Effect of Cyclic Loading on Permeability of Bentonite Coated Gravel (BCG)

THESIS

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Abstract

Bentonite coated gravel (BCG) is a relatively new material that can be used in many applications ranging from pond construction, flood mitigation, well-sealant and grouts, dam/berm construction, wetland restoration, anti-seep collars, trench dams, slope stabilization, temporary and diversion dams, landfill liners, and many other applications. It is a versatile material when an impermeable (or very low permeability) layer needs to be installed or constructed. BCG is coarse aggregate that has been coated with bentonite (using cellulosic polymer as a binder) allowing the material to hydrate and create a low permeability layer as it hydrates, making it very useful when free water is available. There is a wealth of knowledge on similar materials used as landfill liners such as compacted clay liners and sand bentonite liners but since bentonite coated gravel is still a relatively new material for landfill liners, there is a great deal to learn about BCGs and their response to the environments in which they are placed. This study was carried out because little or no information is available in literature if cyclic/dynamic loading impacts its low permeable properties. The main objective of this research is to determine the ability of BCGs to retain their original low hydraulic conductivity during cyclic loading. In order to examine this specific material property, the hydraulic conductivity at cyclic intervals of loading was compared with the initial hydraulic conductivity before cyclic loading was applied. Three separate mixes of varying bentonite (15%, 20%, &
30%) to coarse aggregate (85%, 80%, & 70%) contents, were prepared and tested in triaxial cells for cyclic testing. Each sample was agitated by subjected it to up to 600 cycles at 1% axial cyclic strain and 2% axial cyclic strain for up to an additional 600 cycles. The hydraulic conductivity was measured every 200 cycles. Testing the samples at two different cyclic axial strains (1% and 2%) allowed for a study of the impact of the strain level on the sample permeability. The initial hydraulic conductivity was compared with values measured after every 200 cycles. Sample with lower bentonite content (15%) showed no change in hydraulic conductivity with cyclic loading. For the higher bentonite percentage samples (20% and 30%), there was a very small change in hydraulic conductivity but the change was insignificant. Therefore, these higher bentonite mixtures (20% and 30%) indicated negligible increase in hydraulic conductivity with cyclic loading. All recorded hydraulic conductivity measurements remained within the order of $10^{-9}$ cm/s. It is concluded that the hydraulic conductivity of bentonite coated gravel is not significantly impacted by cyclic loading in terms of number of cycles (up to 1,200) or the axial cyclic strain level (up to 2%).
Dedication

This master’s thesis is dedicated to my family and most importantly my loving mother who raised me to be the person that I am today and always supported me and my goals. I am also grateful for everyone that has helped me from high school teachers, soccer coaches, professors, friends and their parents for helping and guiding me throughout my life.
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Chapter 1: Introduction

1.1 Background

Traditionally, landfill liners and impermeable (or low permeability) layers are made by compacting clay until it has a low enough permeability to meet minimum hydraulic conductivity requirements. Recently, new materials similar to clay are increasingly being used to create liners such as sand bentonite mixtures and bentonite coated gravel. Bentonite coated gravel is exactly as it is described: it is gravel that has been coated with bentonite using a cellulosic polymer binder. Bentonite is an expansive clay material which will hydrate and swell once it comes into contact with water or liquid. This expansive nature of bentonite allows for the creation of bentonite coated gravel (BCG) liners that have very low permeability. Gravel fill has a high void ratio and therefore, a high permeability. The bentonite fills the voids in between the coarse aggregates, causing a low hydraulic conductivity. This is different from regular low permeability soil liners as they tend to be a mix of aggregate and non-expansive clay and at certain percentages of gravel, the non-expansive clay soil will not fill the voids in the liner (Shelley & Daniel, 1993). This problem is not encountered with BCGs as the bentonite swells upon hydration to fill those voids. This allows for the material to be placed easily and can create a low permeability layer in the field with little or no
compactive effort unlike compacted clay liners. There has been limited research done on bentonite coated gravels and the impact of cyclic loading on its permeability. This thesis presents research into the impact of cyclic load testing on the hydraulic conductivity of BCG materials.

1.2 Purpose

Due to increasing use of BCG liners, the hydraulic conductivity of these liners needs to be tested. Some testing has been done on this material but little to none has been done on the permeability of BCGs subjected to cyclic loading. This testing is of value because if this material were to be used to fill around an oil pipeline, used as a liner for a landfill or as a lining for an acid mine drainage pond, it is important that the material retain its very low hydraulic conductivity at a reasonable level while being subjected to cyclic service loading.

1.3 Objective and Approach

The main objective of this research is to determine the ability of BCGs to retain their original low hydraulic conductivity during cyclic loading. In order to examine this specific material property, the hydraulic conductivity at cyclic intervals of loading was compared with the initial hydraulic conductivity before cyclic loading was applied.

Three BCG mixtures were provided by AquaBlok; 2080, 3070, and 1585. These samples correlate to the amount of bentonite by weight to the amount of aggregate by weight (for example, 2080 sample has 20% bentonite to 80% aggregate). Using these
mixtures, three samples were created and placed into triaxial cells. Initial permeability testing was done before any cyclic loading was applied to the samples. After enough measurements had taken place to get a suitable average of the sample hydraulic conductivity, the samples were exposed to cyclic triaxial testing. Each sample was subjected to up to 600 cycles at 1% axial cyclic strain and an additional 600 cycles for 2% axial cyclic strain. The hydraulic conductivity was measured every 200 cycles. Testing the samples at two different cyclic axial strain amplitudes (1% and 2%) allowed for a study of the impact of the strain level on the sample permeability. The initial hydraulic conductivity was compared with values measured after every 200 cycles.

1.4 Thesis Outline

This thesis is comprised of five chapters that include background, research objectives and approach, and results from the study. Chapter 1 delves into important background information about the material being used and applications of the material, in addition to objectives of the study and approach that the researcher took in testing. Chapter 2 covers literature review of bentonite coated gravel and similar landfill liners. Chapter 3 presents the design of the experiments, which covers sample preparation and implementation of cyclic loading tests. Chapters 4 and 5 present the results attained and summarize the results while outlining the conclusions and recommendations for bentonite coated gravels. Appendix A contains hydraulic conductivity measurements for tests performed for this research while Appendix B presents the applied displacement and measured force results during cyclic loading tests.
Chapter 2: Literature Review

2.1 Introduction

Geosynthetic clay liners (GCLs) and bentonite coated gravel (BCG) are increasingly being used as a material for impermeable (or very low permeability) landfill liners in order to mitigate water table contamination from leachate or chemicals harmful to the environment that may drain from the landfill. BCGs and GCLs are being used for landfill liners for many reasons: raw materials are widely available, they are easy to construct, offer resistance to differential settlement, exhibit material manufacturing uniformity, and often are more cost effective than compacted clay liners. Current data shows that geomembrane/GCL liners are as effective as, and may be more effective than, geomembrane/clay liners (Bureau of Waste Management Wisconsin Department of Natural Resources, 2000). In order to place the BCG material, it can be poured into contaminated ponds and water bodies from barges or boats and because the bentonite is coated around coarse aggregate, the aggregate-like material can flow to the bottom and congregate with each other. This material is often shipped in bags and in order to pour the material, cutting the bag open and allowing the material to pour out as seen in Figure 2-1 will sufficiently distribute the material until it is hydrated. The coated bentonite material then hydrates to expand and forms a low permeable layer. The expansive nature of
bentonite allows for the material to achieve low permeability while being strong since it combines the low hydraulic conductivity of bentonite clay with the shear strength of the gravel aggregate. There have been many studies on landfill clay liners and on bentonite. Discussion of behavior of clay liners, bentonite material, bentonite sand mixtures, and bentonite coated gravel are provided in this chapter.

Figure 2-1. BCG material directly poured from shipping bag (VanTuyl & Vatland, September/October 2012)

2.2 Clay Liners

Clay liners have been a widely used material for landfill liners due to their low permeability. Once compacted, the hydraulic conductivity of these liners is about $10^{-7}$ cm/s or less (Benson, Zhai, & Wang, 1994). This was found to be the maximum allowable hydraulic conductivity for landfill liners as most studies reviewed mentioned $10^{-7}$ cm/s or lower as the barometer for hydraulic conductivity of a landfill liner. For
compacted clay liners, factors that influence hydraulic conductivity are: water content during compaction, method and effort involved in compaction, clod size of clay, and interlocking of layers (Bagchi, 2004). They are quite effective as low permeable liners as long as the liner is constructed appropriately according to the factors previously mentioned. However, this can be difficult to perform in field as many of the factors can be difficult to control. As shown in a field study which analyzed the field performance of clay liners that were explicitly made to achieve a low hydraulic conductivity ($10^{-7}$ cm/s or lower), about one in four failed to meet this standard (Benson, Daniel, & Boutwell, 1999). They found that one of the leading causes of this high rate of failure is that the water content of the compacted material often deviated from the optimum, either higher or lower. In the field, it can be very difficult to have the exact water content that may be required to achieve low permeability standards due to factors that cannot be adequately controlled. Although they concluded that liners can be made with a large variety of clay soils (Benson, Daniel, & Boutwell, 1999), there can be a high probability that the liner may not meet minimum permeability standards.

2.3 Bentonite

For the purpose of this thesis, it is important to understand what bentonite is and how it behaves. One important characteristic of bentonite is the amount of montmorillonite minerals present in a bentonite rich hydraulic barrier. This is important as the montmorillonite minerals will determine the barrier's engineering properties, i.e. swelling ability, hydraulic conductivity, freeze-thawing resistance and etc. (Roberts,
Soils which contain montmorillonite exhibit a considerable potential for volume change. Because of this characteristic, they are sometimes known as expansive soils (Powrie, 2004). Due to this expansive ability, water particles will not only be absorbed into the layers but also will be attached, or bonded, to the external surface area. This expansive ability due to high content of montmorillonite in bentonite clay makes this expansive soil an ideal candidate for liner applications as the expansive material fills voids that are left in the liner that normally would not get filled. Salt cations, such as sodium, calcium, magnesium, and potassium, dissolved in soil water are absorbed on the clay surfaces as exchangeable cations to balance the negative electrical surface charges. Hydration of these cations and adsorptive forces exerted by the clay particles themselves can cause the accumulation of a large amount of bound water between the clay particles (Nelson & Miller, 1992). Water molecules that have bonded to the clay particle surface cause the pore space to be significantly filled by the bound water. The stagnant or bonded water molecules can occupy a significant portion of the total pore space, leaving a limited volume of free pore space through which water can flow as seen in Figure 2-2 (Roberts, 2007). This can give rise to low hydraulic conductivity even for clays that may have a relatively high initial void ratio but contain significant amount of bentonite (Rowe, Mukunoki, & Bathurst, 2006).
A small increase in bentonite, from 2 to 5%, can dramatically increase the thickness of the coating and fill the pore-throats between particles that are responsible for conducting flow through the liner (Abichou, Benson, & Edil, 2002). As seen in Figure 2-3, the bentonite expands to fill the voids in between the coarse aggregates thereby filling the likely flow paths for water. The hydraulic conductivity starts to decrease rapidly with even a slight increase in bentonite content, to a hydraulic conductivity of $7 \times 10^{-7}$ cm/s (Abichou, Benson, & Edil, 2002).
The most common type of bentonite for clay liners is sodium bentonite. Its potential for low hydraulic conductivity makes it the ideal material for clay liners (Roberts, 2007). This is due to the fact that more swelling can occur in a sample having exchangeable sodium (Na$^{2+}$) cations than in a sample with calcium (Ca$^{2+}$) cations (Nelson & Miller, 1992). Calcium bentonite is another form that is more permeable than sodium bentonite. However, sodium bentonite is particularly susceptible to shrinkage when exposed to certain chemicals and shrinkage can lead to cracking and large increases in hydraulic conductivity. Due to its high shrink-swell potential, sodium bentonite is more susceptible to these types of deleterious reactions than other types of bentonite (Gleason, Daniel, & Eykholt, 1997). It is important to note that when very low or high pH values of permeating liquid are anticipated, using calcium bentonite may result in a lower
hydraulic conductivity values. However, sodium bentonite results in lower hydraulic conductivity with permeating liquids of near neutral pH values.

2.4 Bentonite Coated Sand

One of the materials that can benefit from having bentonite added to it is sand. There have been many research studies on the properties and capabilities of sand-bentonite mixtures. In particular, the hydraulic conductivity of sand bentonite mixtures is a well-researched topic. Many researchers have investigated the topic and have come to a similar conclusion that a hydraulic conductivity that meets landfill requirements of $10^{-7}$ cm/s or lower (Kenny, van Veen, Swallow, & Sungaila, 1992; Pandian, Nagaraj, & Raju, 1995; Sivapullaiah, Sridharan, & Stalin, 2000; Mollins, Stewart, & Cousens, 1996) is achievable given the construction parameters are properly met. Hydraulic conductivity depends on the properties of the bentonite and on the continuity of the bentonite matrix within the soil-liner mixture, where the distribution and amount of bentonite crucial to this property (Kenny, van Veen, Swallow, & Sungaila, 1992).

One issue that arises from bentonite coated sand is its low shear strength. Hydrated sodium bentonite has relatively low internal shear strength and is more susceptible than clay liners to foreign objects punching through the liner (Bureau of Waste Management Wisconsin Department of Natural Resources, 2000). Even though bentonite sand mixtures have been shown to meet the $10^{-7}$ cm/s or lower hydraulic conductivity requirement for landfill liners, its low shear strength is often a constraint in landfill design with shear strength ranging from 5.8 kPa to 6 kPa (Gleason, Daniel, &
Eykholt, 1997). One concern is that the friction angle ($\varphi$) of sand is low and because of this low friction angle, the internal shear strength of GCLs constructed with bentonite sand liners strongly depends on the type of bonding (needled or stitched fibers that penetrate through the thickness of the bentonite sand liner, or the adhesive to bond the clay to the geotextiles) since the clay that fills the voids will not have a high strength resistance (Benson, Bouazza, Fratalocchi, & Manassero, 2005). As can be seen in Figure 2-4, there is a significant difference in the strength of reinforced versus unreinforced GCLs made of bentonite sand liners. This is understandable as sand is widely considered a low shear strength soil and will need some sort of reinforcing to increase the bonding potential of the soil because bentonite will not be able to carry large loads. If the stresses in a landfill liner are of paramount importance, stronger materials such as bentonite coated gravel have to be considered.
Figure 2-4. Shear Strength of reinforced vs unreinforced GCLs made of bentonite sand layer (Benson, Bouazza, Fratalocchi, & Manassero, 2005)

2.5 Bentonite Coated Gravel

Bentonite coated gravel (BCG) is coarse aggregate that has been coated with bentonite (using cellulosic polymer as the binder) as shown in Figure 2-5. Typically, the polymer is added to the mix for pre-hydration binding of the material. Bentonite is an expansive montmorillonite rich clay material which will hydrate and swell once it comes into contact with water or liquid (see Figure 2-6). For BCGs the typical bentonite contents range from 15 to 30% while the rest is coarse aggregate. This section deals with the swelling, compressibility, shear strength, and permeability characteristics of BCGs.
Figure 2-5. BCG material (AquaBlok, Ltd., 2016)

Figure 2-6. Depiction of BCG hydration and swelling (AquaBlok, Ltd., 2016)
2.5.1 Swelling Characteristics

As mentioned previously, the ability for bentonite to hydrate and swell (Figure 2-7) and fill voids makes BCG a good material prospect for landfill liners or low permeable layers. The swelling properties of BCG liners are of paramount importance as the amount the liner swells will have a large impact on the properties of the hydraulic barrier, most importantly the hydraulic conductivity (Neaman, Pelletier, & Villieras, 2003). To increase the overall shear strength of the liner, gravel is added to the bentonite. For compacted clay liners, the amount of gravel must be under 50-60% as it was found that clayey soils may not fill the voids if the gravel percentage is above 50-60%, thereby resulting in high hydraulic conductivities (Shelley & Daniel, 1993). For BCG materials, gravel percentages can range from 70-85% (AquaBlok, Ltd., 2016). If one were to add the same amount of gravel that is found in BCGs to clay liners, the compacted clay liners would most likely not meet the maximum $10^{-7}$ cm/s requirement as the voids would not be completely filled.

Roberts (2007) examined the swelling of BCGs depending on the type of liquid it was absorbing. It was found that many factors affect the swelling of BCGs: cation valence, cation ionic radii, solution concentration, and solution pH (Roberts, 2007). As seen in Figure 2-7, the quality of water and the type of chemicals in the water have a large effect on the swelling ability of bentonite and therefore a significant impact on the permeability of the liner. It can be seen that as the quality of water decreases, the swelling decreases dramatically. The quality of water used to hydrate the sample will have a
significant impact on its swell potential. Solution pH can have a large effect on the swelling of BCGs as it was noted in samples that less swelling was observed in samples soaked in solutions containing pH values above or below a range of 5-9. In addition to the pH, the swelling caused by the cations in the hydrating liquid on the clay will be dictated by the solution concentrations rather than their valence (Roberts, 2007). Hence calcium bentonite is useful in creating a low permeable liner when the pH values of contact liquid are above or below a range of 6-10 but if this is not a consideration in design, sodium bentonite is more likely to provide a lower hydraulic conductivity barrier.

Figure 2-7. Effect of the quality of liquid on swelling of bentonite coated gravel (Roberts, 2007)
2.5.2 Compressibility and Shear Strength

The shear strength of the BCG is an important material attribute that needs to be considered as the barrier needs to be strong enough to support its own weight and loadings that are typically encountered by a landfill liner: weight of the landfill, dynamic loading caused by landfill equipment, and service dynamic loads etc. (Roberts, 2007). One-dimensional consolidation tests were performed by Roberts (2007) which showed that for BCGs, the calculated compressibility ($C_c$) ranged from 0.05 to 0.08 for the highest compactive effort to uncompacted specimen respectively (Roberts, 2007). The low compressibility of BCGs is attributed to the high gravel content of the samples. When the material hydrates, the aggregate particles are pushed away from each other and results in a low shear resistance but as it is compressed, the aggregate particles come into contact with one another and the load is carried by the in-contact aggregates acting as a skeleton (Roberts, 2007). Roberts noted that with higher compactive effort, one risks cracking the aggregate, leading to channels to form when the bentonite does not exist and can allow for water to pass through. Consolidated undrained triaxial testing was done on these three variously compacted samples as well up to a maximum axial strain of 15%. The results of the testing are displayed in Figure 2-8 and Figure 2-9. The cohesion of the material ranged from 104 kPa to 140 kPa while the internal friction angles ranged from 12.9 to 17.5 degrees (Roberts, 2007). Due to the gravel content, higher shear strengths are possible with BCGs with relatively little or no compaction.
RP: Reduced Proctor, SP: Standard Proctor, IP: Intermediate Proctor

Figure 2-8. Stress-strain curves for BCG testing (Roberts, 2007)
RP: Reduced Proctor, SP: Standard Proctor, IP: Intermediate Proctor

Figure 2-9. Mohr circles for BCG testing (Roberts, 2007)
Measured moisture content during compaction has a considerable influence on the shear strength of BCGs. It was observed during cone penetration testing (CPT) that depending on the compactive effort and the water content, the cone penetration resistance can decrease dramatically. As seen in Figure 2-10, when considering the super modified (SM) proctor compacted sample, it was observed that penetration resistance was three times less when the water content was 2% below optimum and 19 times less when it was 2% above optimum whereas the CPT resistance did not change much with the other compaction methods (Roberts, 2007). It is critical when using BCGs that the material is not over compacted as a small variance in the moisture content can lead to a weakened liner.

![CPT results for BCG as a function of water content](image)

**Figure 2-10.** CPT results for BCG as a function of water content (Roberts, 2007)
2.5.3 Hydraulic Conductivity

Compaction is an engineering technique to densify soils by packing the particles closer together and a reduction in the volume of air can lead to a decrease in the permeability if the water content is less than or at optimum (Attom, 1997). Roberts (2007) analyzed the effect of various compactive efforts on BCG as well, as it is well known that compaction can have a large effect on the permeability of any soil material, not just BCGs. To test for the effect of compactive effort on BCG permeability, five compactive efforts were studied (standard proctor, modified proctor, reduced proctor, intermediate proctor and super modified proctor). Using samples compacted with these various compactive efforts, the permeability was tested. The hydraulic conductivity of the material ranged from $3.5 \times 10^{-9}$ cm/s to $6.1 \times 10^{-10}$ cm/s with the lowest energy compaction resulting in the highest permeability and a lower permeability resulting from intermediate or higher proctor energy levels seen in Figure 2-11 (Roberts, 2007). It should be noted that compactive effort slightly affected hydraulic conductivity as all samples had a hydraulic conductivity value to the order of $10^{-9}$ cm/s to $10^{-10}$ cm/s. He concluded that for the materials studied, low permeability is attainable with minimal compactive effort even though gravel makes up 70% of BCG material tested. This contrasts with what is presented by Shelly and Daniel where they suggest that for clay liners that contain gravel contents of greater than 50-60%, the clayey soil does not completely fill the voids resulting in a higher hydraulic conductivity (Shelley & Daniel, 1993). Very low hydraulic conductivity is clearly possible with the BCG material with little or low compactive effort because of the expansive nature of the bentonite.
2.6 Proposed Work

As described above, there has been a great deal of effort researching the effectiveness of compacted clay liners and bentonite sand mixtures as a suitable landfill liner but limited studies have been carried out on the effectiveness of BCG liners. Furthermore, cyclic loading or dynamic loads, such as those experienced during earthquake loading, has not been a topic of investigation. In this work, it is proposed that dynamic cyclic testing be done on BCGs to better understand the behavior of this material. Roberts (2007) studied the chemical composition of BCGs and examined the material properties of BCGs to determine if this material can be used for landfill liners (swelling, shear strength, compressibility, hydraulic conductivity). This material may be subjected to dynamic loading due to compaction equipment, dump trucks, construction
techniques, and earthquake loading, and thus investigating the dynamic response of these material is important. In particular, researching if a BCG liner will retain its original low hydraulic conductivity during dynamic loading is critical. No work to date has been done on the residual permeability of BCGs after cyclic loading and if this is to be used in the field as a low permeable liner, it must be known if the material will retain its low permeability properties when subjected to these dynamic loads. Therefore, it was proposed that the impact of cyclic loading on the hydraulic conductivity of BCGs be studied in this thesis.
Chapter 3: Experiment Design

3.1 Introduction

In this chapter, the experimental design is covered for preparing and testing of three separate mixes of varying bentonite (15%, 20%, & 30%) to coarse aggregate (85%, 80%, & 70%) contents. These samples were prepared and tested in triaxial cells for cyclic testing. Each sample was subjected to up to 1,200 cycles at varying axial cyclic strain levels and the hydraulic conductivity was measured every 200 cycles. Two different cyclic axial strain amplitudes (1% and 2%) were used to test the impact, if any, of the amplitude of cyclic loading on permeability. The initial hydraulic conductivity was compared with values measured after every 200 cycles for both strain amplitudes.

3.2 Sample Materials

The materials for this research were provided by AquaBlok and were sent in buckets of three separate mixes. Three BCG mixes of 2080, 1585, and 3070 were received by The Ohio State University for testing. The mix numbers are the amount of sodium bentonite coating to amount of limestone aggregate (gravel) by weight. For example, 2080 means that by weight there is 20% of bentonite to 80% gravel aggregate for that mix. Cellulosic polymer was used by AquaBlok as the pre-hydration binder in the
preparation of the mixes. A summary of the sample mixtures can be found in Table 3-1. All samples received had AASHTO #8 gradation with a nominal aggregate size 3/8 inches (Ohio Department of Transportation, 2002).

Table 3-1. Sample mix composition

<table>
<thead>
<tr>
<th>Sample</th>
<th>% Bentonite by Weight</th>
<th>% Aggregate by Weight</th>
<th>Aggregate Gradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1585</td>
<td>15</td>
<td>85</td>
<td>AASHTO #8</td>
</tr>
<tr>
<td>2080</td>
<td>20</td>
<td>80</td>
<td>AASHTO #8</td>
</tr>
<tr>
<td>3070</td>
<td>30</td>
<td>70</td>
<td>AASHTO #8</td>
</tr>
</tbody>
</table>

3.3 Sample Preparation

In order to prepare the BCG specimens, a split mold was assembled first. When considering how to prepare the samples, it was of paramount importance that the sample diameter (2.8 inches) was maintained throughout the height of the sample. To constrain the sample in the transverse direction, the samples were prepared within the split mold. Figure 3-1 shows the split mold set up where it is ready for sample deposit. The split mold has been placed on the bottom loading cap and the constraining O-ring has been fully tightened and the rubber membrane pulled over the split mold, thereby reducing wrinkles as much as possible.
BCG samples were prepared by taking one-inch lifts of dry BCG material and pouring the material into the split mold and then adding enough deaired water to submerge all of the material as seen in Figure 3-2. This is similar to how this material will hydrate when poured in the field. A target dry unit weight of 70 to 90 pcf was used and this density was used to determine the amount of material to be poured in per lift.
To constrain the material to the target height of about one inch per lift, the team developed an attachment to go onto the triaxial loading rods that would allow access to free water for the sample but would constrain any excessive macro-swelling in the vertical direction. The attachment is a plastic disk that has drilled holes that allow for the sample to access water while still constraining the height. A filter paper was then placed between the material and the disk to keep the material from sticking to the disk. The lift was then allowed to hydrate and swell for approximately 12-18 hours with weights placed on top of the sample in order to keep the sample to the desired height (Figure 3-3). By constraining the material to a predetermined height, light compaction was possibly
achieved without risking cracking of the aggregate through using proctor compaction methods (Roberts, 2007).

![Figure 3-3. BCG hydrating while confining sample height](image)

After the allotted time, another lift was added by pouring in more BCG. These steps were repeated until the sample had the desired height for the test. After the final lift was added, some material was left over that would not fit in the split mold. This material was then measured and subtracted from the total target weight to get actual weight of material used. The final specifications of the sample were a minimum height of 2.25 inches and a diameter of 2.8 inches. A height of 2.25 inches was determined by referencing the ASTM D5084-16a which states “The diameter and height of the specimen
shall each be at least 6 times greater than the largest particle size within the specimen.”

AASHTO #8 aggregate gradation, which has a nominal aggregate size of 3/8 of an inch, gave a minimum height of 2.25 inches. This minimum size was chosen because the permeability of the material is so low that in order to test the hydraulic conductivity within a reasonable time period, the height needed to be as short as the ASTM specifications would allow.

After the final layer had hydrated for specified amount of time, the rest of the triaxial cell was assembled around the sample. First, filter paper, porous stone and then the loading cap were placed on top of the sample. The rubber membrane was then pulled over the loading cap and rubber O-rings were pulled around the loading cap to isolate the sample as seen in Figure 3-4. The triaxial cell wall and triaxial cell were then assembled around the sample and connected to the pressure board (Figure 3-5).
Figure 3-4. BCG sample with membrane, O-rings, and saturation tubes connected
3.4 Triaxial Cyclic Testing

The samples were attached to permeability boards and a confining pressure of 11 psi was applied to the samples. The backpressure was set to 9 psi and the top pressure was set to 1 psi to allow for water to pass from the bottom to the top of the samples. These pressures resulted in a hydraulic gradient of approximately 100. ASTM D5084-16a recommends that for low permeable soils that the hydraulic gradient be no greater than 30. However, since the hydraulic conductivity of the material is so low, a hydraulic gradient of 100 was chosen to allow for permeability readings within a reasonable time frame and a gradient of 100 is common for testing permeability of GCLs and bentonite rich soils (Shackelford, Benson, Katsumi, Edil, & Lin, 2000; Roberts, 2007). The values
of 11 psi, 9 psi, and 1 psi were selected as they were the lowest possible pressures that would allow for a high hydraulic gradient. The cell pressure allowed for the flexible membrane around the sample to stay adhered to the sample and only allowed the water inside the sample to flow through it and not along the interface between the sample and the membrane. Once water passing through the sample reached a steady state condition, hydraulic conductivity readings were taken and at least 4 readings were taken to calculate a suitable average for the initial hydraulic conductivity.

Consolidated drained cyclic tests were performed on an MTS 55 kip hydraulic biaxial load frame with a load cell of 500 lb attached to the frame to monitor load output during testing. The testing configuration can be seen in Figure 3-6. The triaxial cell was placed on the base of the moving piston and the top of the loading rod was attached to the loading frame with a ball head attachment that allows for axial deformation to be applied during testing. The valves on the triaxial cell were kept open to allow for water to drain out or into the sample during testing so that there would not be significant excess pore water pressures. Once it was connected to the frame, the amount of load placed on the system was taken to zero and the knob that was securing the loading rod was unscrewed, thereby releasing it and cyclic testing could begin.
To make contact with the sample and to establish a reference point for the program, 1 psi contact stress was applied to the sample. This reference point was then taken as zero displacement and once the stress was stable, strain controlled cyclic loading was applied. Cyclic loading was performed in strain control to successfully agitate the sample. A total amplitude of 0.0225 inches, or 1% of the sample height, was applied on the sample in a 0.5 Hz sinusoidal wave for a total of 200 cycles. This percentage is well above reasonable strain that a clay like soil may experience. In clay-like soils, the post-earthquake volumetric strains due to cyclic softening will be less than those experienced
by sand-like soils due to cyclic liquefaction and a typical value of 0.5% or less is appropriate for most clay-like soils (Robertson & Cabal, 2015). The sine wave was applied to the sample for 200 cycles and then the program was stopped and slowly unloaded the sample. The loading rod was then secured, and the triaxial cell was taken off the MTS machine and permeability readings began. This process was repeated for 400 and 600 cycles for each of the three BCG mixtures. This process was then completed with the same procedure but with a total sine amplitude of 2% for another 600 cycles for each BCG mixture. The testing was performed at 0.5 Hz in order to conform to ASTM D5311 which states, “Dynamic loading equipment used for load-controlled cyclic triaxial tests shall be capable of applying a uniform sinusoidal load at a frequency range of 0.1 to 2.0 Hz.” for liquefaction testing even though liquefaction was not a parameter of concern in this research. Applied displacement and measured load were recorded through the MTS machine and these graphs can be seen in Appendix B.

3.5 Permeability Testing

Hydraulic conductivity testing before cyclic loading and after each repetition of 200 cycles was measured using the falling head permeability test procedure as provided by ASTM 5084-16a Method B, Falling Head Permeability Test. As previously mentioned a hydraulic gradient of 100 was used. The hydraulic conductivity of the sample was calculated by Equation 1 once steady state flow was achieved. Steady state flow is described by ASTM D5084-16a as “the ratio of outflow to inflow rate is between 0.75 and 1.25, and the hydraulic conductivity is steady.” In order to allow for more accurate
measurements of the hydraulic conductivity, a ratio of outflow to inflow rate of 0.8 to 1.20 was used instead.

\[ k = \frac{a+L}{2A+\Delta t} \ln \frac{\Delta h_1}{\Delta h_2} \] (1)

3.6 Closing Remarks

To establish the effect of cyclic loading on the permeability of BCGs, permeability testing was combined with cyclic triaxial testing. Cyclic triaxial tests was performed for 200 cycles, and then the sample was removed from the testing apparatus. The sample was then placed back on the table and hydraulic conductivity testing began immediately after cyclic testing had concluded. This procedure was repeated for 400 additional cycles performed with a 1% axial cyclic strain and also for 600 additional cycles performed at 2% axial cyclic strain.
Chapter 4: Results and Discussion

4.1 Introduction

The main objective of this research is to determine the ability of BCGs to retain their original low hydraulic conductivity during cyclic loading. In order to examine this specific material property, the hydraulic conductivity at cyclic intervals of loading was compared with the initial hydraulic conductivity before cyclic loading was applied. This was accomplished by subjecting 3 separate mixes, with varying bentonite contents (15% to 30%) to 1,200 total cycles of a strain controlled cyclic testing. First 600 cycles were performed at 1% axial cyclic strain and then an additional 600 cycles were performed at 2% axial cyclic strain. The results from this research will benefit engineers designing landfill liners by providing them with a better understanding of this BCG material and its permeability.

4.2 Sample Characteristics

Sample height and diameter were measured before subjecting the samples to cyclic testing and after cyclic testing was complete (see Table 4-1). It should be noted that at the end of cyclic loading the height of the sample was slightly less than the initial height and the final diameter was slightly larger than the initial diameter. After all cyclic
and permeability testing was completed, the B-Value of the samples were measured to verify that the samples were reasonably saturated. These results are also shown in Table 4-1. The B-values for all the samples were 0.95 or higher indicating that all three samples were nearly saturated. The samples were then disassembled and their unit weight and moisture contents were measured which are shown in Table 4-1. The dry unit weights obtained for the three samples were within the target dry unit weight range of 70 to 90 pcf. Furthermore, the 1585 sample had the highest dry unit weight because it has the highest amount of coarse aggregate by weight compared to the other samples. It can also be observed that as the amount of coarse aggregate decreased and the amount of bentonite increased, the dry unit weight decreased. The measured sample moisture contents are higher than those presented in Roberts (2007). The procedure used in this thesis allowed for maximum hydration of the samples by allowing free access to water during sample preparation. This caused the moisture contents to be higher because the material was allowed to continue to hydrate throughout sample preparation. As can be seen in Table 4-1 the sample with the highest bentonite content has the highest moisture content. The water contents can be assumed to be close to the maximum amount of water that the samples can absorb. It has been shown that the maximum time for bentonite to swell to its peak value was at most seven days (Komine, 2004) and all three nearly-saturated samples tested in this work were exposed to free-flowing water throughout the entirety of the test for about two months. The moisture content was also recorded in order to calculate the final dry unit weight of all samples tested. Because the B-values for all
samples were at 0.95 or higher, the maximum moisture content that nearly-saturated BCGs may have is approximately 21% to 28% for the samples investigated in this study.
Table 4-1. Summary of material properties of the samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average Initial Height (in)</th>
<th>Average Final Height (in)</th>
<th>Average Initial Diameter (in)</th>
<th>Average Final Diameter (in)</th>
<th>B-Value</th>
<th>Moisture Content (%)</th>
<th>Total Unit Weight (pcf)</th>
<th>Dry Unit Weight (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1585</td>
<td>2.24</td>
<td>2.19</td>
<td>2.76</td>
<td>2.84</td>
<td>0.95</td>
<td>21.95</td>
<td>116.16</td>
<td>87.50</td>
</tr>
<tr>
<td>2080</td>
<td>2.32</td>
<td>2.30</td>
<td>2.78</td>
<td>2.79</td>
<td>0.99</td>
<td>23.48</td>
<td>114.54</td>
<td>84.28</td>
</tr>
<tr>
<td>3070</td>
<td>2.25</td>
<td>2.25</td>
<td>2.76</td>
<td>2.97</td>
<td>0.96</td>
<td>27.89</td>
<td>107.43</td>
<td>73.89</td>
</tr>
</tbody>
</table>
4.3 Effect of Cyclic Loading on Hydraulic Conductivity

The effect of cyclic loading on the permeability of BCG materials was examined by testing three different BCG mixtures of varying bentonite content. Cyclic loading was applied in steps of 200 cycles at a time and hydraulic conductivity was tested after each 200 cycles. The first 600 cycles were implemented at 1% axial cyclic strain amplitude and the last 600 cycles were carried out at 2% axial cyclic strain amplitude. The hydraulic conductivity measurements of each sample were compiled into tables and were compared to the initial hydraulic conductivity after every 200 cycles.

The results of permeability testing are presented in Table 4-2 through Table 4-4. For each BCG mixture, the table presents the 4 hydraulic conductivity readings that were used to get an average for the permeability after each cyclic loading test. These tables are also shown visually in Figure 4-1 though Figure 4-4 to better visualize how cyclic loading was affecting the hydraulic conductivity of BCG mixtures tested. The dashed vertical line indicates where axial cyclic strain amplitude increased from 1% to 2%.
Table 4-2. Sample 1585 Hydraulic Conductivity Measurements

<table>
<thead>
<tr>
<th>Sample: 1585</th>
<th>1% Axial Cyclic Strain</th>
<th>2% Axial Cyclic Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 Cycles</td>
<td>200 Cycles</td>
</tr>
<tr>
<td>K (cm/s)</td>
<td>K (cm/s)</td>
<td>K (cm/s)</td>
</tr>
<tr>
<td>6.56 E-09</td>
<td>6.55 E-09</td>
<td>6.01 E-09</td>
</tr>
<tr>
<td>6.09 E-09</td>
<td>6.51 E-09</td>
<td>6.32 E-09</td>
</tr>
<tr>
<td>6.13 E-09</td>
<td>5.57 E-09</td>
<td>6.08 E-09</td>
</tr>
<tr>
<td>5.93 E-09</td>
<td>6.32 E-09</td>
<td>5.72 E-09</td>
</tr>
<tr>
<td>Average</td>
<td>6.18 E-09</td>
<td>6.24 E-09</td>
</tr>
</tbody>
</table>

Table 4-3. Sample 2080 Hydraulic Conductivity Measurements

<table>
<thead>
<tr>
<th>Sample: 2080</th>
<th>1% Axial Cyclic Strain</th>
<th>2% Axial Cyclic Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 Cycles</td>
<td>200 Cycles</td>
</tr>
<tr>
<td>K (cm/s)</td>
<td>K (cm/s)</td>
<td>K (cm/s)</td>
</tr>
<tr>
<td>4.01 E-09</td>
<td>4.97 E-09</td>
<td>4.37 E-09</td>
</tr>
<tr>
<td>4.65 E-09</td>
<td>4.66 E-09</td>
<td>4.99 E-09</td>
</tr>
<tr>
<td>4.34 E-09</td>
<td>4.44 E-09</td>
<td>4.53 E-09</td>
</tr>
<tr>
<td>4.38 E-09</td>
<td>3.83 E-09</td>
<td>4.77 E-09</td>
</tr>
<tr>
<td>Average</td>
<td>4.34 E-09</td>
<td>4.47 E-09</td>
</tr>
</tbody>
</table>

Table 4-4. Sample 3070 Hydraulic Conductivity Measurements

<table>
<thead>
<tr>
<th>Sample: 3070</th>
<th>1% Axial Cyclic Strain</th>
<th>2% Axial Cyclic Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 Cycles</td>
<td>200 Cycles</td>
</tr>
<tr>
<td>K (cm/s)</td>
<td>K (cm/s)</td>
<td>K (cm/s)</td>
</tr>
<tr>
<td>3.06 E-09</td>
<td>3.08 E-09</td>
<td>3.09 E-09</td>
</tr>
<tr>
<td>2.87 E-09</td>
<td>3.36 E-09</td>
<td>2.57 E-09</td>
</tr>
<tr>
<td>3.14 E-09</td>
<td>3.32 E-09</td>
<td>3.69 E-09</td>
</tr>
<tr>
<td>2.80 E-09</td>
<td>2.41 E-09</td>
<td>2.66 E-09</td>
</tr>
<tr>
<td>Average</td>
<td>2.97 E-09</td>
<td>3.04 E-09</td>
</tr>
</tbody>
</table>
Figure 4-1. Effect of cyclic loading on hydraulic conductivity

Figure 4-2. Ratio of cyclic hydraulic conductivity to initial hydraulic conductivity vs number of cycles
Figure 4-3. Sample vs. regulatory (maximum $10^{-7}$ cm/s) hydraulic conductivity

Figure 4-4. Hydraulic conductivities measured
Roberts (2007) used sample mixture 3070 to study if compaction had any significant effect on the permeability of BCGs. It was found that the hydraulic conductivity of BCGs ranged from of $3.5 \times 10^{-9}$ cm/s (little to no compaction) to $6.1 \times 10^{-10}$ cm/s (maximum compaction). As can be seen from Table 4-4, the initial hydraulic conductivity for this 3070 sample (which was not compacted) was $2.97 \times 10^{-9}$ cm/s, which is close to the value reported by Roberts (2007) for little or no compaction. It can also be seen from Table 4-2 to Table 4-4 that as the bentonite content in the mix increases, the initial measured permeability slightly decreases.

Figure 4-1 and Figure 4-2 illustrate the impact of cyclic loading on the permeability of the mixes as the number of cycles increase. Figure 4-1 also includes the range of measurements taken for the average hydraulic conductivity values and trendlines for these values at 1% and 2% cyclic axial strain. The permeability of these BCG materials increased very slightly with number of cycles except for sample 1585. The hydraulic conductivity of sample mixtures 2080 and 3070 both increased very slightly over the course of cyclic testing at roughly a linear rate. The slope of the hydraulic conductivity measurements up to 600 cycles were $9 \times 10^{-12}$ cm/s/cycle for 2080 and $4 \times 10^{-13}$ cm/s/cycle for 3070 and the slopes of the hydraulic conductivity measurements from 600 to 1,200 cycles were $2 \times 10^{-12}$ cm/s/cycle for 2080 and $7 \times 10^{-13}$ cm/s/cycle for 3070. The difference in slopes after the cyclic amplitude was increased to 2% is negligible. As shown in Figure 4-2, the maximum change from initial hydraulic conductivity to final hydraulic conductivity (at the end of 1,200 cycles) was a 5% increase for sample 1585, 32% increase for sample 2080, and a 24% increase for 3070. These increases only appear
large because of the linear scale on Y-axis that is being used to show the changes in permeability in Figures 4-1 and 4-2. Since the exponential of the hydraulic conductivity is most important when considering permeability (not the absolute values of hydraulic conductivity), the hydraulic conductivity values were also plotted on a logarithmic scale as seen in Figure 4-4. As can be observed in Figure 4-3 (linear scale on Y-axis) and Figure 4-4 (logarithmic scale on Y-axis), all hydraulic conductivity measurements (being to the order of $10^{-9}$ cm/sec) are graphically seen to be far below the maximum requirement (of $10^{-7}$ cm/sec) for the permeability of liners.

In essence, the number of cycles does not significantly impact the permeability of BCGs materials tested. All hydraulic conductivity readings are in the order of $10^{-9}$ cm/s. No compactive energy was exerted on the samples but by constraining the volume to which it could swell during sample preparation, as the bentonite expanded it had nowhere to expand other than the voids between the aggregates thereby reducing the permeability to the lower level noted. These values for the hydraulic conductivity of BCG materials are also within the range of permeabilities that numerous other researchers attained for other landfill lining material (Stępiewski, Widomski, & Horn, 2011; Shackelford, Benson, Katsumi, Edil, & Lin, 2000; Gleason, Daniel, & Eykholt, 1997; Sivapullaiah, Sridharan, & Stalin, 2000; Pandian, Nagaraj, & Raju, 1995; Kenny, van Veen, Swallow, & Sungaila, 1992; Mollins, Stewart, & Cousens, 1996; Abichou, Benson, & Edil, 2002; Shelley & Daniel, 1993; Roberts, 2007). The values for permeability fall within, or close to, the range of $3.5\times10^{-9}$ cm/s to $6.1\times10^{-10}$ cm/s for hydraulic conductivity that was presented by an earlier study on BCG material (Roberts, 2007). This also reinforces the
conclusion that compaction has little effect on the permeability of BCGs. The number of cycles and the axial cyclic strain amplitude did not significantly impact the permeability of the BCG samples studied in this work.

4.4 Observations

During 1% axial cyclic testing, it was observed that the water in the bottom pipette on the permeability board oscillated by about 0.2 cm. During 2% axial cyclic testing, it was observed that the water level in the pipette for the bottom oscillated by about 0.4 cm. It was also observed that after cyclic loading was applied, air bubbles would be present in the triaxial tubbing which could be the result of cavitation in the sample. Once all testing had been completed, it was observed that there were slight deformations in the sample from the cyclic loading process. As can be seen in Figure 4-5 through Figure 4-8, after cyclic testing was completed the samples exhibited bulging in the bottom third of the sample. Note that in Figure 4-6, sample 1585 was placed upside down so the bulging can be observed in the top third of the sample.
Figure 4-5. Sample 3070 deformation immediately after testing
Sample placed upside down

Figure 4-6. Sample 1585 after testing completed

Figure 4-7. Sample 2080 after testing completed
4.5 Problems Encountered

Initially, samples with height of 6 inches were prepared but after roughly a month all samples were showing signs that they were still consolidating as well as hydrating. It was decided that to accelerate the permeability testing process, the sample height had to be reduced. All sample heights were then reduced to 2.25 inches to conform to minimum ASTM D5084-16a height requirements for permeability testing. The aggregate gradation given for the mixes was AASHTO #8 for which the nominal aggregate size is 3/8 inches (AquaBlok, Ltd., 2016). The ASTM specification states “the diameter and height of the specimen shall each be at least 6 times greater than the largest particle size within the specimen” which results in a height of 2.25 inches. To reduce the sample height from 6
inches to 2.25 inches, a guide was used to make sure the height of the samples would meet the minimum height requirements. This guide can be seen in Figure 4-9.

![Sample height guide](image)

**Figure 4-9. Sample height guide**

The triaxial chambers were disassembled and the samples were trimmed down to the required heights using the guide shown in Figure 4-9. The triaxial cell was then reassembled in the same way as described earlier in the section but with an added loading bar to account for the loss in height.
Another problem that was encountered was the presence of air bubbles in the triaxial tubes after cyclic testing. This problem was solved by clearing the tubes with water before permeability readings were initiated.
Chapter 5: Summary and Conclusions

5.1 Summary

Bentonite coated gravel (BCG) is coarse aggregate that has been coated with bentonite (using cellulosic polymer as the binder). Typically, a polymer is added to the mix for pre-hydration binding of the material. Bentonite is an expansive montmorillonite rich clay material which will hydrate and swell once it comes into contact with water or liquid. For BCGs the typical bentonite contents range from 15 to 30% while the rest is coarse aggregate.

The main objective of this research is to determine the ability of bentonite coated gravel (BCGs) to retain their original low hydraulic conductivity during cyclic loading. In order to examine this specific material property, the hydraulic conductivity at cyclic intervals of loading was compared with the initial hydraulic conductivity before cyclic loading was applied.

The effect of cyclic loading on the permeability of bentonite coated gravel material was investigated in this study. Three BCG mixtures of varying bentonite (15%, 20%, & 30%) to gravel contents (85%, 80%, & 70%) were examined. To study the effect of cyclic axial loading on permeability, the three samples were subjected to a total of 1,200 strain controlled sinusoidal cycles of loading. 600 cycles were with a total cyclic axial
strain amplitude of 1% and another 600 cycles were at a total cyclic axial strain amplitude of 2%. These cycles were applied in 200 cycle increments and the hydraulic conductivity of each sample was measured at the end of each 200-cycle increment. The hydraulic conductivity readings were taken in accordance with ASTM 5084-16a for Method B, Falling Head Permeability Test. After enough readings were taken so that a suitable average was calculated, another 200 cycles were applied until 1,200 total cycles were completed. All the hydraulic conductivities were then compiled into tables and graphed. These hydraulic conductivities were compared with the initial hydraulic conductivity measurements to evaluate the effect of cyclic loading on the permeability of BCGs.

5.2 Conclusions

From this research, it can be concluded that cyclic loading has an insignificant effect on the low permeability of bentonite coated gravels. The permeability of all the samples after final testing had increased very slightly but the increase in each sample permeability was negligible. All hydraulic conductivity measurements showed that the hydraulic conductivity was always on the order of $10^{-9}$ cm/s. Because the hydraulic conductivity measurements were always of this order, it can be concluded that the permeability was not affected by cyclic axial loading in terms of number of cycles applied or amplitude of cyclic axial strain. The requirement for landfill liners is widely established as $10^{-7}$ cm/s or lower. All permeability readings were two orders of magnitude lower than this maximum allowable hydraulic conductivity requirement even
after all 1,200 cycles were completed. Therefore, bentonite coated gravels can be used as landfill liners where the liner will be exposed to cyclic/dynamic loading and will maintain its very low hydraulic conductivity.

Of all the samples that were tested, a bentonite content of 15% (i.e. sample 1585) provides sufficiently low hydraulic conductivity for the use of the material as a liner (which is to have a maximum hydraulic conductivity of $10^{-7}$ cm/s). The materials cost of BCGs may be further reduced possibly by decreasing the bentonite content to 10% but this requires further testing.

5.3 Recommendations for Future Work

To conclusively say that the permeability of bentonite coated gravels remains relatively constant under cyclic loading, more triaxial tests will need to be conducted as only 3 specimens were run through cyclic loading and then tested for hydraulic conductivity. To add on to this, 6-inch samples tested at 1% and 2% strain can also provide a better idea for how full-thickness landfill liners may react. Note that for these samples to be tested, adequate time will be needed to be allowed for the samples to fully hydrate and consolidate.

The cost of the BCG material may possibly be further reduced by decreasing the bentonite content to 10%. This additional testing may need to be carried out.

Further work on BCGs needs to be done for torsional cyclic loading. While this thesis only dealt with cyclic loading in the axial direction, dynamic loading in the field
can happen in three dimensions and it is important it know how the sample will behave under torsional loading as well.

Long-term testing also needs to be done on these liners. BCGs are still a relatively new type of material and it is unknown how these liners will behave decades after construction. Case studies should be carried out in the field to evaluate if the hydraulic conductivity and shear strength are retained over the service life of these structures or if these liners need any maintenance.

Another future research endeavor might be to examine if compaction effort will have any effect on the permeability of BCGs after cyclic loading. This could be useful in order to know how much compaction, if any, is needed so that BCG liners will retain their permeability during cyclic loading.
References


Ohio Department of Transportation. (2002). *703 AGGREGATE*. Ohio Department of Transportation.


Appendix A: Hydraulic Conductivity Tables
### Table A-1. Pre-Cyclic Loading Permeability Measurement for Sample 1585

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### Table A-12. Post 800 Cycles Permeability Measurement for Sample 2080

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### Table A-13. Post 1,000 Cycles Permeability Measurement for Sample 2080

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62
Table A-14. Post 1,200 Cycles Permeability Measurement for Sample 2080

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Table A-15. Pre-Cyclic Loading Permeability Measurement for Sample 3070

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Table A-16. Post 200 Cycles Permeability Measurement for Sample 3070

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### Table A-21. Post 1,200 Cycles Permeability Measurement for Sample 3070

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Appendix B: Measurements for Cyclic Loading
Figure B-1. Applied Displacement Graph of Sample 1585 0-200 Cycles at 1% Cyclic Axial Strain
Figure B-2. Measured Force Graph of Sample 1585 0-200 Cycles at 1% Cyclic Axial Strain
Figure B-3. Applied Displacement Graph of Sample 1585 200-400 Cycles at 1% Cyclic Axial Strain
Figure B-4. Measured Force Graph of Sample 1585 200-400 Cycles at 1% Cyclic Axial Strain
Figure B-5. Applied Displacement Graph of Sample 1585 400-600 Cycles at 1% Cyclic Axial Strain
Figure B-6. Measured Force Graph of Sample 1585 400-600 Cycles at 1% Cyclic Axial Strain
Figure B-7. Applied Displacement Graph of Sample 1585 600-800 Cycles at 2% Cyclic Axial Strain
Figure B-8. Measured Force Graph of Sample 1585 600-800 Cycles at 2% Cyclic Axial Strain
Figure B-9. Applied Displacement Graph of Sample 1585 800-1,000 Cycles at 2% Cyclic Axial Strain
Figure B-10. Measured Force Graph of Sample 1585 800-1,000 Cycles at 2% Cyclic Axial Strain
Figure B-11. Applied Displacement Graph of Sample 1585 1,000-1,200 Cycles at 2% Cyclic Axial Strain
Figure B-12. Measured Force Graph of Sample 1585 1,000-1,200 Cycles at 2% Cyclic Axial Strain
Figure B-13. Applied Displacement Graph of Sample 2080 0-200 Cycles at 1% Cyclic Axial Strain
Figure B-14. Measured Force Graph of Sample 2080 0-200 Cycles at 1% Cyclic Axial Strain
Figure B-15. Applied Displacement Graph of Sample 2080 200-400 Cycles at 1% Cyclic Axial Strain
Figure B-16. Measured Force Graph of Sample 2080 200-400 Cycles at 1% Cyclic Axial Strain
Figure B-17. Applied Displacement Graph of Sample 2080 400-600 Cycles at 1% Cyclic Axial Strain
Figure B-18. Measured Force Graph of Sample 2080 400-600 Cycles at 1% Cyclic Axial Strain
Figure B-19. Applied Displacement Graph of Sample 2080 600-800 Cycles at 2% Cyclic Axial Strain
Figure B-20. Measured Force Graph of Sample 2080 600-800 Cycles at 2% Cyclic Axial Strain
Figure B-21. Applied Displacement Graph of Sample 2080 800-1,000 Cycles at 2% Cyclic Axial Strain
Figure B-22. Measured Force Graph of Sample 2080 800-1,000 Cycles at 2% Cyclic Axial Strain
Figure B-23. Applied Displacement Graph of Sample 2080 1,000-1,200 Cycles at 2% Cyclic Axial Strain
Figure B-24. Measured Force Graph of Sample 2080 1,000-1,200 Cycles at 2% Cyclic Axial Strain
Figure B-25. Applied Displacement Graph of Sample 3070 0-200 Cycles at 1% Cyclic Axial Strain
Figure B-26. Measured Force Graph of Sample 3070 0-200 Cycles at 1% Cyclic Axial Strain
Figure B-27. Applied Displacement Graph of Sample 3070 200-400 Cycles at 1% Cyclic Axial Strain
Figure B-28. Measured Force Graph of Sample 3070 200-400 Cycles at 1% Cyclic Axial Strain
Figure B-29. Applied Displacement Graph of Sample 3070 400-600 Cycles at 1% Cyclic Axial Strain
Figure B-30. Measured Force Graph of Sample 3070 400-600 Cycles at 1% Cyclic Axial Strain
Figure B-31. Applied Displacement Graph of Sample 3070 600-800 Cycles at 2% Cyclic Axial Strain
Figure B-32. Measured Force Graph of Sample 3070 600-800 Cycles at 2% Cyclic Axial Strain
Figure B-33. Applied Displacement Graph of Sample 3070 800-1,000 Cycles at 2% Cyclic Axial Strain
Figure B-34. Measured Force Graph of Sample 3070 800-1,000 Cycles at 2% Cyclic Axial Strain
Figure B-35. Applied Displacement Graph of Sample 3070 1,000-1,200 Cycles at 2% Cyclic Axial Strain
Figure B-36. Measured Force Graph of Sample 3070 1,000-1,200 Cycles at 2% Cyclic Axial Strain