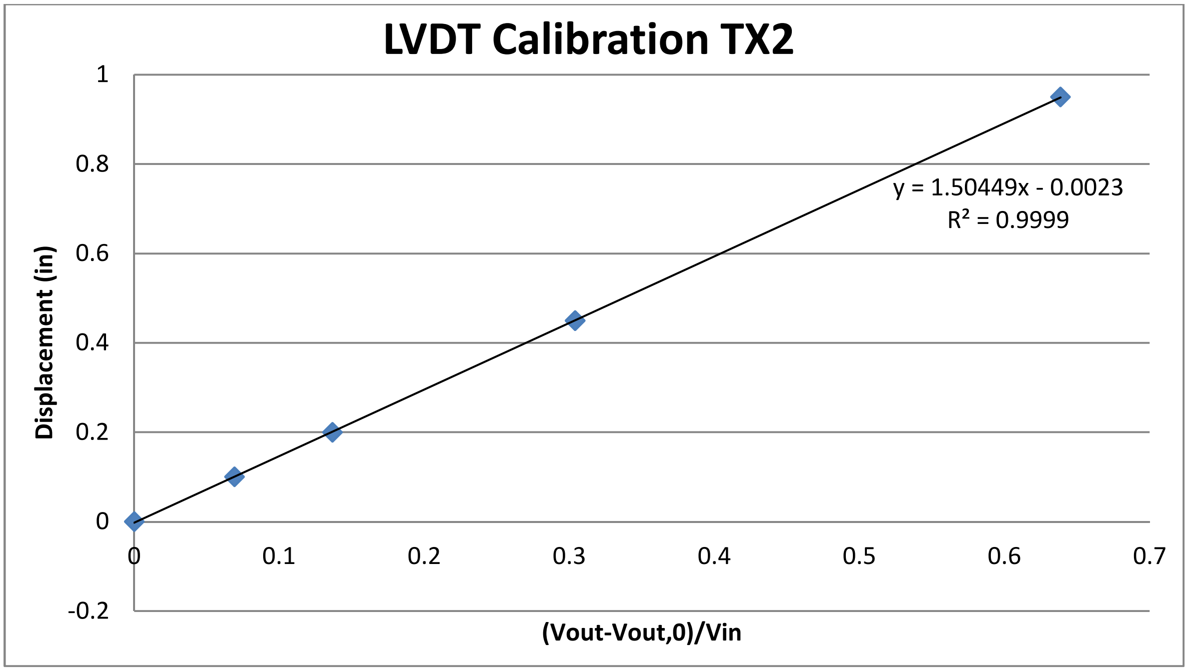

Figure 3-9: LVDT Calibration Triaxial Station 2

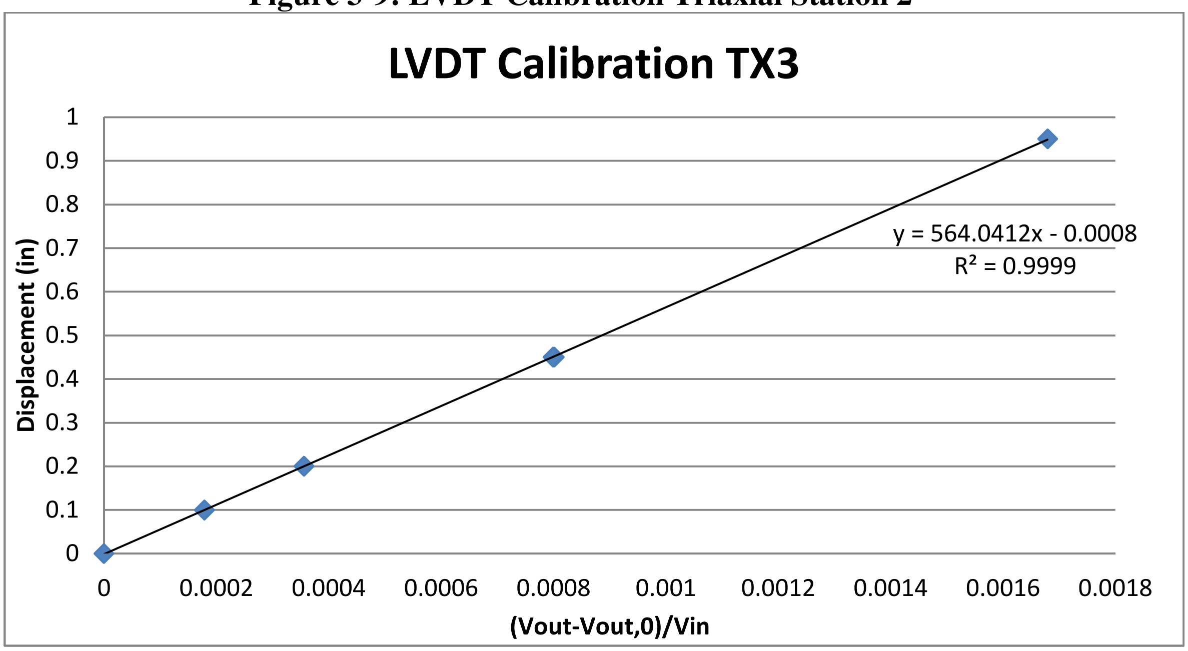

Figure 3-10: LVDT Calibration Triaxial Station 3

External load cells are used to determine magnitudes of loads transferred from the loading pistons to specimens while testing. In this study, loads were determined as a function of cell pressures and input manually into Sigma-1CU. Since the specimens were not sheared, the load cells were only used to measure the applied vertical force to account for uplift compensation. This is yet another modification from standard flexible wall testing procedures where the specimen is not in contact with a vertical piston and there is no need for uplift compensation calculations. However, when testing dry-mixed specimens, the vertical piston is needed to calculate volume changes to the specimen during flushing and hydration/swelling stages. This is done by measuring the vertical strains and assuming isotropic elastic behavior in the specimen. Hydration/swelling stages are when the specimen is not saturated enough to rely on water movement in and out of the specimen to account for volume changes in the specimen. Figure 3-11 through Figure 3-13 show proper calibration factors used for each external load cell in this study. External loads transferred to specimens were within the range used for calibration.

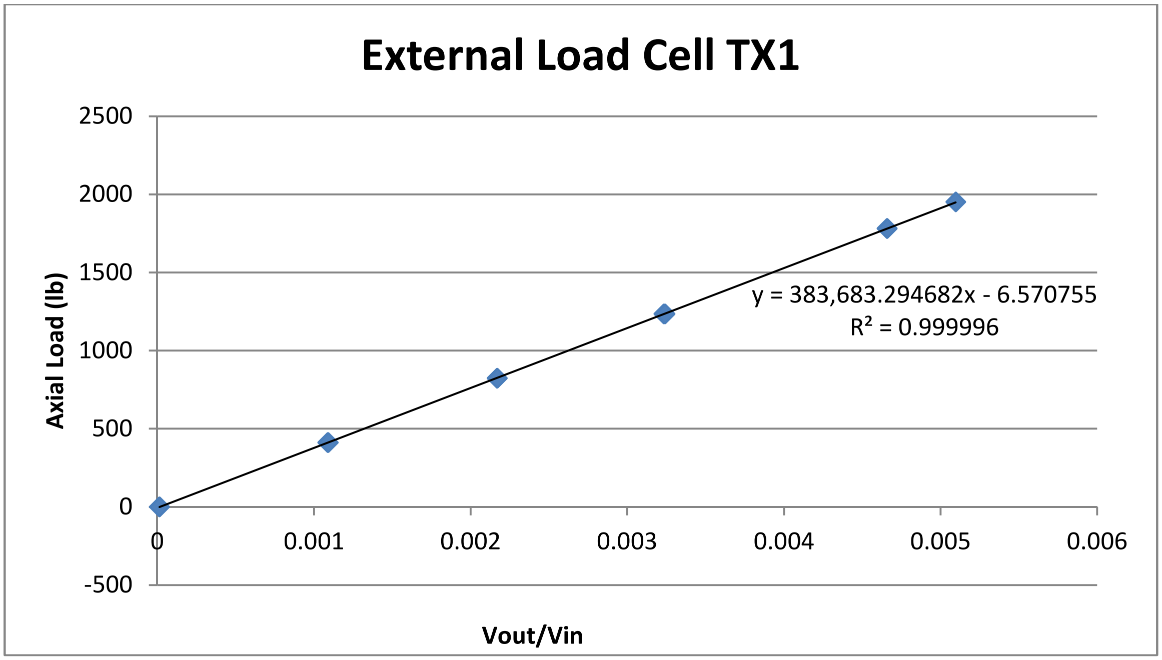

Figure 3-11: External Load Cell Triaxial Station 1

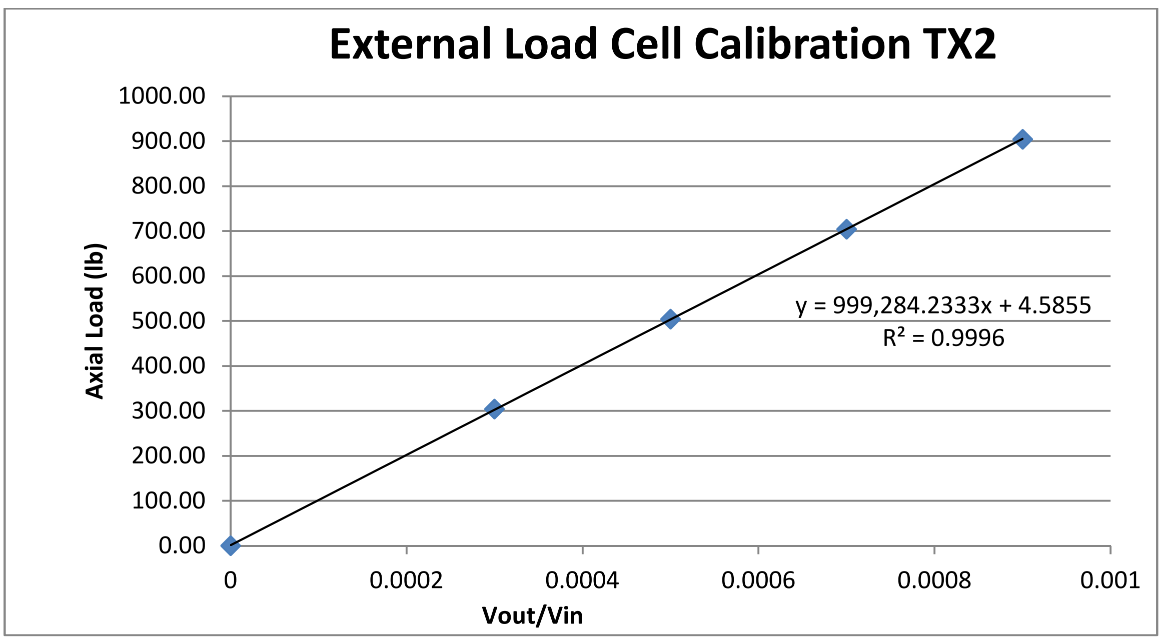

Figure 3-12: External Load Cell Calibration Triaxial Station 2

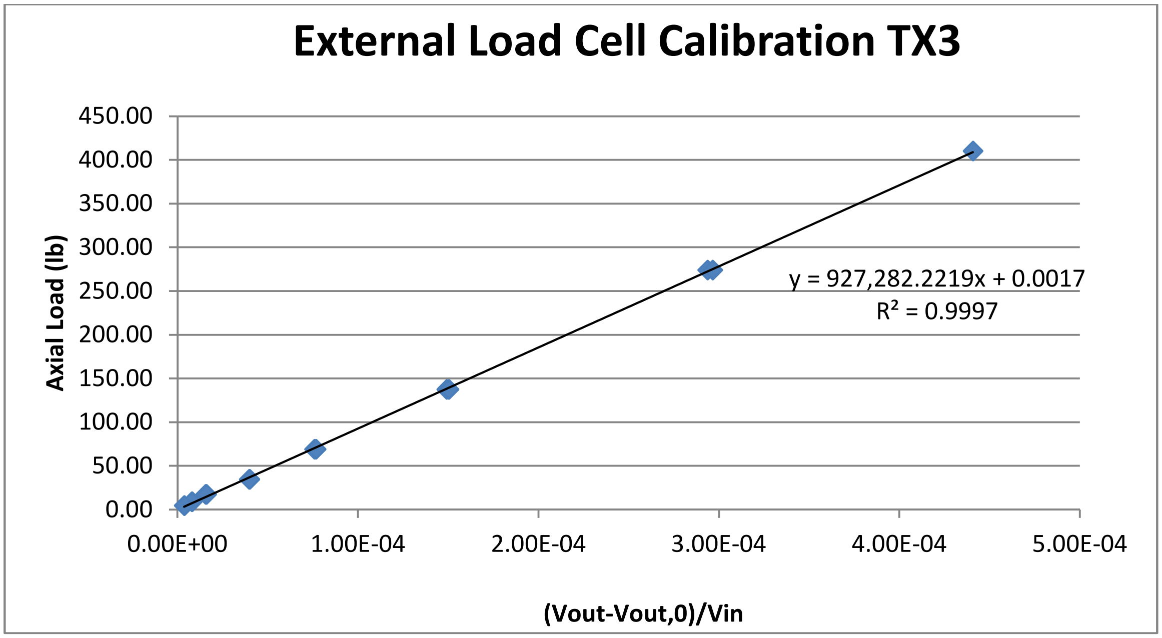

Figure 3-13: External Load Cell Calibration Triaxial Station 2

Pore pressure and cell pressure transducers are used to determine magnitudes of pore and cell pressures transferred from the pressure panel to specimens while testing. Although the Sigma-1CU interface displays units of psi and calibration factors were derived for psi, in this study units were converted to kPa using the calibration factor such that values displayed on the interface were in units of kPa. Calibration factors determined for psi were converted to kPa using the conversion factor 6.8947 kPa/psi. Figure 3-11 through Figure 3-13 show proper calibration factors used for each pore pressure and cell pressure transducers in this study. Pore and cell pressures delivered to specimens were within the range used for calibration.

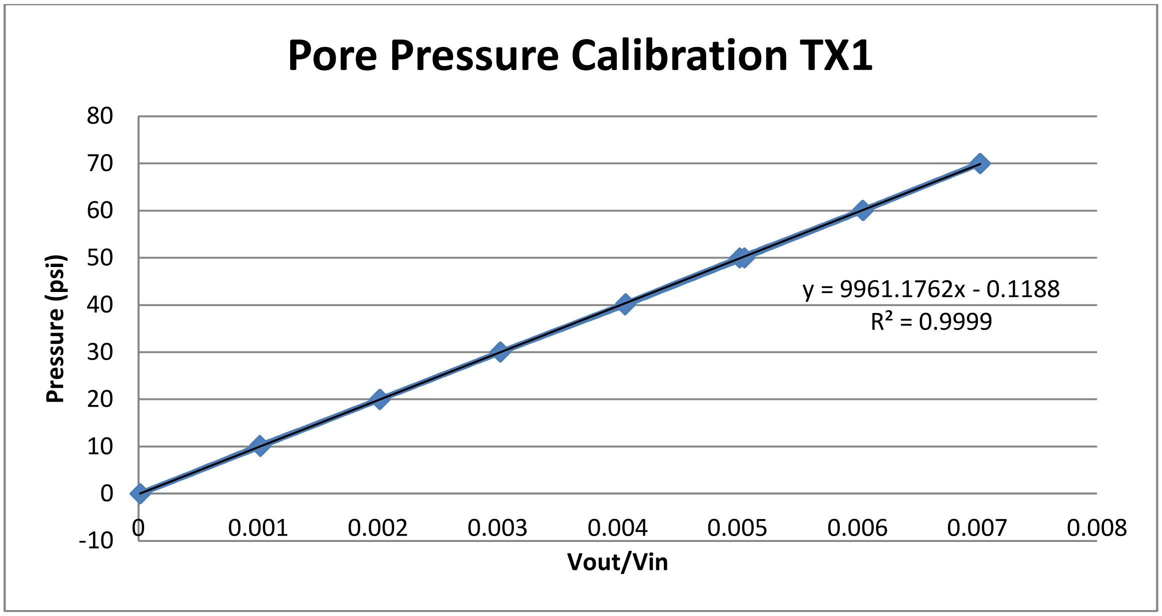

Figure 3-14: Pore Pressure Transducer Calibration Triaxial Station 1

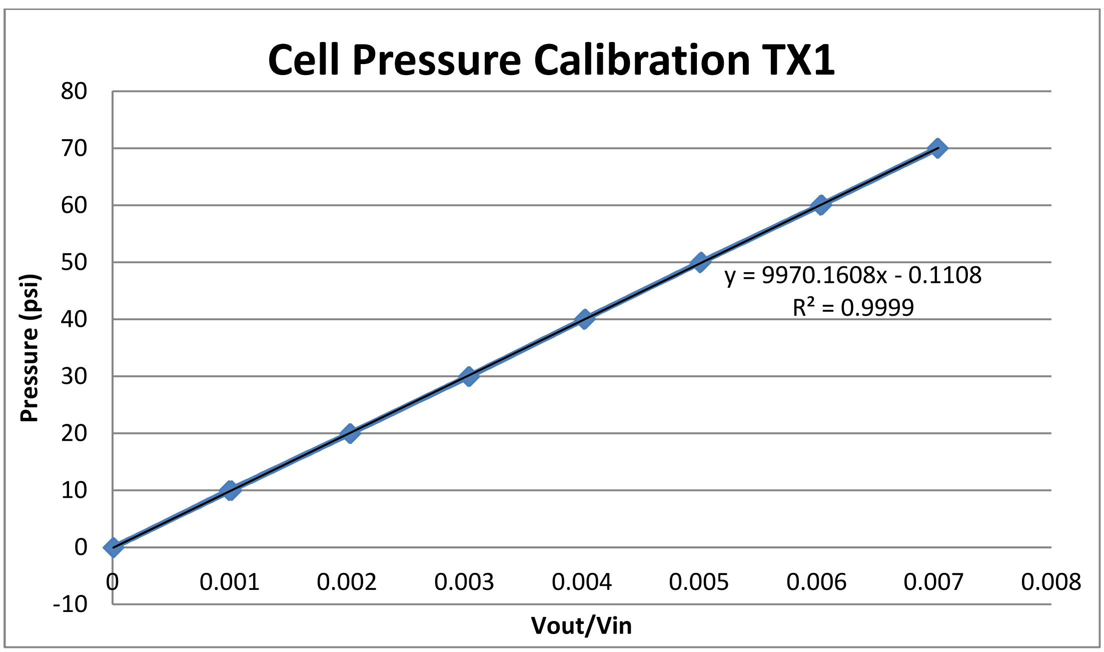

Figure 3-15: Cell Pressure Transducer Calibration Triaxial Station 1

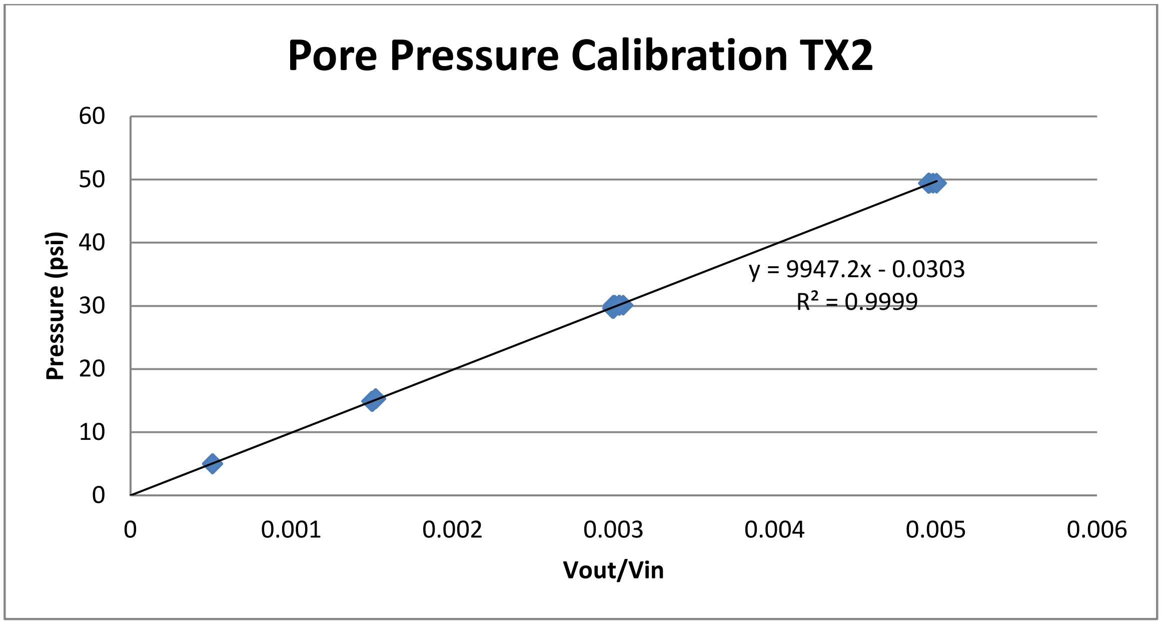

Figure 3-16: Pore Pressure Transducer Calibration Triaxial Station 2

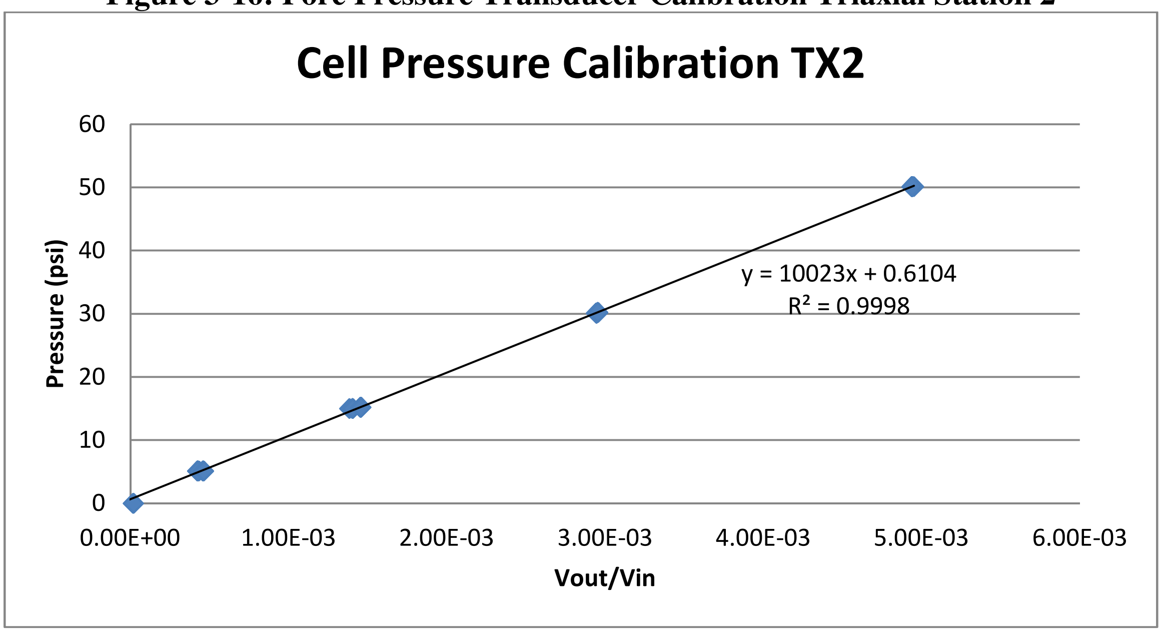

Figure 3-17: Cell Pressure Transducer Calibration Triaxial Station 2

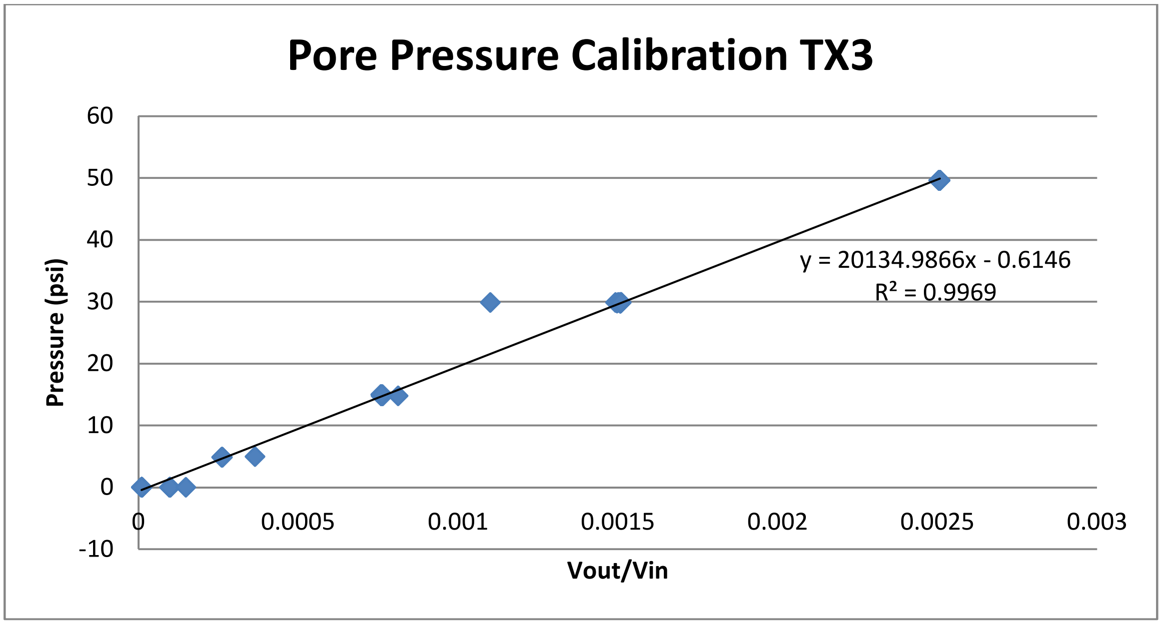

Figure 3-18: Pore Pressure Transducer Calibration Triaxial Station 3

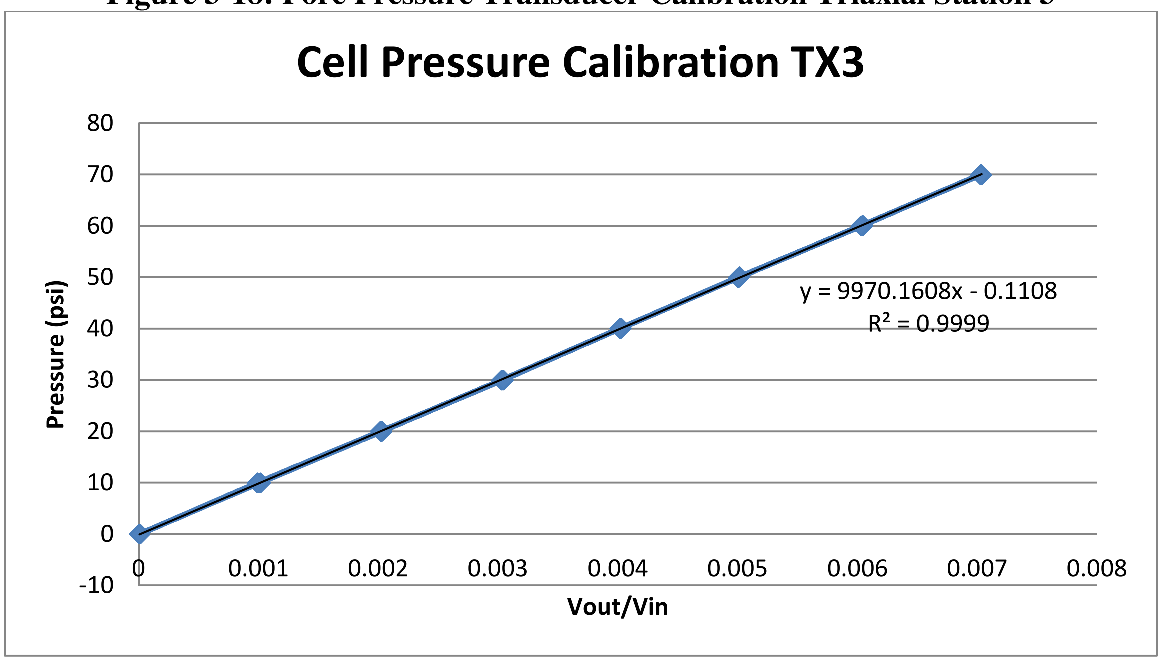

Figure 3-19: Cell Pressure Transducer Calibration Triaxial Station 3

3.4 PREPARATION OF SPECIMENS

Preparation of specimens is a dynamic process of working with the materials and equipment to develop conditions suitable for testing. The goal is to create a specimen that is fully saturated to represent the saturation of a cutoff wall in the field and the case where hydraulic conductivity is highest. Before beginning any preparation of materials, preparing equipment for testing is essential. An initial step is to turn the deaired water tank from vacuum to vent. This will allow use of the tank to distribute water to the cell. Turning on the Sigma-1 CU program and all transducers initiates recording data to minimize scatter when attaching valves to specimen. All transducers, tubes, valves, etc. should be clean and dry; any sand or bentonite particles from prior tests should be removed.

Before using a new membrane to hold the specimen, clean it because it might have powder in it. Cut the membrane to the length desired. Measure the length of two platens, two porous stones, and two filter papers, make sure filter paper is of a diameter exactly matching that of the porous stone. Measure twice the thickness of membrane. Apply grease on sides of bottom platen; put the porous stone and then the membrane on the bottom platen. Place three O-rings on the outside of the membrane to secure it to the platen. While putting on O-rings do not apply pressure on porous stone. Put on split mold. Put O-rings on top of split mold and roll top of membrane over, stretching membrane so that it takes the shape of inner mold. Apply vacuum between the split mold and membrane to have the membrane adhering to the inside of the mold. Place filter paper over the porous stone to protect the porous stones from fines migrating from the specimen and reduces chances of clogging the porous stones. Prepare the soil mixture according to dry mixing or wet mixing as detailed in the following section then follow the corresponding specimen preparation specified below.

3.4.1 Dry Mixing

Recall in Chapter 2 that dry mixing is the process of mixing dry amounts of sand and bentonite together; no water is added to the mixture. Dry mixing is done by first weighing the bowl to be used for mixing and adding sand to the bowl around 1000 grams. Use Equation 3-1 and Equation 3-2 to determine the amount of dry bentonite used to achieve the desired bentonite content, where M_b is mass of bentonite, M_s is mass of sand, bc is the percentage of bentonite content desired in the mixture, $M_{dry\ b}$ is the mass of dry bentonite, and wc_b is the percentage of natural water content of bentonite. Recall the natural water content of bentonite used in this study is 6.7%.

$$\boldsymbol{M_{dry\ b} = M_s \times \frac{bc}{100\%}} \qquad \textbf{Equation 3-1}$$

$$\boldsymbol{M_b = M_{dry\ b} \times \left(1 + {}^{wc_b}/_{100\%}\right)} \qquad \textbf{Equation 3-2}$$

To create the specimen within the mold, start with all lines, porous stone and filter papers completely dry. This approach would prevent the bentonite to have access to water before the flushing stage starts and therefore, prevent a filter cake from forming that would prevent water flushing. After thoroughly mixing the sand with bentonite, air pluviate the sand from a constant height of about 5 cm, in a circular motion, moving from the perimeter of the specimen to the center. Soil at the top of the specimen must have a flat surface; soil can be smoothed and leveled by using a small spatula, otherwise while applying the load it could tilt the porous stone and break it. Put the filter paper on, then the porous stone. Securely attach both effluent pressure valves from the triaxial base to the top platen. This allows the vacuum to reach the specimen. Put the top platen in such a way that valves attached to the platen cross each other (to minimize the twisting of the top drainage lines). Level the top platen using a level. Attach the vacuum line to the specimen from the influent pressure valve. Attach the pore pressure transducer to the second influent pressure valve. Tighten vacuum and pore pressure transducer connections with wrench.

To remove the split mold, apply vacuum to the specimen. Make sure all the valves are closed while applying vacuum (except bottom inlet valve and pore pressure transducer valve). Increase the vacuum to 25 kPa, which can be confirmed by the Sigma-CU program reading of the pore pressure transducer. Close the vacuum supply valve and monitor the vacuum reading in the pore pressure transducer. If the vacuum is not constant or if it is constantly decreasing at a high rate, this is an indicator that there is a leak in the specimen. If there is a leak, check the membrane at the top and sides looking for holes; make sure pore pressure tubes are connected, examine O-rings. Re-create sample until no leak is detected. Close the vacuum supply of split mold. Remove the split mold.

Take three height measurements of the specimen from the base of the triaxial cell to the top of the top platen and three diameter measurements of the specimen along its height. From the averages of these values, calculate the height and diameter of the sample by subtracting the length of two platens, two porous stones, and two filter papers (from the measured total height to get the net height of the specimen) and by subtracting twice the thickness of the membrane (from the average diameter to calculate the net diameter of the specimen), respectively.

Clean the bottom of the triaxial cell so that there are no soil particles. If needed, apply a thin film of grease on the base of the cell on top of the O-ring to create a water tight seal between the base and cell. Place the cell, the top of the cell and the three holding rods to complete the cell assembly. While tightening the holding rods, make sure the piston is not locked to avoid shear the specimen. Be sure to tighten holding rods in increments so that each holder is level with the others, without one being closed down tighter than any of the others. Before filling the cell with water, make sure the pressure release valve is open at the top of the triaxial cell to prevent any undesired pressure from building up in the cell. Fill the cell with water until it covers the top of the specimen. Make sure the valve used to transfer water is dry of water before using it to apply cell pressure. Zero cell pressure transducer and place into cell. The cell pressure of the tank with water in it is about 3 kPa. To avoid applying pressure to the specimen while adjusting the load cell, lower the piston to achieve contact with the top platen and then lock the piston; lower down the load cell to just touch the piston, this can be seen by a sudden increase in the load cell. Reduce the load on the specimen to a minimal seating load to make sure the external load cell has contact with the specimen and then unlock the piston. Failure to ensure contact of the load cell with the piston means the load will not affect the specimen and changes in height (and volume) will not be recorded properly. Zero the LVDT sensor to reflect net vertical displacement in the specimens during the remaining stages of testing.

Flushing CO2

Use the CO2 tank in the lab, open to allow CO2 to flow through the valves. Adjust pressure of CO2 exiting tank by placing the flow line in a beaker with water in it to make sure appropriate amount of CO2 will be entering the specimen. Adjust pressure such that approximately two bubbles per second are being expelled into the beaker. Dry the valve after removing from water. Create a new task called “Flushing CO2” with readings every 5 minutes, put this in a folder titled “ Effective Stress Amount kPa-Month/Day/Year” where effective stress amount is typically 50, which denotes the maximum consolidation effective stress.

Connect CO2 line with influent pressure valve that was used to apply the vacuum. Connect a tube to one of the effluent PP valves and place the other end of the tube into the beaker filled with water to see bubbles coming out. The rate of bubbles coming out should still be approximately two bubbles per second. The other effluent pressure valve is closed. A slight increase in pore pressure will occur due to the CO2 flushing; adjust cell pressure to make sure the effective stress is still 25 kPa (difference between the CP and PP). At this point, CO2 is replacing air; air bubbles are coming out of the specimen, into the beaker. This step is necessary because it is easier to dissolve CO2 (rather than air) in water under pressure while saturating the sample. CO2 Flushing should last for at least 20 minutes. If bubbles are leaving the specimen at a rate higher than CO2 is entering, or if bubbles are generated without CO2 being flushed through the specimen, this implies that there is a leak between the specimen and the cell. If a lot of bubbles come into the beaker at once and then stop, this may mean one of the porous stones are moist. This will affect results; stop testing and let the porous stone dry (in oven for a few hours or on the table for 24 hours). Once CO_2 flushing is complete, turn off the influent pressure valve connected to specimen to discontinue CO_2 flushing into specimen. Turn off the CO_2 tank. Remove CO_2 valve and drain any remaining CO_2 in the lines.

Flushing Water

Create a new task called "Flushing H_2O" with readings of about every 1 minute, put this in the folder titled " Effective Stress Amount kPa- Month/Day/Year." Using the pressure panel, fill the annulus and pipette of pore pressure position labeled "Pore Pressure- influent" with water by switching to "tank" on the position of the panel and making sure top dial is on "Both". Make sure to turn the valve to tank slowly since the tank is under a constant pressure and to avoid over filling. Turn from "tank" to "off" once full. Connect the influent pressure line to the influent pressure valve on the triaxial base that was used to flush CO_2. Turn the bottom dial on the position of the panel from "off" to "on" to let water fill the PP influent line before connecting it to the base of the triaxial cell. Control the water flow rate through the bottom valve on the panel to ensure that water is not flowing too fast through the specimen to reduce "local liquefaction" within the sand specimens and bentonite flushing out for the dry-mixed speicmens. Water flow rate can be evaluated based on the rate of bubbles coming out or rate of water level drop in the pipette.

For flushing sand-bentonite mixtures, increase pressure on pressure panel to speed up the process of flow, be sure to increase cell pressure by half of the increased pore pressure to maintain 25 kPa effective stress on the specimen (the effective stress will be lower at the base and higher at the top, but on average, should remain equal to 25 kPa). It is important to maintain a constant flow rate during flushing the dry mixed specimens to avoid full hydration of the bottom portion of the specimen before flushing out the top, which will create large contrast in the hydraulic conductivity of the top versus bottom halves. When the specimen is halfway flushed, use a very small screwdriver to bleed out any trapped air in the pore pressure transducer. Be very careful when placing the screw back into the transducer, it should take no force, simply twist it and make sure that it is being screwed back in aligned with the hole, not on a slant.

Record the pipet volume reading when bubbles are no longer coming out of effluent pressure valve, and instead water is coming out. Once drops of water are coming out into the beaker, this denotes one pore volume of water was flushed through the specimen. Flush another pore volume through specimen; close the effluent valve that was connected to the beaker and open the second effluent valve to drain any air in the second top drainage line. The water flushing stage is completed when all the air is flushed ont of the second top drainage line. Turn on the bottom dial on the pressure panel position labeled “Pore Pressure-outflow” and let water go through the effluent PP line. Once drops of water are coming out of the effluent line, connect to the effluent valve at the base of the triaxial cell. This saturates the line before attaching it to the specimen. The flushing water should last 20 minutes. If the specimen is not required to undergo a swelling stage, then proceed to backpressure saturation as described in Section 3.4.3.

Swelling

For some specimens, a swelling stage is included between end of water flushing and applying backpressure to enhance and monitor bentonite swelling within the pore space. For the swelling stage, make sure the water level in the pore pressure (outflow) pipette is low enough so that if water is expelled from the specimen, there is enough room for it in the pipette and it won't overflow. If specimen is to swell for 48 hours, turn bottom dial on the position of the panel from "on" to "off" for influent pressure. Record the pipet volume reading in the effluent pressure. Leave this valve open to allow specimen to release or absorb more water. This stage can also be referenced as seating time. If specimen is not swelling, proceed to back pressure as described in Section 3.4.3.

3.4.2 Suspension Mixing

Recall in Chapter 2 that suspension mixing combines water and bentonite to create slurry to add to the sand. Water and bentonite are mixed using a high shear mixer shown in Figure 3-20, causing bentonite to suspend in water.

Figure 3-20: Hamilton Beach High Shear Mixer with timer

To prepare materials for testing, soak porous stones and filter papers in water**.** Flush one of the influent pressure valves and one of the effluent pressure valves. Unlike the dry method, the suspension method requires that all valves are flushed with water except for the valve that will be attached to the vacuum.

To prepare the mixture place approximately 1250 grams of sand in a mixing bowl. Calculate the amount of dry bentonite added to the mixture using the mass of the sand, also taking into consideration that the water content of stored bentonite is 6.7%. Calculate the mass of the water added to the specimen using Equation 3-3 through Equation 3-8.

$$Gs \times w = S \times e \qquad \textbf{Equation 3-3}$$

$$v_{void} = \frac{w \times m_{sand}}{\rho_{water}} \qquad \textbf{Equation 3-4}$$

$$v_{bentonie} = \frac{bc \times m_{sand}}{Gs_{bentonite} \times \rho_{water}} \qquad \textbf{Equation 3-5}$$

$$v_{water\ added} = v_{void} - v_{bentonite} - \frac{w_{bentonite} \times bc \times m_{sand}}{\rho_{water}} \qquad \textbf{Equation 3-6}$$

$$m_{water\ added} = \frac{v_{water\ added}}{\rho_{water}} \qquad \textbf{Equation 3-7}$$

$$m_{w.b.added} = \frac{bc \times m_{sand}}{Gs_{bentonite} \times \rho_{water}} \times (1 + w_{bentonite}) \qquad \textbf{Equation 3-8}$$

Where *Gs* is specific gravity of sand, *w* is water content of sand (if completely saturated and no bentonite is added), *S* is saturation of sand if no bentonite is added (assumed 100% for this analysis), *e* is the desired skeletal void ratio to determine the necessary water content of the sand, v_{void} is the volume of skeletal voids in the specimen, m_{sand} is the mass of sand, ρ_{water} is the density of water, $v_{bentonite}$ is the volume of bentonite particles in the mixture, therefore filling some of the volume of voids, $Gs_{bentonite}$ is the specific gravity of bentonite ,$w_{bentonite}$ is the water content of bentonite as stored, *bc* is the desired bentonite content of the mixture (dry mass of bentonite divided by dry mass of sand), $v_{water\ added}$ is the volume of water that needs to be added, $m_{water\ added}$ is the mass of water that needs to be added and $m_{w.b.added}$ is the total mass of bentonite to be mixed with the water to for the bentonite slurry.

Add half of the water into a mixing cup, add the total amount of bentonite into the mixing cup, and add the last half of water into a mixing cup. Proceed to mix the water with bentonite using the high shear mixing. The total mixing consists of at least three intervals of 5 minutes; scrape the sides of the container and its base between each interval to prevent having any flocks attached to the mixing cup. Mix until the suspension reached a consistency is that of a milkshake without any visible non-uniformities; if needed, add mix for additional 5 minute intervals. Add the bentonite suspension to the sand, and mix with a spatula to reach a uniform mixture. When mixing, avoid lifting up the mixture from the bowl but rather mix using a downward push to reduce volume of entrapped air. Take 4 samples of the mixture, each about 25 grams, and run water content and bentonite content tests on them as described later in Section 3.5.2.

Place 1/5 of wet mixture into membrane with mold after inserting porous stone and filter paper, use compaction rod to compact the mixture. Add mixture in increments of 1/5 until membrane is full, tapping 20 times with the compaction rod per layer. Scarify the top of each lift before placing the soil for the second lift. Place top filter paper and porous stone on specimen. Before removing mold, flush pore pressure transducer by allowing water to flush from the influent valve while the bleed screw is loose on the transducer. After flushing transducer turn off influent valve. Put on the top platen, connect the flushed effluent pressure line, flush water through the top platen before connecting the dry effluent pressure line to the top platen so that the connection inside the top platen is filled with water. Be sure that all valves are closed except the valve attached to the pore pressure transducer. Apply vacuum to the effluent valve that is not saturated; wait until vacuum is throughout the entire specimen by noticing the pore pressure transducer measurements. Close the vacuum supply valve and monitor the recorded value of negative pore pressure. If the vacuum is decreasing, then there is a leak in the specimen; disregard the specimen, remove it from the triaxial cell and prepare a new specimen. If there are no leaks, remove the split mold and take measurements of specimen. Finish assembling the triaxial cell and fill cell with water. Proceed to assembling the triaxial, locking the piston, achieve contact between load cell and piston, and zero LVDT similar to the detailed procedure listed in Section 3.4.1.

Start gradually increasing the cell pressure to 25 kPa, while allowing water from influent valve to replace vacuum (after closing the top line connected to the vacuum). Once water stop entering the specimen, open the vacuum line effluent valve and flush water through the specimen until effluent valve is completely flushed with water. Flush water through the effluent pressure line before connecting to the effluent valve at the base of the triaxial cell. Apply a small gradient by increasing the influent pressure to allow the water to flow, if necessary. Flush some water through the second top line into a beaker. Following this, proceed to back pressure saturation stage as described in Section 3.4.3

3.4.3 Back Pressure Saturation

Back pressure saturation is the process of compressing the size of entrapped air (or CO_2) bubbles and partially dissolving them in water through increasing pore pressure and cell pressure simultaneously, such that there is no change to the effective stresses. To begin this process, create a new task called “Back pressure” with readings of about every 5 minutes, put this in a folder titled “ Effective Stress Amount kPa- Month/Day/Year” where effective stress amount is typically 50, which denotes the maximum consolidation effective stress. Close both effluent pressure valves. No change in pore pressure should occur during this time; if the pore pressure changes, then there is a leak in the specimen and the test should be aborted. To simplify the testing procedures, the effluent pressure valves are closed during back pressure and B-value stages. This would reduce the required pressures to be adjusted from three (cell pressure and influent and effluent pore pressures) to two (cell pressure and influent pressure). In load control, put the value of uplift load corresponding to the next increase in cell pressure and then press start. Increase the cell pressure and back pressure simultaneously so that effective stress remains constant. For example if effective stress is at 25 kPa now, then increase back pressure (pore pressure influent) to 25 kPa and cell pressure to 50 kPa. A drop in the pipet with time will occur, let sit for 5 minutes for the sands, 10 minutes for sand-bentonite mixtures. With increase in back pressure, CO_2 gets dissolved in the water and then pores fill up with water, which is depicted by a drop in water level in pipet. Again increase the back pressure to 75 kPa, increase cell pressure to 100 kPa. Before each stage, change the applied vertical load to correspond to the uplift at the new cell pressure.

Again increase back pressure (BP) and cell pressure (CP), do the same thing until no drop in water level is observed. If the specimen is prepared properly, a BP is 200 kPa should be efficient to achieve the desired B-value. The entire back pressure can be extended to 1 to 2 hours by waiting longer in between increasing the back pressure to allow the water in the pores to reach equilibrium before increasing to the next level. In some cases BP may need to exceed 200 kPa and overall time may need to exceed 24 hours.

3.4.4 B-value Check

Skempton's (1954) B-value, which is a pore pressure coefficient, is used to approximate saturation of each specimen. The B-value is the ratio of the change in pore pressure corresponding to an increase in cell pressure under undrained conditions. Specimens with B-values greater than 0.95 have acceptable saturation in this experiment as outlined in ASTM D4767. In order to check the B-value, close the BP valve. Now increase the CP by 50 kPa and then notice the increase in the pore pressure. Calculate the B-valueI as the ratio of the increase in BP over the increase in CP. If the B-value is less than 0.95 for sands and sand-bentonite mixtures, return CP to original pressure (should be only 25kPa greater than BP) and open the BP (influent) valve. Increase BP and CP, and record water changes. Repeat previous step at a maximum of two to three times to obtain the desired B-value. Once the desired B-value is obtained, proceed to bridging the influent and effluent lines to allow water flow through the specimen.

3.4.5 Bridging Influent and Effluent Pressure on Pressure Panel

Influent and effluent pressure should be equal before testing the hydraulic conductivity of the specimen; this is to ensure that the gradients are controlled by the change in total head. With the influent and effluent pressure valves closed at the base of the triaxial cell, record the water level in the BP pipet. Increase the effluent pipet water level to match that of the influent pipette by switching the dial from “off” to “tank”. Record the BP pressure reading on the panel for the influent pipette. Increase the effluent pressure reading to this same value so that the pressure of influent and effluent are equal. Connect the pressure source to both pipettes by bridging them on the pressure panel to eliminate any partial pressure difference between the two lines (this is one feasible for tests where the maximum hydraulic gradient can be achieved by controlling the water levels in the pipettes and doesn’t require any additional pressure head in the influent line). Open both pore pressure valves on the triaxial cell to allow pressures to equilibrate and water to balance. At the end of bridging the pipettes, proceed to consolidating the specimen to its final effective stresses during testing.

3.4.6 Consolidation

Consolidation is the process of decreasing soil volume by expulsing water due to an increase in total stresses. At the conclusion of consolidation, the change in total stresses is converted to a change in effective stresses and all excess pore pressures are dissipated. Begin consolidation by first creating a new task called “Consolidation” using the Consolidation reading schedule, put this in a folder titled “Effective Stress Amount kPa- Month/Day/Year.” With both pore pressure valves closed on the specimen, increase the cell pressure by 25 kPa (for a final effective stress of 50 kPa) and adjust the vertical load to compensate for the additional uplift forces. Open the pore pressure valves and allow consolidation to occur while monitoring the changes in height of the specimen. The consolidation is concluded when no more volume changes are recorded and the specimen reaches equilibrium under its new effective stresses. For the clean sand tests, the hydraulic conductivity was measured at multiple effective stresses; the same procedure was used with stresses increased in stages to reach the final target effective stress. At the conclusion of consolidation, proceed to running the hydraulic conductivity tests

3.5 HYDRAULIC CONDUCTIVITY TESTS

Falling head rising tail tests were conducted in compliance with ASTM D5084-10 with an exception that the height to diameter ratio of specimens is two and not one. The height of each specimen is approximately 140 mm and the diameter approximately 70 mm. Hydraulic gradients used did not exceed 2 as the recommended maximum hydraulic gradient for a hydraulic conductivity of 10^{-5} cm/s.

3.5.1 Hydraulic Conductivity Test

To begin the hydraulic conductivity testing, close both influent and effluent pressure valve on specimen and pressure panel. Drain water from the effluent pipet so that there is 10mL difference or greater in between the effluent and influent volume readings. A 10mL head difference corresponds to a total head difference of 11.5 cm and a hydraulic gradient of 0.8-0.9, depending on the final height of the individual specimen. Record the water level in both effluent and influent pipettes before starting the test. Open effluent and influent valves and simultaneously begin timer to record flow versus time.

At this point the water from the influent pipet is flowing through the specimen to the effluent pipet.

Take readings after volumes of water in increments of 0.5 mL have passed through the specimen. After each designated interval, close influent valve and stop timer. Record level of each pipet and reopen influent valve and simultaneously begin timer again. Do three readings for three trials. After first three readings for trial one, increase the head difference to 10mL or greater before starting the next trial. Do the same after three readings for trial two. When finish with test, make sure effluent pressure water level is equal to influent pressure water level. Open both valves. Hydraulic conductivity tests are terminated after influent and effluent volumes are equal in the pressure panel and four successive measurements of hydraulic conductivity are within $\pm$ 25% of their mean value.

3.5.2 Bentonite Content Analysis

Following hydraulic conductivity tests, it is necessary to confirm the bentonite content of the specimens. It is important to know the total bentonite content of each specimen, as well as the bentonite content of different sections of each specimen to determine uniformity of the bentonite throughout each specimen. Wet sieving is the process of using water to separate a mixture of particles based on particle diameter. It is advantageous to use wet sieving as opposed to dry sieving in this case because SBMs behave like a cemented sand once dried out and cannot be sieved in their dry state. Using water to break down the mixture allows the sand and bentonite particles to be separated.

Using the No. 200 sieve, bentonite is washed through the sieve, leaving only sand particles remaining in the sieve.

In order to conduct wet sieving tests, specimens are removed from triaxial cells after hydraulic conductivity testing is complete, pore pressure and cell pressure reduced and the triaxial setup disassembled (all this is be done with all drainage valves closed to retain specimen properties and geometry). Remove specimens from triaxial base, remove top platen, and top and bottom porous stones and filter papers. Cut the membrane using scissors, divide the specimen into three sections (top, center and bottom) and place the sections into pre-weighed bowls that are labeled to distinguish between specimens and sections of specimen. Weigh each section and place into oven for 48 hours. After 48 hours have elapsed, remove from oven and weigh each section. The difference of the mass of each section before oven placement and after oven placement is the mass of water. The mass of water can be used to determine the water content of each section to determine uniformity of void ratio across each specimen.

Each section is then placed in a pre-weighed No. 200 sieve that is labeled to distinguish between specimens and sections of specimen. Weigh each section in sieves as shown in Figure 3-21. This value represents the dry mass of sand and bentonite once the mass of the sieve is subtracted. Wash each section with water until no presence of bentonite is visible in each sieve. Bentonite will typically look like dark gray spots amongst sand, so washing should occur until no dark gray spots are visible. The pressure of water used should be low so that no mass of sand is lost, as this will cause misleading results. After washing each section, place into oven to dry for 48 hours. After 48 hours have elapsed, remove from oven and weigh each section. The difference in the mass of each section before washing and after oven placement is the mass of dry bentonite. The mass of dry bentonite divided by the mass of sand is the actual bentonite content. These values of bentonite content should be close to the bentonite content values used for creating mixtures prior to preparing each specimen.

Figure 3-21: Weighing Specimen in Sieve

Chapter 4: Results and Analyses

4.1 Introduction

The effects of bentonite swelling and uniformity on sand-bentonite mixtures is observed through changes in hydraulic conductivity, as properties of mixtures vary with each specimen. This chapter presents the results of hydraulic conductivity experiments conducted on dry-mixed and suspension-mixed specimens using three triaxial setups, and the water and bentonite content tests conducted after completion of hydraulic conductivity testing.

4.2 Specimen Parameters

Results from 7 sand specimens and 11 sand-bentonite specimens are presented. Properties of each specimen such as height and diameter, void ratio and relative density, and water content and bentonite content are provided. The calculations for bulk and skeletal void ratio, bulk and skeletal relative density, and hydraulic conductivity are illustrated. Lastly, the mixing method for each specimen is provided and measures used to quantify bentonite hydration and uniformity are described.

4.2.1 Properties of Specimens

Height and Diameter

The height and diameter of the specimens were not in compliance to ASTM for hydraulic conductivity standards; the specimens' height and diameter were both larger than the 25mm minimum, but the height to diameter of the specimens was on the order of

2, twice the specified ratio of 1. Table 4-1 and Table 4-2 show the height and diameter of sand specimens and sand-bentonite mixtures respectively. As shown in the tables, the height of specimens range from 130 mm to 150 mm, diameters range from 69 mm to 74 mm, and height to diameter ratios (H to D ratio) range from 1.8 to 2.0. The height to diameter ratios were close to 2 with diameters greater than 33 mm in accordance to ASTM standards for CU triaxial tests.

Table 4-1: Height and Diameter of Sand Specimens

Specimen #	Height mm	Diameter mm	H to D ratio
1	133.23	72.48	1.84
2	140.07	69.13	2.03
3	136.43	72.27	1.89
4	137.45	71.51	1.92
5	139.34	69.55	2.00
6	130.99	72.49	1.81
7	134.48	70.82	1.90

Table 4-2: Height and Diameter of SBMs

Specimen #	Height mm	Diameter mm	H to D ratio
8	138.97	74.06	1.88
9	141.92	73.13	1.94
10	147.64	72.91	2.03
11	149.70	72.80	2.06
12	152.02	72.77	2.09
13	147.98	72.80	2.03
14	149.78	72.48	2.07
15	145.57	72.13	2.02
16	149.58	72.89	2.05
17	147.17	73.74	2.00
18	156.41	73.43	2.13

Void Ratio and Relative Density

Properties such as void ratio and relative density provide better insight about the void space in each specimen. Void ratio is the ratio of volume of voids to volume of solids. While volume of voids is commonly comprised of air and water, in this study, the bentonite in the void space within the sand is also counted as part of the void space; this void ratio is often referred to as skeletal void ratio. Additionally, the bentonite is expected to swell and fill most of the remaining void space and can be treated as its own porous medium with a different void raito. Therefore, two void ratios are calculated for each specimen, the skeletal void ratio and the bentonite void ratio (usually referred to as clay void ratio). A third void ratio can be calculated, the bulk void ratio. The bulk void ratio of the specimen accounts for the bentonite as part of the solids while the voids are the water and air (if not completely saturated). Equation 4-1 was used to determine the volume of the specimen using measurements of area and height. Equation 4-2 was used to determine the volume of sand using the measurement of the mass of sand. Specific gravities were used to form an equivalent specific gravity for sand-bentonite mixtures depending on the bentonite content of the specimen, which is shown in Equation 4-3. Equation 4-4 and Equation 4-5 show skeletal and bulk void ratios respectively. For the purposes of this experiment, the skeletal void ratio is more relevant than the bulk void ratio because it is important to see how the voids of sand are being filled by swelled bentonite. Note that for clean sand, skeletal and bulk void ratios are equal and no distinction is needed between the two.

$$\boldsymbol{V_{specimen} = A_{specimen} \times H_{specimen}}$$ **Equation 4-1**

$$\boldsymbol{V_{sand} = \frac{m_{sand}}{G_{sand} \times \rho_{water}}}$$ **Equation 4-2**

$$\boldsymbol{G_{s,eq} = \frac{G_{bentonite} \times G_{sand} \times (1 + \frac{bc}{100})}{\frac{bc}{100} \times G_{sand} + G_{bentonite}}}$$ **Equation 4-3**

$$\boldsymbol{e_s = \frac{(V_{specimen} - V_{sand})}{V_{sand}}}$$ **Equation 4-4**

$$\boldsymbol{e_b = \frac{M_{specimen}}{G_{s,eq} \times (1 + \frac{w}{100})}}$$ **Equation 4-5**

Initial skeletal void ratios represent specimens under vacuum, these values ranged from 0.60 to 0.73 for SBMs. Skeletal void ratio measurements were taken after each stage in preparing the specimen for hydraulic conductivity testing. The void ratios of each specimen in its initial stage and after consolidation are listed in Table 4-3, where e_0 denotes initial skeletal void ratio and e_f denotes the skeletal void ratio after consolidation. The changes between initial and final void ratios are minor for sand specimens and dry-mixed SBMs, however there is a significant decrease in void ratio during preparation for suspension-mixed specimens. The significant decrease in void ratio prior to hydraulic conductivity testing for suspension-mixed specimens may be attributed to higher swelling of the bentonite within suspension-mixed specimens in comparison to dry-mixed specimens. It should be noted that distilled water was used to hydrate the bentonite instead of the deaired tap water that was used to hydrate the dry-mixed specimens. The use of deaired tap water versus distilled water will be further discussed in Section 4.4.

Relative density is a reference used to determine the state of compactness of a soil. Relative density for sand can be expressed as the ratio of the difference between the maximum void ratio of sand and the void ratio of a given specimen, to the difference between the maximum and minimum void ratios of sand. Equation 4-6 uses the skeletal void ratios of SBMs with e_{min} and e_{max} measured for the clean sand; for SBMs the initial relative density, RD_0, ranged from 21% and 62% as shown in Table 4-3.

$$\boldsymbol{RD = \frac{(e_{max} - e_s)}{(e_{max} - e_{min})} \times 100\%} \qquad \textbf{Equation 4-6}$$

Table 4-3: Void Ratios and Relative Densities of Specimens

	Specimen #	TX #	σ_c' (kPa)	OCR	e_0	$e_{0,\,bulk}$	RD_0 (%)	e_f	RD_f (%)	$e_{bentonite}$	K_{avg} (cm/s)
Sand Specimens	1	1	100	1	0.66	-	44.81	0.65	47.53	-	2.93E-02
	2	1	200	1	0.61	-	59.79	0.61	59.58	-	2.62E-02
	3	1	50	1	0.65	-	47.35	0.65	47.36	-	3.01E-02
	4	1	100	1	0.65	-	45.69	0.65	45.65	-	3.11E-02
	5	1	100	2	0.34	-	150.74	0.34	150.71	-	4.15E-02
	6	1	25	6	0.65	-	47.70	0.65	47.69	-	2.87E-02
	7	1	50	4	0.65	-	46.25	0.65	46.23	-	2.94E-02
Dry Mixed Specimens	8	1	50	1	0.72	0.66	23.99	0.72	23.97	19.07	7.41E-05
	9	1	50	1	0.63	0.58	52.61	0.63	52.36	22.32	1.40E-03
	10	3	50	1	0.65	0.60	46.57	0.69	33.97	25.32	3.92E-04
	11	1	50	1	0.63	0.56	52.25	0.62	56.29	12.84	3.88E-04
	12	2	50	1	0.62	0.54	56.55	0.61	61.03	12.41	7.69E-04
	13	3	50	1	0.63	0.56	51.68	0.64	49.38	11.51	5.74E-04
	14	1	50	1	0.60	0.53	62.27	0.60	62.58	12.76	2.26E-04
	15	2	50	1	0.63	0.55	53.37	0.62	55.90	12.89	1.78E-04
	16	3	50	1	0.66	0.58	43.71	0.67	40.41	13.20	2.04E-04
Suspension Mixed Specimens	17	1	50	1	0.73	0.66	21.11	0.48	102.43	12.45	1.85E-05
	18	2	50	1	0.62	0.54	57.64	0.52	91.62	13.67	3.46E-06

Water Content, Bentonite Content, and Saturation

Measuring the water content and bentonite content after the completion of the hydraulic conductivity tests are important in determining if the target bentonite content and full saturation were achieved along with the uniformity of the bentonite across a given specimen. Table 4-4 shows that the water content varied from 20% to 27% while the bentonite content varied from 2.7% to 5.0% for all SBM speicmens. As stated previously, both water content and bentonite content are percentages of the mass of water and dry bentonite to the mass of dry sand, respectively. Using the water content by mass to determine the volume of water, the percentage of volume of water divided by volume of voids represents saturation, as illustrated in Equation 4-7. All saturation values exceeded 95%. B-values were also used to ensure that specimens reached a high saturation level before consolidation and measuring hydraulic conductivity. During the preparation of the mixtures, the target bentonite content was 3% for specimens 8-10, and 5% for specimens 11-18. Since the bentonite contents determined from wet sieving tests typically deviated from the target bentonite contents, showing the actual bentonite content values will help in determining the relationship between hydraulic conductivity and bentonite content, which will be examined in Section 4.3.2.

$$\boldsymbol{S = \frac{V_{water} \times 100\%}{V_{voids}}} \qquad \textbf{Equation 4-7}$$

Table 4-4: Water and Bentonite Contents of SBMs

Specimen #	TX#	w (%)	bc (%)
8	1	24.96	3.6
9	1	21.81	2.7
10	3	26.75	2.9
11	1	20.96	4.61
12	2	20.83	4.7
13	3	21.57	4.4
14	1	20.62	5.0
15	2	21.12	4.63
16	3	21.57	4.62
17	1	21.70	4.9
18	2	23.20	4.8

It was of interest to see how the bentonite content varied throughout the specimen. Therefore, each specimen was divided into three sections (top, middle, and bottom) to determine the uniformity of the bentonite. The total bentonite content is the percentage of total mass of dry bentonite divided by the dry mass of sand for all three sections combined. Figure 2-1 shows the bentonite content of each section in reference to the total bentonite content of each specimen. Nine out of the eleven specimens (82%) had their bentonite content throughout all three sections within $\pm$ 15% from the total bentonite content. The top sections had the highest average of bentonite content of segment divided by total bentonite content, the middle sections had values closest to 1, and the bottom sections had the lowest average. This could be due to bentonite particles being flushed out from the bottom to the top during CO2 and water flushing of the specimen.

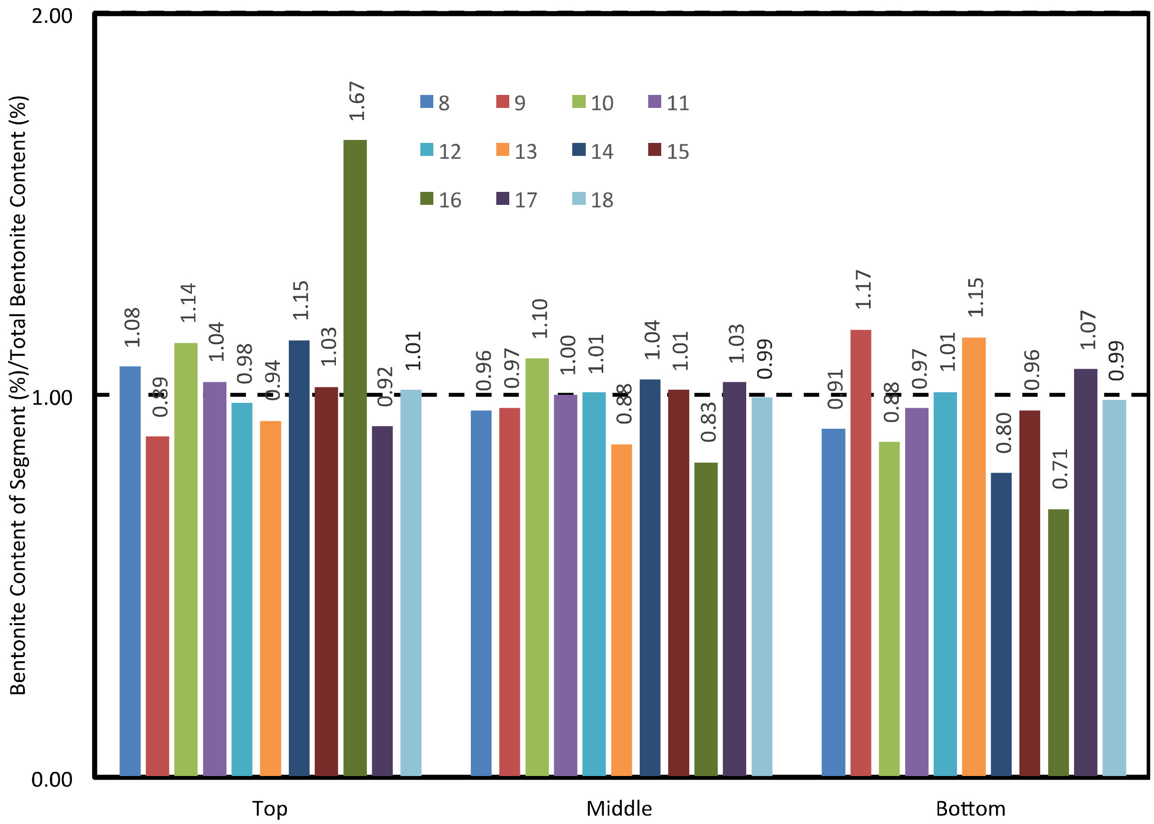

Figure 4-1: Bentonite Content vs. Location in Specimen

4.2.2 Hydraulic Conductivity

Hydraulic conductivity values are calculated using Equation 4-8 which corresponds to the falling head with rising tail water ASTM standard where $\boldsymbol{k}$ is hydraulic conductivity, $\boldsymbol{a_{in}}$ is the cross-sectional area of the reservoir supplying the influent, $\boldsymbol{a_{out}}$ is the cross-sectional area of the reservoir containing the effluent, $\boldsymbol{L}$ is the length of the specimen, $\boldsymbol{A}$ is the cross-sectional area of the specimen, $\boldsymbol{t}$ is the time elapsed between the initial and final readings of headwater loss across the specimen initially, $\boldsymbol{h_1}$, and the headwater loss across the specimen after time $\boldsymbol{t}$, $\boldsymbol{h_2}$. In this experiment the cross-sectional area of reservoirs containing the influent and effluent are equal, simplifying this calculation to Equation 4-9, where $\boldsymbol{a}$ is the area of the reservoirs.

$$\boldsymbol{k} = \frac{\boldsymbol{a_{in} a_{out} L}}{\boldsymbol{At(a_{in}+a_{out})}} \mathbf{ln}(\frac{\boldsymbol{h_1}}{\boldsymbol{h_2}}) \qquad \textbf{Equation 4-8}$$

$$\boldsymbol{k} = \frac{\boldsymbol{aL}}{\boldsymbol{2At}} \mathbf{ln}(\frac{\boldsymbol{h_1}}{\boldsymbol{h_2}}) \qquad \textbf{Equation 4-9}$$

Hydraulic conductivity measurements ranged from 3.4×10^{-6} cm/s to 1.4×10^{-3} cm/s for SBMs and 2.6×10^{-2} cm/s to 4.2×10^{-2} cm/s for sand specimens. Hydraulic conductivity measurements were considerably high for the SBMs although the hydraulic conductivity for SBMs are usually on the order of 10^{-7} cm/s or less. None of these specimens fit the regulations for SBM cutoff walls because the hydraulic conductivity values do not fall below 1×10^{-7} cm/s. The potential causes of the high hydraulic conductivity measurements for SBMs will be further investigated in Section 4.4.3.

Due to the high hydraulic conductivity of the sand, it was necessary to check the maximum flow rate that can flush through the setup to ensure that the measured hydraulic conductivities are not controlled by the limits of flow rate of the setup. To measure the flow rate through the setup, an empty triaxial setup was used in which a porous stone, two filter papers and the top platen are placed on top of the bottom platen. A latex membrane is then placed around them and O-rings are used to hold the membrane tight to the platens. The triaxial cell is the assembled and a minimal cell pressure of 25 kPa is applied. Water is the flushed through all lines in a similar procedure to that used in preparing the dry-mixed specimens to ensure a fully saturated setup. Note that the lines were not backpressure saturated to simulate the worst-case scenario since the recorded flow rate would be lower with lower degree of saturation. A head difference is then setup between the influent and effluent and water flow is measured over a constant period of time. Figure 4-2 shows the flow rate versus initial height different for the empty triaxial setup and a clean sand specimen. At a given head difference, the maximum flow rate in the empty triaxial setup is about 5 times larger than that in sand. Therefore, it was concluded that the triaxial setup is nor causing any bias in the data. Note that the results are presented in terms of head difference since a "height of specimen" couldn't be defined for the empty setup and therefore, hydraulic gradients couldn't be calculated.

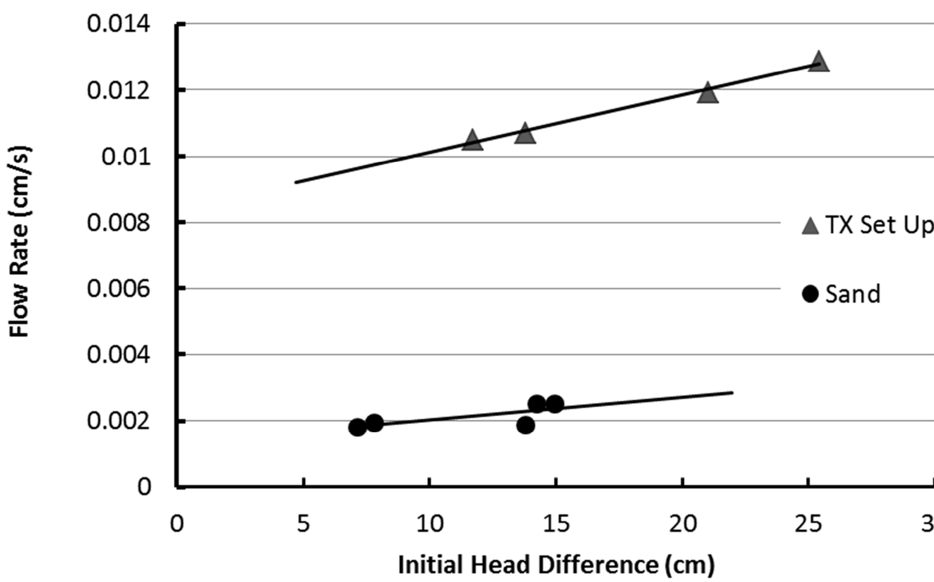

Figure 4-2: Flow rate versus initial height difference for clean sand and empty triaxial setup.

Bentonite Hydration

Bentonite hydration denotes the onset of swelling of bentonite. When bentonite is exposed to water, bentonite hydration occurs and bentonite begins to swell within the voids of the sand (Komine and Ogata, 1994, Komine, 2003, and El Mohtar, 2008). Water levels in burettes that delivered pore pressure and backpressure were monitored to note changes indicating swelling, saturation, or consolidation during testing. Cell pressure values were maintained at 25 kPa during flushing of water into specimens and during periods where the specimen was allowed to swell before proceeding to backpressure. Hydration time is the time that a specimen is first exposed to water to the beginning of backpressure. Hydration time does not include backpressure because studies have shown that an increase in vertical pressure would result in a significant decrease in volumetric swelling strains (El Mohtar, 2008). In addition, any stages after backpressure would not be included in hydration time.

Figure 4-3 is a plot of the average hydraulic conductivity after consolidation versus hydration time. Some specimens were left with effluent pore pressure valves open to allow water to expel from sand voids from swelling of bentonite. On this plot and those following, specimens that were given time for swelling are denoted by “S”. Specimens that were subjected to backpressure immediately after flushing with water and were not allotted time for swelling are denoted by “US”. Finally, suspension-mixed specimens are denoted by “SU”. It is clear to see that while seven SBMs experienced hydration times less than 5,000 minutes and four specimens experienced hydration times greater than 5,000, there is no continuity of hydraulic conductivity when hydration time approaches 5,000 minutes from the right or left. This is just one example to illustrate that hydration time did not affect hydraulic conductivity greatly in this study. There are two cases where hydration time for the BC=5%-US specimens exceed the hydration time for the BC=5%-S specimens, this means that the US specimens experienced a longer flushing time than the S specimens. In comparing the US specimens to the S specimens it can be seen that hydraulic conductivities were lower for S specimens. However, this difference is less than one order of magnitude and with other parameters varying, there isn't a clear effect of hydration time on final average hydraulic conductivity.

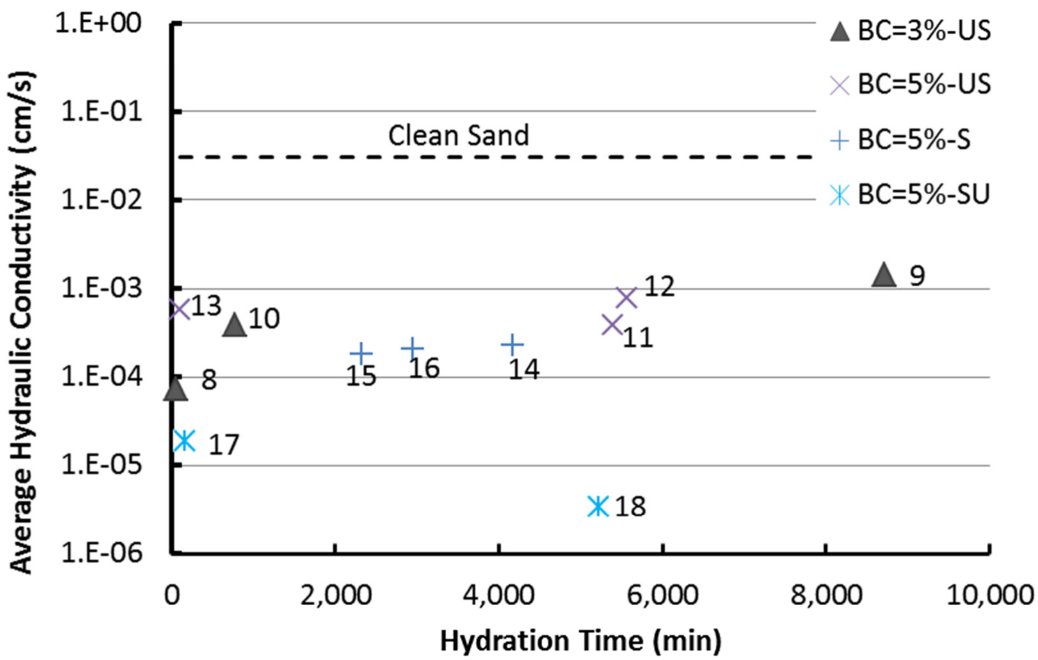

Figure 4-3: Average Hydraulic Conductivity vs. Hydration Time

4.3 Effects of Experimental Factors

All SBMs were tested within a range of physical properties such as height to diameter ratio, void ratio, and relative density to lessen the variability of hydraulic conductivity due to testing different sand structures. Hydraulic gradients less than 2 were used throughout testing, which complies with ASTM standards. This allows for better comparisons of the effects of time, bentonite content, clay void ratio, and mixing method on hydraulic conductivity.

4.3.1 Time

Studies often report the changes in hydraulic conductivity with time (Chalermoyant and Arrykul, 2005, El Mohtar, 2008, and Hwang 2010). In Figure 4-4 the time reported is the total time from the end of consolidation until the hydraulic conductivity tests are completed. The hydraulic conductivity tests lasted from 10,000 minutes to 20,000 minutes. There are no trends in hydraulic conductivity with post-consolidation time for this experiment.

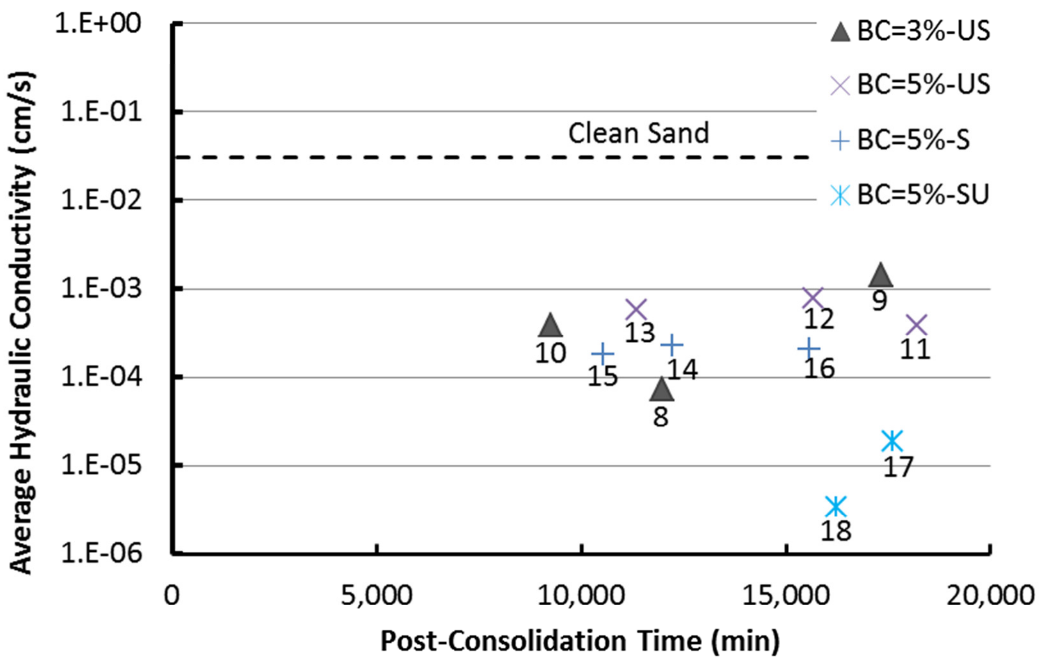

Figure 4-4: Average Hydraulic Conductivity vs. Post-consolidation Time

4.3.2 Bentonite Content

Figure 4-5 shows changes in hydraulic conductivity with respect to changes in bentonite content. The dashed line represents the average hydraulic conductivity of all sand specimens tested in this study. The average hydraulic conductivity of the sand specimens is approximately 3.1 $x10^{-2}$cm/s. While there is a minor decreasing trend in dry-mixed SBMs with 3% BC, the dry-mixed SBMs at 5% BC do not exhibit any trend; all dry-mixed specimens seem to have a hydraulic conductivity between 1 $x10^{-3}$ cm/s and 1 $x10^{-4}$ cm/s without a significant decrease in hydraulic conductivity when increasing bentonite content from 3% to 5%. Suspension-mixed SBMs also have a decreasing trend with increased bentonite content, but the data is too limited to make any conclusions. Bentonite content does not seem to have a significant impact on the hydraulic conductivity of dry-mixed SBMs in this study.

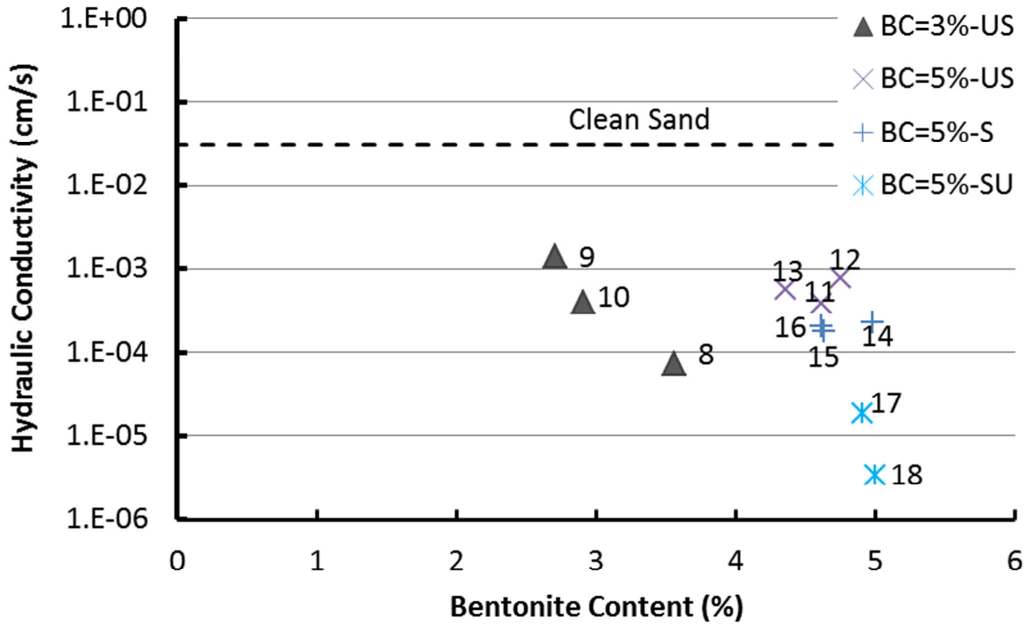

Figure 4-5: Hydraulic Conductivity vs. Bentonite Content

4.3.3 Bentonite Void Ratio

Under ideal conditions, the skeletal pores within the sand are filled with swelled bentonite; under such conditions, the permeant travels thorough the micro-scale void space within the bentonite, as the macro-scale skeletal pores are blocked. Bentonite void ratio is a ratio of volume of water to volume of bentonite for a given saturated SBM. For each specimen, bentonite void ratios were calculated from water content and bentonite content measurements after disassembling the speimcens. Figure 4-6 shows that as the bentonite content increases, the bentonite void ratio decreases. However, the results do not show any trends in hydraulic conductivity based on bentonite void ratio.

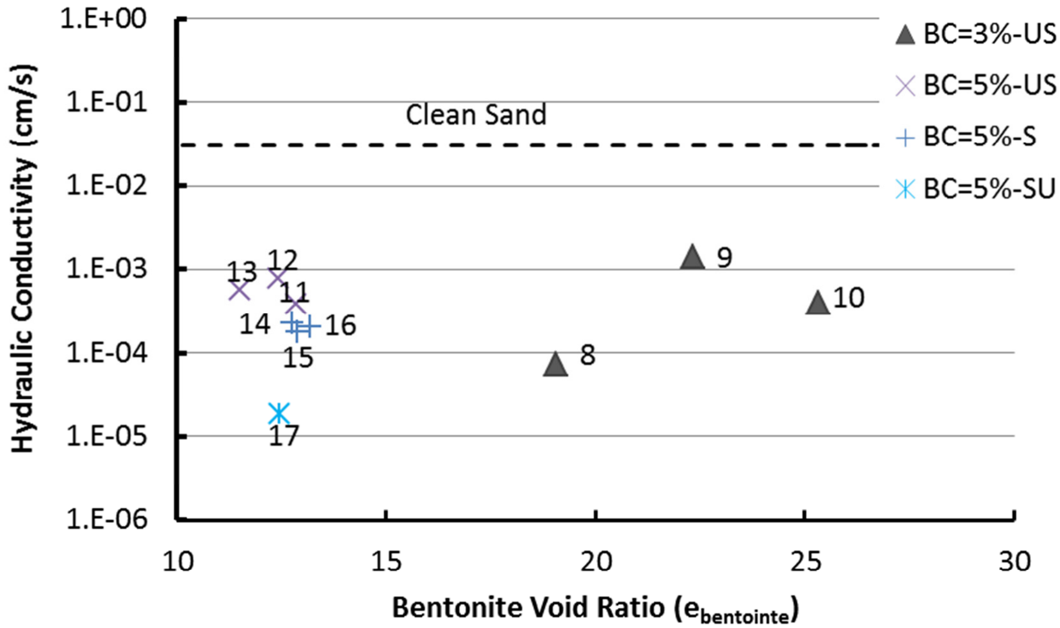

Figure 4-6: Hydraulic Conductivity vs. Bentonite Void Ratio

4.3.4 Mixing Method

While nine SBMs were mixed using dry mixing and only two SBMs were mixed using suspension mixing, there is a great contrast in the hydraulic conductivity values of the specimens depending on the preparation method. For example, the median hydraulic conductivity for dry mixed specimens is on the order of 10^{-4} cm/s while the median for suspension mixed specimens is on the order of 10^{-6} cm/s. This shows that hydrating bentonite before mixing with dry sand will yield a lower hydraulic conductivity, which is desirable when constructing hydraulic barriers. However, it should be noted that the suspension mixing specimens were prepared with distilled water while the dry-mixed specimens were prepared with deaired tap water.

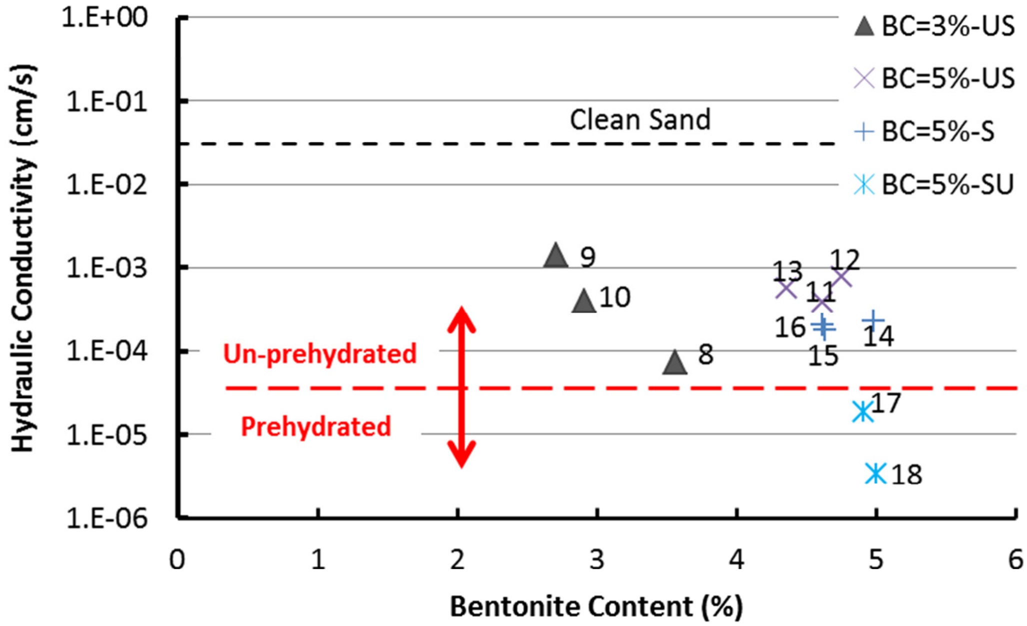

Figure 4-7: Hydraulic Conductivity vs. Bentonite Content

4.4 Comparison Of Results With Literature

Comparisons of results from this experiment with results from the literature are important in determining if procedures were followed properly during testing, If proper testing was completed it would yield similar results to other tests carried out using the same procedures, specimen preparation methods, and materials. Comparisons of hydraulic conductivity of sand, differences in using deaired water versus distilled water, and comparisons of hydraulic conductivity of SBMs are presented in this section. Due to limited results using the suspension mixing method, this section will only focus on the results obtained from specimens prepared using the dry-mixed method.

4.4.1 Sand

Hydraulic conductivity tests completed on sand are in agreement with those reported in the literature. Recall that initial and final void ratios ranged from 0.51 to 0.65, with relative densities from 45% to 91%. Hydraulic conductivity values of sand corresponding to these properties are 3.11 x10^{-2} cm/s to 4.15 x10^{-2} cm/s, respectively. For relative densities of 45.7% and 93.3%, Hwang (2010) reported hydraulic conductivities of 6.03 x10^{-2} cm/s and 2.58 x10^{-2} cm/s. Figure 4-8 shows the measured hydraulic conductivity in this study using the flexible wall setup versus the values reported by Hwang (2010) using a rigid wall setup.

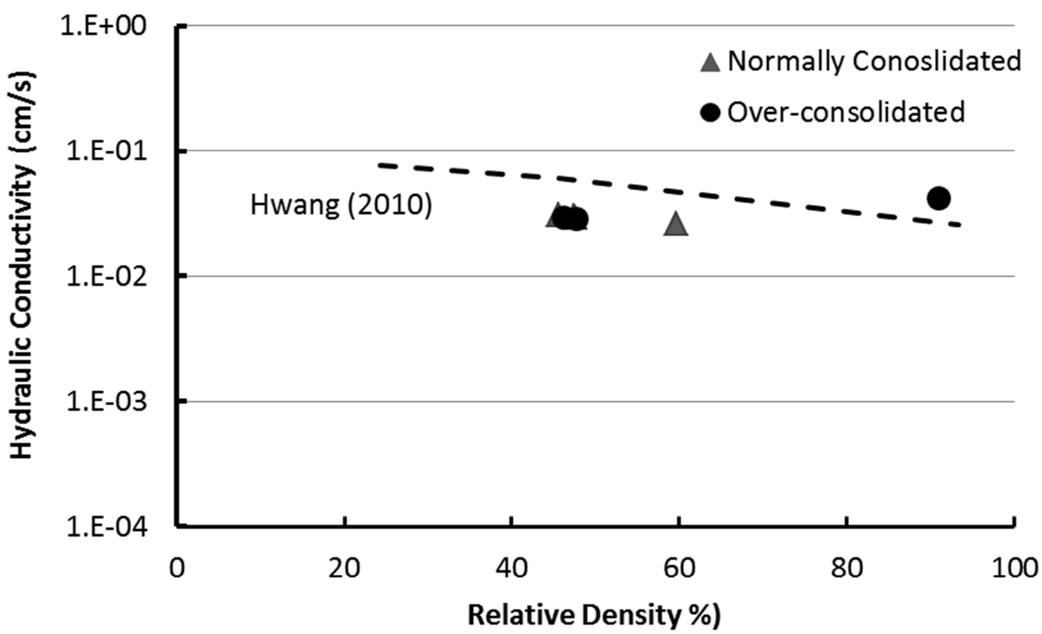

Figure 4-8: Hydraulic Conductivity of sand vs. relative density

4.4.2 SBMs

Comparisons of results on hydraulic conductivity tests in literature reveal that there is a discrepancy with the results in this experiment. Most hydraulic conductivities of SBMs with 3% or greater have reported hydraulic conductivity on the order of 10^{-7} cm/s or lower (Abichou et. al, 2002, Arrykul and Chalermyanont, 2005, Hwang, 2010, Komine, 2004, and Yamagouchi et. al, 2006). Figure 4-9 shows the values of measured hydraulic conductivity from this study plotted as a function of the calculated bentonite void ratio based on final specimen measurements. Also included in the figure are the results reported by Hwang (2010) for SBMs prepared using wet mixing and suspension mixing methods, both of which give high degree of bentonite hydration and swelling. The hydraulic conductivities measured in this study are four to five orders of magnitude higher than the values reported by Hwang (2010) at the same clay void ratio. This major conflict between the results is due to the use of tap water in this study as compared to distilled water in Hwang's (2010) experiments.

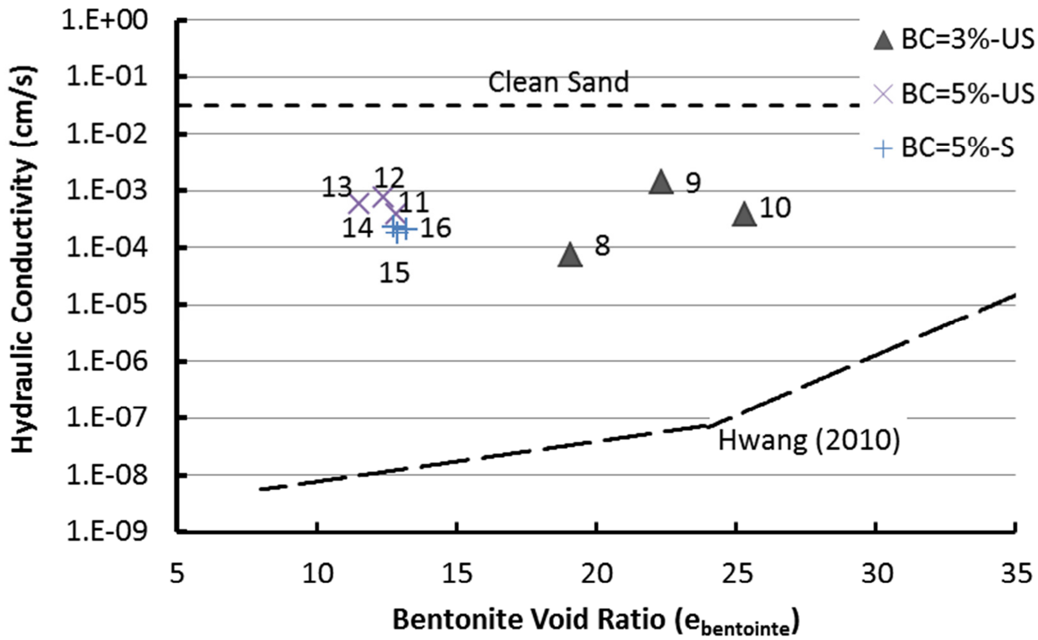

Figure 4-9: Hydraulic Conductivity of SBMs versus literature

4.4.3 Deaired Water vs. Distilled Water

As mentioned in the literature review, the diffuse double layer of bentonite is affected by the ions in water (both concentration and covalence). Sodium bentonite is commonly used in geotechnical applications due to its higher swelling capacity; however, when the water used to hydrate bentonite has a high ionic strength this swelling reaction may be interrupted (Yamagouchi et al., 2006). Throughout this experiment it was noted that deaired tap water was used to hydrate dry-mixed SBMs. It is important to quantitatively and qualitatively asses this difference to determine its effect on the hydraulic conductivity of SBMs. The conductivity, ionic strength, and hardness of dionized water and tap water are reported in Table 4-5 The Conductivity and hardness tests were performed by fellow graduate students in the EWRE program at The

University of Texas at Austin using CDM230 conductivity meter and titration method, respectively.

Table 4-5: Quality of tap versus distilled water

	Conductivity	Ionic Strength	Hardness
	μS/cm	mM	mg/L
distilled water	< 1.39	< 2.22E-05	<3.9
tap water	309	4.94E-03	110.31

The results in Table 4-5 show two orders of magnitude difference in the Ionic strength of tap water versus distilled water. If we assume the ions to be identical in both waters, this implies that the concentration of ions in the tap water is 222 times that of the distilled water; therefore, the bentonite double layer in the tap water should be 15 times smaller than that in the distilled one (the thickness of the double layer is inversely proportional to the square root of the concentration). These preliminary calculations imply that the swelled bentonite is blocking a smaller portion of the voids because of the reduced double layer and therefore, allowing water to flow through faster. However, the bentonite void ratio doesn't reflect the degree of bentonite swelling since it is defined as the ratio of the void space (skeletal void minus volume of bentonite particles) to the volume of the bentonite particles (not the swelled volume). This explains the conflict in the results from this study compared to the ones presented in the literature, particularly by Hwang (2010) as shown in Figure 4-9.

4.4.4 Effective Clay Void Ratio

The concept of the clay void ratio is appealing to determine flow through a porous media with plastic fines filling its pores. The concept of clay void ratio allows for plotting samples with small variability in relative density over a large range of bentonite contents, all at once and have all the data fit within a "blocked" flow or "partially blocked" flow (Figure 4-10). If clay void ratio is high, the permeant travels through macro-pores in the sand structure and the hydraulic conductivity of the soil increases. Lower clay void ratios indicate that the permeant is travelling through micro-pores within the clay fines, which will yield a smaller hydraulic conductivity of the soil (Mollins et. al, 1996 and Hwang, 2010).

However, this approach seems to be flawed if the clay is not allowed to fully swell within the pore space. The current calculation of clay void ratio is based on volume of bentonite particles alone and not the swelled volume, and therefore, for two identical specimens, the fully swelled bentonite in Hwang (2010) and partially swelled bentonite in this study would yield the same bentonite void ratio, even though the hydraulic conductivities are different.

The following section presents a new concept called the effective clay void ratio. The main idea behind this new concept is that if the clay is not fully swelled, then using the traditional clay void ratio would underestimate the hydraulic conductivity (produce higher values of hydraulic conductivity) because it would assume that the clay is blocking more of the void space than it actually is. Alternatively, using an effective clay void ratio as a function of the clay void ratio would account for the limited swelled volume. The main framework for calculating the effective clay void ratio and corresponding hydraulic conductivity is:

1) For a given percentage of swell (PS%), calculate the volume of partially swelled clay (V_{PSC}) as a function of the volume of fully swelled clay (V_{FSC}) shown in Equation 4-10:

$$\boldsymbol{V_{PSC} = \frac{PS \times V_{FSC}}{100}} \qquad \textbf{Equation 4-10}$$

2) Calculate the clay void ratio (e_{clay}) as shown in Equation 4-11, where ρ_d is the dry density of the specimen:

$$\boldsymbol{e_{clay} = Gs_{bentonite}\left[\left(1 + \frac{1}{bc}\right)\frac{\rho_{water}}{\rho_d} - \frac{1}{bc \times Gs}\right]} \qquad \textbf{Equation 4-11}$$

3) Calculate the reduced effective clay void ratio (e'_{clay}) as illustrated in Equation 4-12:

$$\boldsymbol{e'_{clay} = \frac{e_{clay}}{PS/100}} \qquad \textbf{Equation 4-12}$$

4) Compare the volume of partially swelled clay to the volume of skeletal voids. If $V_{PSC} > V_{voids\text{-}skeletal}$, then the skeletal voids are fully blocked. Using the results from Hwang (2010), determine the hydraulic conductivity based on blocked flow as shown in Equation 4-13:

$$\boldsymbol{k(cm/sec) = 10^{0.0701 \times e'_{clay} - 8.8178}} \qquad \textbf{Equation 4-13}$$

5) Compare the volume of partially swelled clay to the volume of skeletal voids. If $V_{PSC} < V_{voids\text{-}skeletal}$, then the flow is partially blocked. Using the results from

Hwang (2010), determine the hydraulic conductivity based on partially blocked flow as shown in Equation 4-14:

$$\boldsymbol{k(cm/sec) = 10^{0.212\times e'_{clay} - 12.273}}$$ **Equation 4-14**

If calculated k > $k_{clean\ sand}$, use $k_{clean\ sand}$ instead. Note that if bc(%) starts exceeding 6%, then $k_{clean\ sand}$ should be reduced to account for presence of fines. A reduction to hydraulic conductivity similar to non-plastic fines can be applied (by the time k approaches $k_{clean\ sand}$, PS(%) would be small enough that the plastic fines start behaving like non-plastic fines.

Figure 4-10 below shows the results for a hypothetical case for sand with a relative density of 45% mixed with 2, 3, 4, 5, and 6% bentonite by dry mass of sand. Note that the ratio plotted on the x-axis is equivalent to PS(%). The bentonite has a free swell of 8mL/g. The figure shows that at bc(%) of 2%, even at PS(%) of 100%, the bentonite cannot block all the skeletal voids and the specimen has a higher hydraulic conductivity. On the other hand, for bc(%) of 5 and 6%, the flow is fully blocked up to a PS(%) of 50 and 40%, respectively. All hydraulic conductivities are capped off at $k_{clean\ sand}$ of 3.1 x10^{-2} cm/sec.

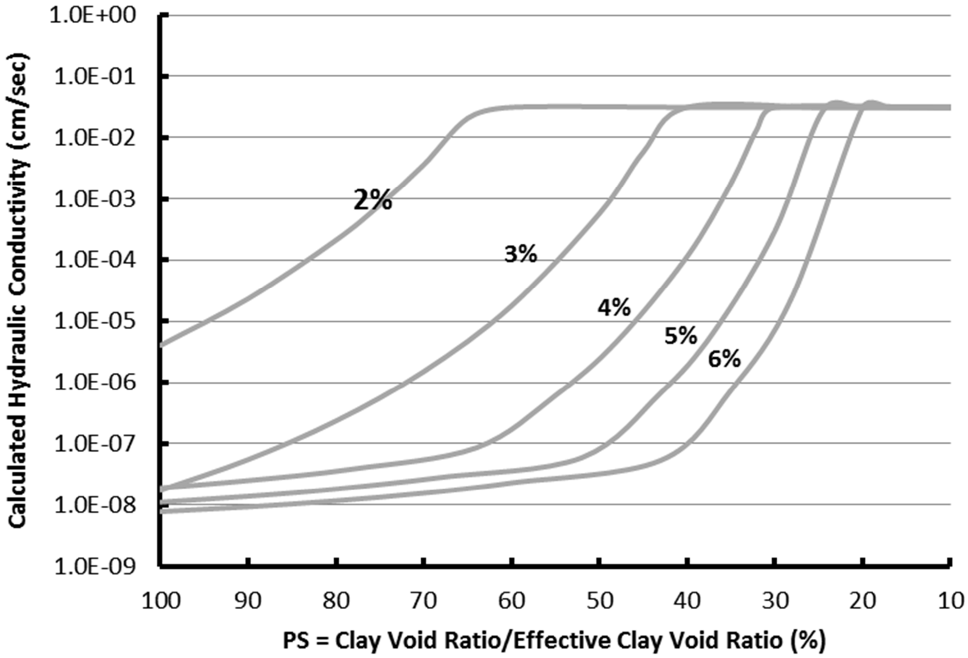

Figure 4-10: Hydraulic Conductivity of SBMs versus literature

For each of the nine tests performed on dry-mixed specimens, a similar curve can be developed based on the measured $k_{clean\ sand}$, bc(%) and skeletal void ratio. These curves are shown in Figure 4-11 along with the measured k values in the lab (black circles). The curves for specimens 9 and 10 didn't show any plateau at high PS(%) indicating that the bentonite content is not high enough to block all the void space. This can be numerically confirmed by calculating V_{FSC} / $V_{voids\text{-}skeletal}$ for the 2 specimens; for blocked flow, the ratio needs to be more than 1. These values are presented in Table 4-6 along with the back-calculated PS(%) and effective bentonite void ratio (back-calculated from the measured k in the lab). Specimen 8 has a V_{FSC} / $V_{voids\text{-}skeletal}$ slightly higher than 1 and that is reflected in a short plateau at high PS(%) values (about 85%). Nonetheless, all three specimens have similar PS(%) values with an average of 53%. Specimens 11 through 16 had a higher bentonite content, resulting in a higher V_{FSC} / $V_{voids\text{-}skeletal}$ ratio and therefore, had a plateau to a higher PS(%) value (45-55%) before the hydraulic conductivity values started increasing dramatically. Again, for all six specimens, PS(%) values were very similar and averaged about 31%.

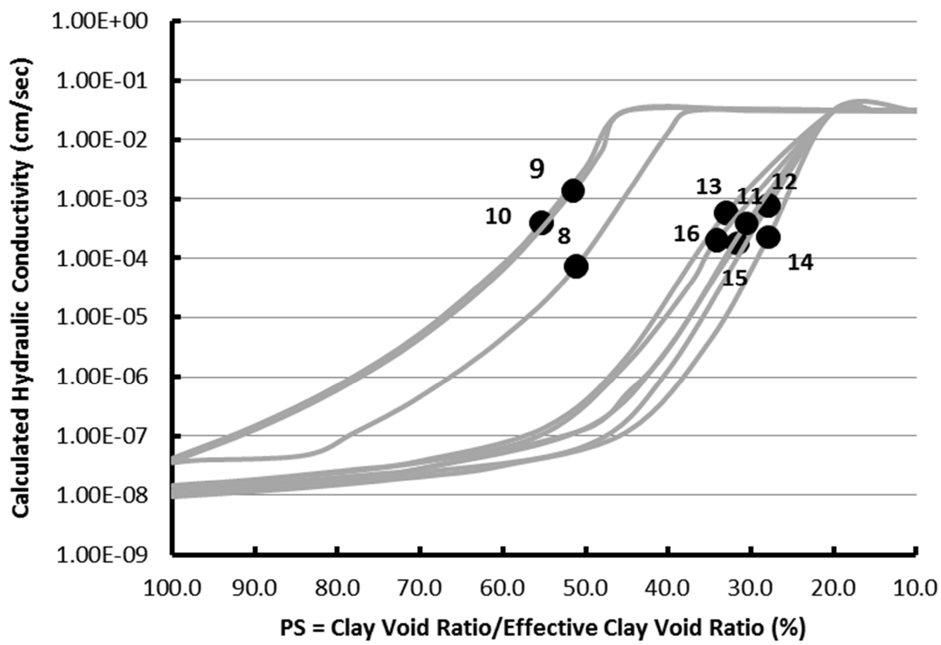

Figure 4-11: Hydraulic Conductivity versus PS(%) for the dry-mixed specimens

Table 4-6: Calculations for effective bentonite void ratio and PS(%)

Specimen #	e_f	bc (%)	$e_{bentonite}$	V_{CFS} / $V_{voids\text{-}skeletal}$	K_{avg} (cm/s)	Calculated to match k	
						PS(%)	$e'_{benonite}$
8	0.718	3.56	19.07	1.05	7.41E-05	51.10	38.29
9	0.633	2.71	22.32	0.91	1.40E-03	51.50	44.27
10	0.688	2.91	25.32	0.90	3.92E-04	55.31	41.70
11	0.621	4.61	12.84	1.57	3.88E-04	30.52	41.67
12	0.607	4.75	12.41	1.66	7.69E-04	27.92	43.08
13	0.642	4.36	11.51	1.44	5.74E-04	32.98	42.49
14	0.602	4.98	12.76	1.75	2.26E-04	27.90	40.58
15	0.622	4.63	12.89	1.58	1.78E-04	31.65	40.10
16	0.669	4.62	13.20	1.46	2.04E-04	34.10	40.36

Figure 4-12 and Figure 4-13 show the calculated percent swell versus bentonite content and $V_{CFS}/V_{void\_skeletal}$, respectively for all specimens. The critical bentonite content and $V_{CFS}/V_{void\_skeletal}$ threshold separating blocked flow from partially blocked flow is included in both figures as well. The PS(%) values are relatively constant within the partially blocked flow region and decreases significantly as the critical threshold is exceeded. When the critical threshold $V_{CFS}/V_{void\_skeletal}$ is more than one, this implies that the void space is not big enough to accommodate full swelling of the bentonite. Therefore, there are two constrains on the bentonite swelling:

1) The physical space available for swelling;
2) The high ionic strength of the tap water used as compared to the distilled water.

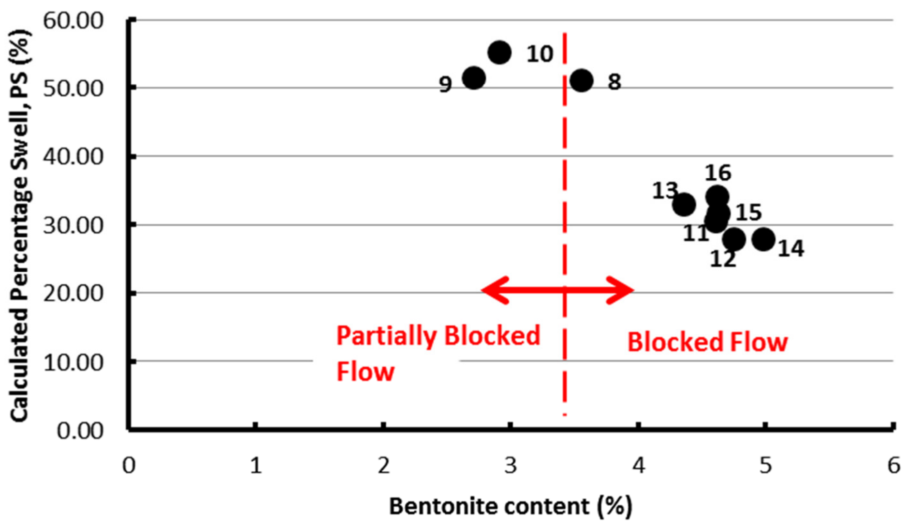

Figure 4-12: Percentage Swell (PS) versus bentonite content

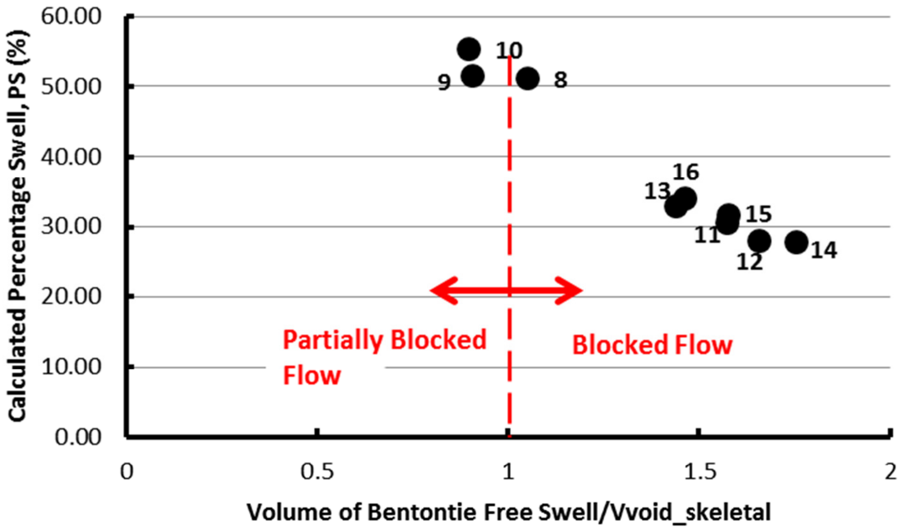

Figure 4-13: Percentage Swell (PS) versus $V_{CFS}/V_{void\_skeletal}$

The effect of the ionic strength of the used water on the free swell of the bentonite is constant and independent on the bentonite content. Therefore, the measured PS(%) value for specimens where $V_{CFS}/V_{void\_skeletal}$ is greater than the critical threshold (which is equal to 1) can be divided into two components: an average of 53% partial swell due to the ionic strength of the tap water and the remaining component should be due to physical constrain because of the limited pore space. Figure 4-13 shows the percentage of swell that was limited due to the available pore space as a function of $V_{CFS}/V_{void\_skeletal}$ for specimens 8, and 11-16. As expected, there is a very good linear relationship between the two parameters.

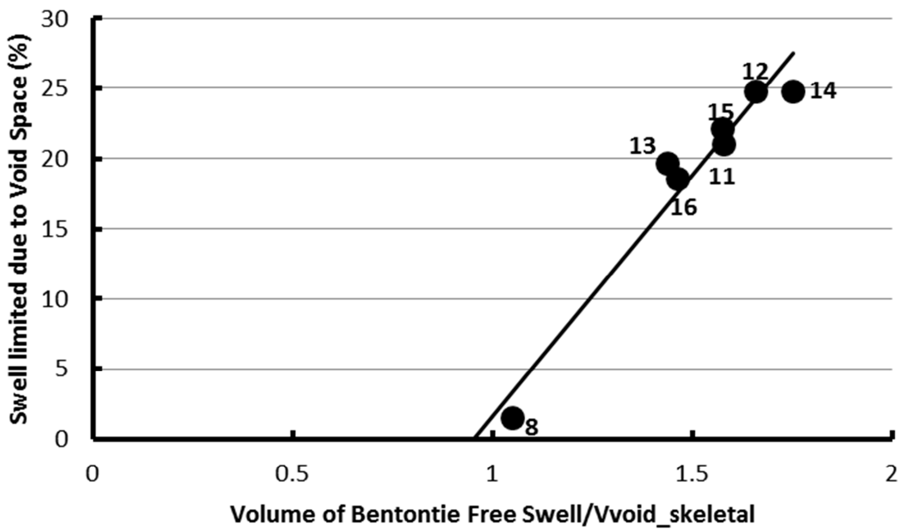

Figure 4-14: Swell limited due to void space (%) versus $V_{CFS}/V_{void\_skeletal}$

Figure 4-15 is a repeat of Figure 4-9 with the hydraulic conductivity being plotted as a function of both, bentonite void ratio and effective bentonite void ratio. The horizontal arrows show the shift of the original data (k versus bentonite void ratio) to the corrected data (k versus effective bentonite void ratio) for each of the specimens. These analyses show that the use of clay void ratio in its current format can be misleading as it doesn't account for the effects of water chemistry, among many other factors that can contribute to alter/limit the free swell of clay, on the effectiveness of the clay to block the pore space. This work opens the door to research a new approach to calculate an effective clay void ratio for cases when full bentonite swelling is not expected.

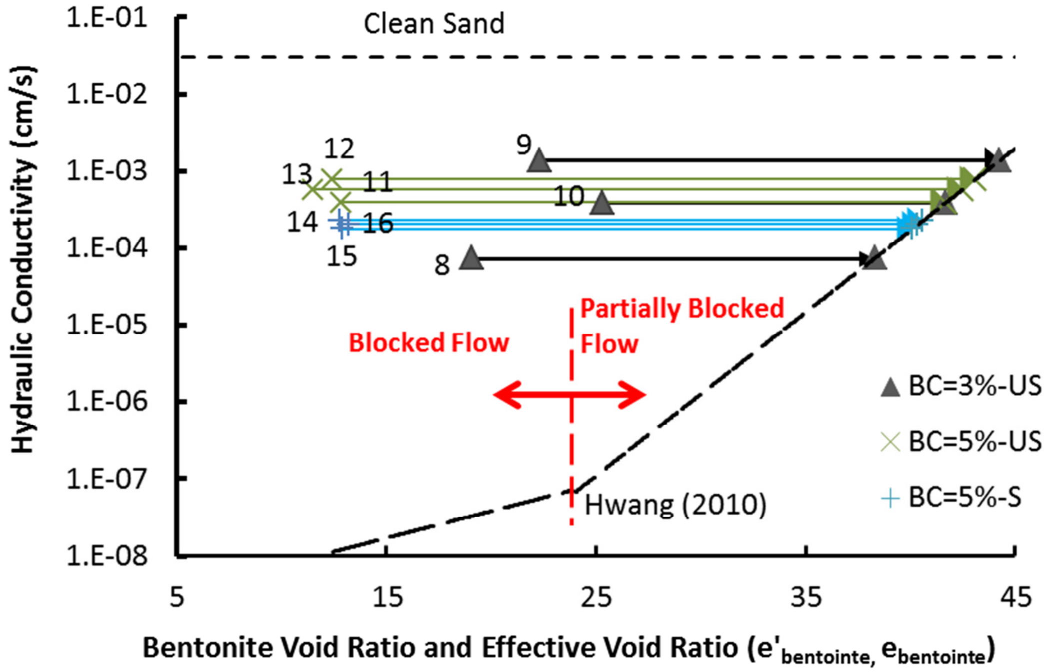

Figure 4-15: Hydraulic Conductivity of SBMs versus e'$_{bentonite}$ and e$_{bentointe}$

Chapter 5: Conclusions and Future Work

The hydraulic conductivities of SBMs were determined using triaxial cells in this experiment to determine the effects of bentonite swelling and uniformity on the use of SBMs as hydraulic barriers. Ottawa sand, adhering to ASTM C-778, and commercially used Wyoming bentonite, sieved through the #200 sieve, were used to create eleven specimens. Nine SBMs were mixed using dry mixing techniques (tap water was used for these specimens), while two specimens were mixed using suspension mixing; bentonite was pre-hydrated using distilled water. Bentonite content of the specimens ranged from 2.7% to 5.0%. Seven sand specimens were also tested to determine the reference hydraulic conductivity for Ottawa sand used in this experiment.

Flushing, back pressure saturation, and consolidation stages for each specimen were monitored using the Sigma-1 and GeoJac automated systems. Three specimens were allotted 48 hours to swell after flushing with water instead of directly applying back pressure once flushing was completed. Water was delivered to the specimen using the Trautwein pressure panel. The panel received deaired water from Geoken nold dearator. Back pressure exceeded 200 kPa for most specimen and lasted for more than 24 hours or until an acceptable B-value was reached. Consolidation to 50 kPa effective confining stress was used for all SBMs. Hydraulic conductivity tests were falling head rising tail water tests that were in accordance to ASTM standards (except for the H/D ratio).

The hydraulic conductivity of sand specimens ranged from 2.6 x10^{-2} cm/s to 4.2 x10^{-2} cm/s and 3.4 x10^{-6} cm/s to 1.4 x10^{-3} cm/s for SBMs. In terms of uniformity, 82% of specimen had bentonite contents for each section (top, middle, and bottom) of the specimen within $\pm$15% of the total bentonite content. Hydration time varied with each specimen, although no relationship was found for hydraulic conductivity and hydration time nor was any trend observed between specimens that were allotted time to swell compared to those that proceeded to back pressure directly after flushing. There are no trends in hydraulic conductivity with post-consolidation time for the tested speicmens. Bentonite content does not seem to have a significant impact on the hydraulic conductivity of dry-mixed SBMs in this study. The results do not show any trends in hydraulic conductivity based on bentonite void ratio. There is a great contrast in the hydraulic conductivity values of the specimens depending on the preparation method; suspension mixing yielded conductivities on the order of two magnitudes less than dry mixing. In comparing data to the literature, this experiment generated the following conclusions:

1. SBMs prepared in this study did not achieve the required hydraulic conductivity of 1 $x10^{-7}$ cm/s.
2. Sand hydraulic conductivity measurements were in agreement with the literature, which validates the testing methods used in this study. Therefore, hydraulic conductivity results using triaxial cells as flexible wall permeameters are reliable when proper testing methods are followed. Using H/D ratio of 2 did not affect the hydraulic conductivity values measured for sand.
3. SBM hydraulic conductivity measurements were three or more order of magnitudes higher than what is reported in the literature. Further comparisons of experimental methods show that specification of water used as the permeant and, more importantly, during bentonite hydration

and swelling is critical, and that this difference could be the cause of the discrepancy.

4. Since the concentration and covalence of ions in water affect the thickness of the diffuse double layer, using tap water instead of distilled water will limit the thickness of the diffuse double layer.
5. A closer look at the concept of clay void ratio shows that, while it is useful to compare specimens with similar relative densities and varying bentonite contents, it may yield misleading results by assuming that the fully swelled bentonite is causing the reduction in hydraulic conductivity.
6. Calculating an effective clay void ratio is necessary to account for the percentage of bentonite swelling, if it does not swell fully. This new concept was developed to provide the effective clay void ratio at different percentages of swelling as a function of the clay void ratio of fully swelled bentonite. By observing if the skeletal voids of sand are fully blocked or partially blocked, the proper method in predicting the hydraulic conductivity can be determined.
7. When comparing hydraulic conductivity of SBMs to the literature using effective clay void ratios, trends can be identified and are in agreement with the literature.

Conclusions from this experiment provide a framework for future studies. The next stages in this research include:

1. Monitoring the hydration and swelling of bentonite in SBMs using specified types of water (tap and distilled), where the conductivity, ionic strength, and hardness are known. Some preliminary centrifuge testing on smaller sample sizes of SBMs could be used to determine swelling and hydraulic conductivity, values can still be compared to literature if bentonite contents and relative densities are similar to literature.
2. Predicting the effective clay void ratio from knowing the swelling of the clay, prior to running the hydraulic conductivity tests.
3. Determining ways to increase uniformity of bentonite content throughout the specimen so that hydraulic conductivity values can be precise when preparation method and bentonite content are the same.
4. Assessing the effects of groundwater on the hydraulic conductivity of SBMs. The hydraulic conductivity results in the lab can be correlated to the expected hydraulic conductivity in the field for cutoff walls.

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Vita

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