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Development of a Hydraulic Conductivity Placement Window using Centrifuge Techniques

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Project Summary

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Institution: University of Arkansas
Classification: Senior
Grade Point Average: 3.86/4.00
Area of Study: Civil Engineering (Geotechnical Emphasis)
Title of Project: Development of a Hydraulic Conductivity Placement Window using Centrifuge Techniques

Abstract

A centrifuge soil testing device, currently operated by researchers at the University of Arkansas, was used to develop a technique to determine a hydraulic conductivity placement window. The purpose of this research was to develop a placement window by means of a centrifuge instead of by means of a panel board. Soil specimens were created at standard Proctor energy and at 50 percent of Standard Proctor energy at -3 percent of optimum, -1.5 percent of optimum, two specimens at optimum, +1.5 percent of optimum, and +3 percent of optimum water content. Values of hydraulic conductivity for the respective specimens were determined to be 1.90E-08, 2.18E-08, 2.10E-08, 1.85E-08, 2.00E-08, and 1.80E-08. Specimens were observed to have been centrifuged at too large of a rotation speed which induced too high of stresses on the specimen, and too large of a gradient across the specimens. Piping, slurry formation, and resedimentation was observed in several of the specimens; specifically piping was observed in the specimens that had porous bronze filters instead of porous stone filters.

Introduction

The use of a centrifuge for testing fine-grained, compacted, soils was first used in the early 20th century. Due to the small size of the small-scale medical centrifuges that were initially used, the practice of centrifuging soils was overlooked by other methods such as pressure plates and Tempe cells (Khanzode et al., 2002). The main advantage of a centrifuge has been the ability of a centrifuge to gather data in a rapid amount of time. Other methods of obtaining soil water characteristic curves (SWCC) from the Tempe cell and pressure plates can take up to 4-6 weeks for 6-8 data points while similar amounts of data can be obtained using a centrifuge in only 6-8 days (Khanzode et al., 2000). In addition to this, the centrifuge has also been used to prepare consolidated specimens for use in the direct simple shear test (Gilbert, 2011) or to evaluate the hydraulic conductivity of soil (McCartney, 2011).

For this research, centrifugation was performed on soil specimens to determine the permeation properties of kaolinite soil. The soil specimens that were tested were similar to the specimens tested by Maldonado and Coffman (2012), except a centrifuge was used to obtain soil hydraulic conductivity values instead of a panel board. Following the Daniel and Benson (1991) method, a placement window was developed using the reduced Proctor curve by determining 1) the compaction properties and 2) the permeation properties. A background on the use of a centrifuge for determination of hydraulic properties, the methods used to find the properties, and the results obtained from the centrifugation that was performed during this research project are presented herein.

Background

Centrifuges have been used to obtain soil properties since Gardner (1937) developed an equation and test method for obtaining data for the capillary tension and moisture content

relationship. By means of the SWCC, Gardner (1937) discovered that the relationship between soil suction and water content or degree of saturation could be determined from just a single test. As per Gardner (1937), when a soil is below the saturation point, soil suction is comparable to the tension in the liquid that is held by a capillary. As soil becomes drier, or further from the saturation point, more energy is required to remove water from the soil. Therefore, to obtain different values on the SWCC, 1) the radial distance to the specimen or 2) the angular velocity of the centrifuge are varied.

Gilbert (2011) used the centrifuge as a method of obtaining consolidated specimens for use in the direct shear test. This practice significantly reduced the amount of time necessary to obtain a consolidated specimen. Likewise, McCartney (2011) used a centrifuge to calculate the hydraulic conductivity of soil specimens under high stresses in small amounts of testing time. Soil permeability is an important soil property that must be understood when constructing soil liners beneath or above landfills. Based on the Daniel and Benson (1991) method, soils should be compacted at modified, standard, and reduced energy in the laboratory prior to field compaction to determine a field placement window to ensure landfill liner performance. As reported by Maldonado and Coffman (2012), laboratory tests have been performed at the University of Arkansas to develop a placement window and then field tests were conducted to verify the hydraulic conductivity of soils at three unique testing pad locations. The laboratory testing that was required to obtain the placement window took over six months to complete using a panel board system that was capable of performing six tests at a given time.

Methods and Materials

The use of a centrifuge as a replacement for the panel board flexible wall permeameter, that was used in Maldonado and Coffman (2012), was the main focus of this research program.

The centrifugation methods and setup, that was used for the research described herein, were similar to what was used in Gilbert et al. (2011), except the focus of this research was on determining the hydraulic conductivity value for the soil specimens rather than the preparation of consolidated soil specimens. Also, instead of the slurry specimens that were used by Gilbert et al. (2011), the soil specimens were compacted at standard energy and 50 percent reduced Proctor energy. Six specimens were compacted at standard and reduced Proctor energy to develop the associated Proctor curves (-3 percent of optimum, -1.5 percent of optimum, two specimens at optimum, +1.5 percent of optimum, +3 percent of optimum water content). After the specimens were created, the specimens were trimmed to allow water to fit into the top of the PVC pipe that was used as the compaction and rigid wall permeability mold. The hydraulic conductivity was then determined through the specimen. The specimens were rotated in the centrifuge at an angular velocity of 1000 rpm for a variety of time intervals until at least two pore volumes of flow permeated the specimens.

Preparation of Soil Specimens

As previously mentioned, soil specimens were compacted to obtain a standard and reduced Proctor curve by compacting the specimens reported in Table 1. Mixed Kaolinite specimens of 500g were prepared by mixing Kaolinite soil (Theive Kaolin, Sandersville, GA) with water, the Kaolinite specimens were mixed to produce specimens with varying water contents to produce the Proctor curves (Table 1). The soil properties of the Kaolinite that was used in this research can be found in Table 2 (Mahmood 2017).

The soil specimens were compacted to PVC pipes, each with a nominal height of 8.24 cm and a nominal diameter of 5.24 cm. The number of drops required for each compaction effort were calculated using the energy equation (Equation 1). The hammer that was used to compact

the specimens is presented in Figure 1. The hammer weighed 2.59 lb and the hammer drop height was 1.02 ft. The number of drops required to produce standard energy was calculated to be 11 drops the for each of three lifts. The number of drops required to produce modified energy was calculated to be 50, 50, 51 drops for each of the three lifts, respectively. The number of drops required to produce 50 percent standard proctor energy was calculated to be five, five, and six drops for each of the three lifts, respectively.

Table 1. Soil specimens prepared for 50 percent of standard Proctor energy identified as Reduced Energy.

Specimen Number	1	2	3	4	5	6
Total Weight (g)	500	500	500	500	500	500
Dry Soil (g)	454.55	448.43	442.48	436.68	431.03	442.48
Water (g)	45.45	51.57	57.52	63.32	68.97	57.52
Target w%	10.00	11.50	13.00	14.50	13.00	16.00
Actual w%	7.73	11.96	10.99	12.04	8.53	13.69
Dry Unit Weight (lb/ft ³)	85.18	81.26	85.90	81.02	86.74	84.35

Table 2. Properties of Kaolinite that was used for this research (from Mahmood 2017).

Property	Kaolinite
Liquid Limit	31.5
Plastic Limit	28.1
Clay Size Fraction	47.2
Specific Gravity, G _s	2.67

$$E = \frac{D_H * N_D * H_W * N_L}{v} \quad \text{Equation 1}$$

E = Energy, ft-lbf/ft³

D_H = Drop Height, ft = 1.02 ft

N_D = Number of Drops, (11, 11, 11 for standard energy; 5, 6, 6 for reduced energy)

H_W = Weight of the Hammer, lb = 2.59 lb

$N_L = \text{Number of lifts} = 3 \text{ lifts}$

$V = \text{Volume, ft}^3 \approx 0.0063 \text{ ft}^3$ (Depending on which PVC pipe was used)

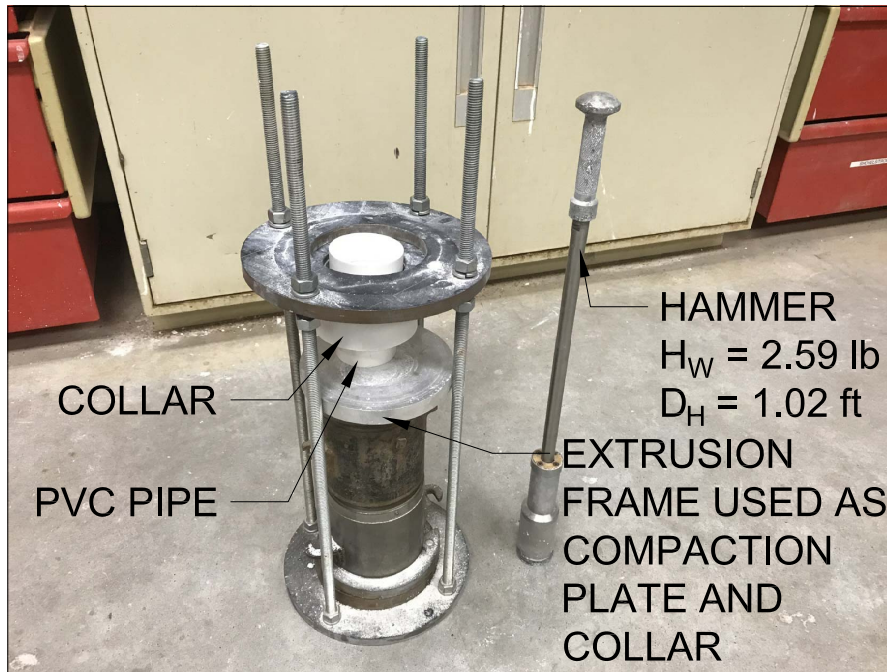
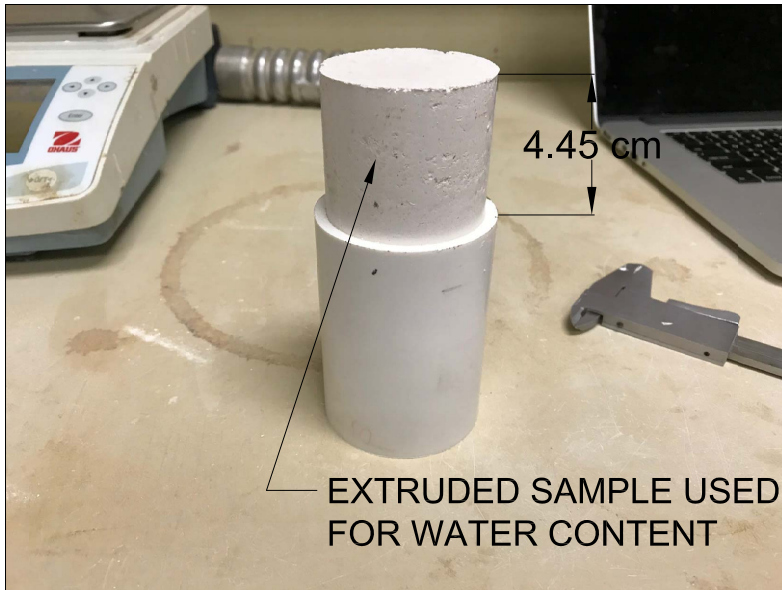
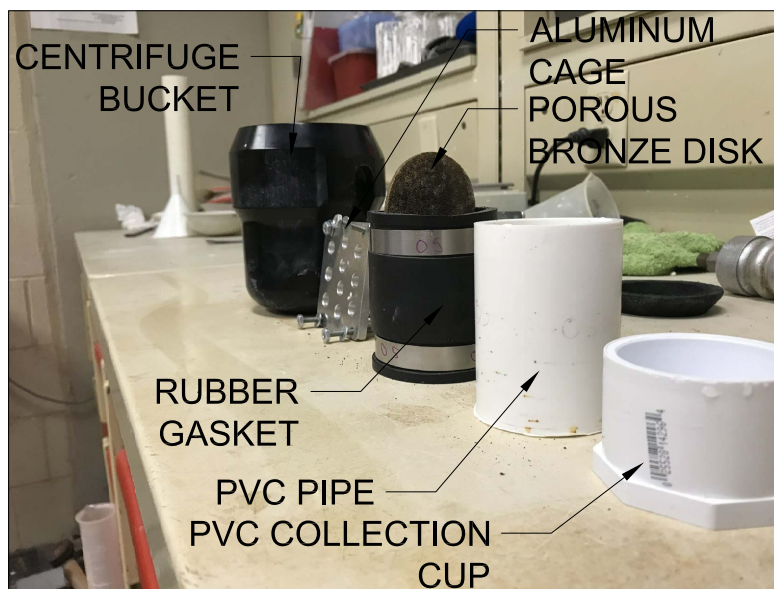


Figure 1. Photograph of apparatus used to compact the soil specimens.

After compaction, each specimen was weighed in the PVC pipe to determine the total unit weight of the specimen. Next, approximately 4.45 cm of the specimen was extruded from the PVC pipe, by means of the GeoTac Sigma-1 load frame (Figures 2 and 3). A portion of the specimen was removed to ensure that an adequate amount of water volume was added to the PVC pipe above the soil specimen. The removed portion of the specimen was used to collect water content data (Figure 2a). The water content data and total unit weight data were used to determine the dry unit weight for the Proctor curve. The specimen remaining in the PVC pipe was then weighed and loaded into the testing apparatus that consisted of the PVC pipe, a rubber gasket, and a bronze porous disk or porous stone (Figure 2b).



(a)



(b)

Figure 2. (a) Photograph of soil specimen after extruding 4.45 cm of the specimen by using GeoTac Sigma-1 load frame. (b) Centrifugation apparatus including rubber gasket, bronze porous disk (or porous stone), PVC collection cup, PVC pipe, centrifuge bucket, and aluminum cage.

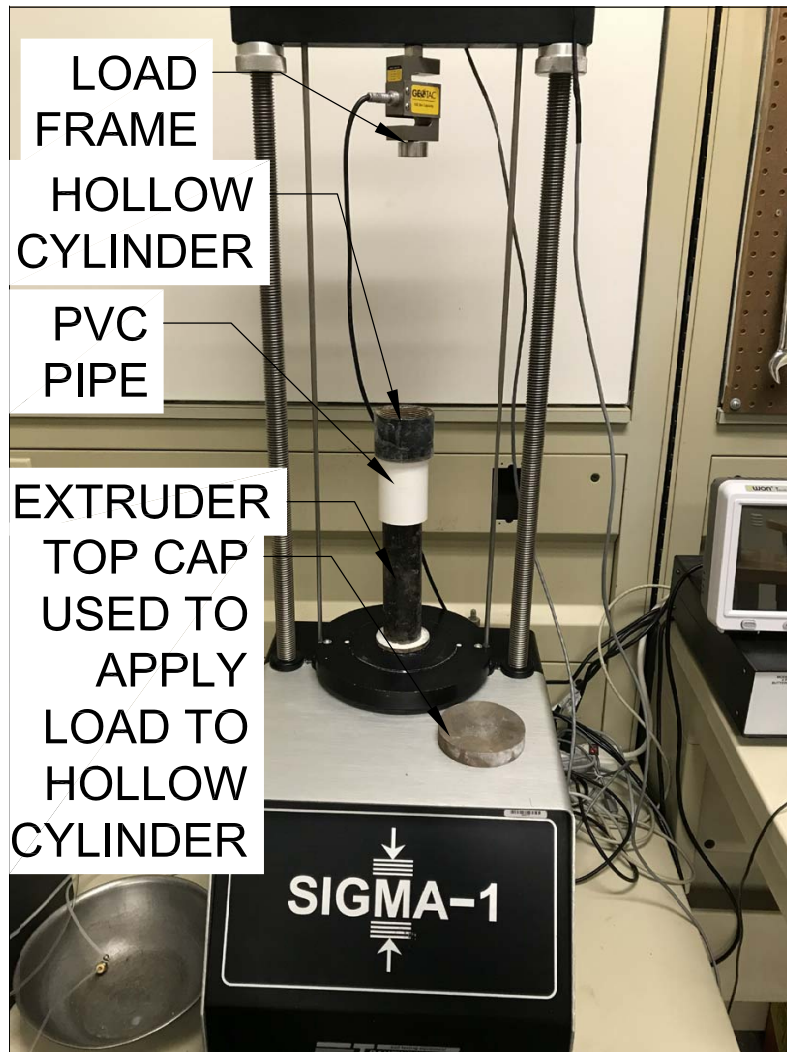


Figure 3. GeoTac Sigma-1 Load frame used to extrude 4.45 cm of each specimen from the PVC pipes.

Testing Apparatus

As previously mentioned, each assembled testing apparatus consisted of: 1) the soil specimen inside of the PVC pipe, 2) a rubber gasket, 3) two hose clamps, 4) a PVC collection cup, and 5) a porous bronze disk or porous stone (Figures 4 and 5). Each of the six apparatuses was assembled by first pushing the PVC collection cup into the rubber gasket and tightening one of the hose clamps to create a seal between the collection cup and rubber gasket interface. Next,

the porous bronze disk or porous stone was placed inside of the rubber gasket and forced into position above the PVC collection cup. The PVC collection cup acted as a structural support for the porous bronze disk or porous stone. The use of a porous bronze disk, instead of a porous stone, was preferred due to the large amount of force that acted upon the testing apparatus during rotation in the centrifuge. In this research, a porous stone was adequate and was recommended, however for larger soil specimens, or at a higher rotational speed, the stone may crack. A piece of filter paper was then installed on top of the porous bronze disk or porous stone, followed by the PVC pipe that contained the soil specimen. The bottom of the soil specimen was placed in intimate contact with the filter paper, the air gap in the PVC that was created by extruding a portion of the soil specimen was located above the soil specimen. While tightening the last hose clamp around the PVC pipe/rubber gasket interface, pressure was applied to the top of the pipe and to the bottom of the collection cup to ensure that no gaps formed between the pieces. If the apparatus was not tight enough, water was observed to seep into the spaces between each piece during centrifugation.



Figure 4. a) A soil testing apparatus and b) each soil testing apparatus in the respective aluminum cage prior to placement into the sampling bucket.

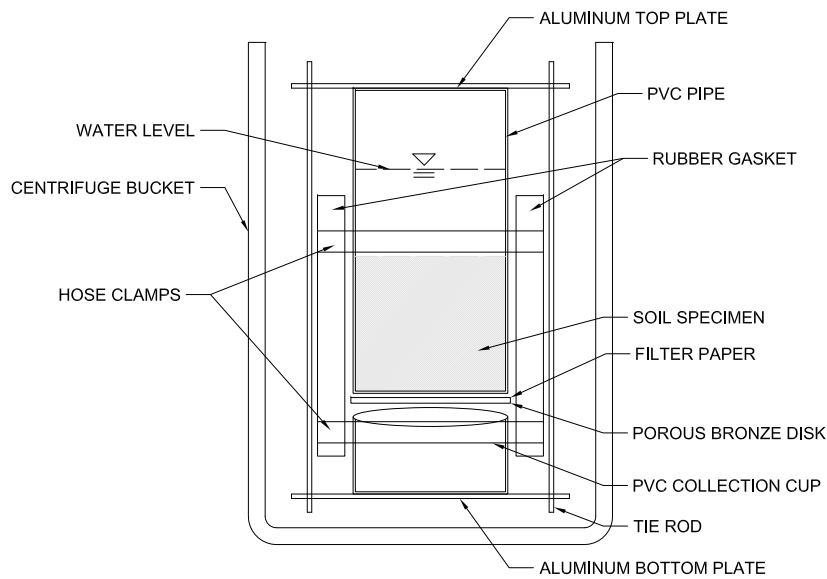


Figure 5. Exploded schematic of centrifugation apparatus.

After the apparatus was assembled, each apparatus was placed into an aluminum cage (Figure 4b). This aluminum cage helped to stabilize the specimen in the centrifuge bucket during centrifugation. After the canisters were assembled, water was poured on top of the specimen until the water level was approximately one centimeter from the top of the PVC pipe. The one centimeter air gap was used to avoid water spilling out of the apparatus during the start and stop (spin up, spin down) when centrifugation was rotating at low rotational speed. The height of the specimen was calculated by using a caliper to measure the distance from the top of the aluminum top plate down to the soil surface; the weight of the PVC and soil specimen was also collected. This same top down measurement procedure was also used to calculate the amount of water on top of the specimen before and after centrifugation.

Centrifugation

After the apparatus was assembled and loaded into the aluminum canister, each specimen was placed into the centrifuge, until all six bays in the centrifuge were occupied. The centrifuge that was used was a Beckman-Coulter Model J6-MI centrifuge. The centrifuge had a six place

JS-4.2A swinging bucket design. The reduced Proctor specimens were centrifuged at an angular velocity of 1000 rpm while being subjected to a temperature of 20°C. This corresponded to an imposed hydraulic gradient of 263.76 and effective stresses of 773.05 kN/m² on the top of the specimen and 2358.70 kN/m² on the bottom of the specimen. The standard Proctor specimens were centrifuged at an angular velocity of 380 rpm while being subjected to a temperature of 20°C. This corresponded to an imposed hydraulic gradient of 263.76 and effective stresses of 773.05 kN/m² on the top of the specimen and 2358.70 kN/m² on the bottom of the specimen.

After centrifugation began, water permeated into the top of the specimen. After enough water had infiltrated the specimen, water exited out of the bottom of the specimen into the collection cup. Specimens were initially centrifuged for one hour and the centrifugation time was increased thereafter based upon hydraulic conductivity of the soil. The reduced proctor energy specimens were centrifuged according to Table 1 in the appendix.

After each centrifugation cycle, the specimens were removed from the centrifuge and remeasured. Measurements from the top of the apparatus were acquired to both the water surface and the soil surface. Measurement from the top of the water surface was used to calculate the amount of water infiltrating into the specimen, Q_{in} . The distance to the soil was used: 1) to track the amount of consolidation that occurred during centrifugation, 2) to calculate the hydraulic conductivity, and 3) to calculate the amount of force applied to the specimen from the centrifuge.

The volume of water that left the specimen was calculated by weighing the PVC collection cup after centrifugation. To remove the cup from the apparatus, the bottom hose clamp was loosened and the PVC collection cup was gently pulled apart from the rubber gasket. Under most circumstances, water spilled out of the apparatus after the hose clamp was loosened. This

spilled water was the water that seeped into the gaps between the individual pieces of the apparatus. Prior to weighing the PVC collection cup, 1) a piece of dry paper towel was tared on the scale, 2) the water on the inside of the rubber gasket was collected with the paper towel, and 3) the spilled water that came out of the apparatus was collected with the paper towel and then the paper towel was weighed. The weight of the water in the wet paper towel was combined with the weight of the water in the PVC collection cup to acquire the total volume of water that left the specimen, Q_{out} .

Calculations

The calculations used in this research were based on acquiring a hydraulic conductivity by means of application of a centrifugal force. The equations that were used can be found in ASTM D6527 (2008). For completeness, the general form of the equation is provided in Equation 2.

$$q = k (\rho * \omega^2 * r) \quad \text{ASTM D6527 (2008)} \quad \text{Equation 2}$$

Where:

q = flux density, cm/sec,

k = hydraulic conductivity, cm/sec,

ρ = water density, gm/cm³ = 1gm/cm³,

r = radius from the center of the specimen to the rotor, cm = 18.37 cm, and

ω = rotation speed, radians/sec = 104.72 radians/sec (For the reduced Proctor specimens).

Equation 3 was developed by rearranging Equation 2 to solve for k .

$$k = \frac{q}{\rho \omega^2 r} \quad \text{ASTM D6527 (2008)} \quad \text{Equation 3}$$

Using Equation 3, the hydraulic conductivity was calculated. The flow rate of the specimen was computed by 1) measuring Q_{out} of the specimen and 2) dividing the Q_{out} value by

the amount of time that the specimen underwent centrifugation. The flux density was obtained by dividing the flow rate by the cross-sectional area of the soil specimen. The nominal radial distance to the center of the specimen was 18.37 cm, which was different than what was used in the same centrifuge by Gilbert et al. (2011). This change was due to the altered centrifugation apparatus.

Data Analysis

The majority of the data discussed in this section were collected for the 50 percent reduced Proctor energy specimens that were centrifuged to compute hydraulic conductivity values. Data are also briefly mentioned for the standard Proctor energy data.

Proctor Compaction

The Proctor curve developed from the 50 percent reduced Proctor energy data is shown in Figure 5. The observed dry unit weight values were low for the given data when compared to typical reduced Proctor curves due to poor compaction techniques. While the technique to compute hydraulic conductivity from centrifugation has been validated, the method of compaction used in this research has not been validated in any previous research.

The calculated optimum water content for the reduced Proctor energy data was 10.17 percent which was lower than the predicted optimum water content of 13 percent. This error was likely due to poor compaction techniques and small sample size of the data. Another source of this error could be due to the low moisture content of the specimens that were compacted. Based on observations in this research, the specimens should be compacted at wetter water contents (9 percent, 11.5 percent, 13 percent, 15.5 percent, and 17 percent water contents).

Secondary research was conducted to validate the compaction methods used in this research. Additional data for standard Energy compaction were added to Figure 6. This

additional data came from six compacted specimens in PVC pipe, like this research used, and six compacted specimens following standard Proctor guidelines that were compacted from the undergraduate soil mechanics course. Both sets of data fit the Proctor curve in Figure 6. Therefore, the compaction method used in this research was determined to be adequate.

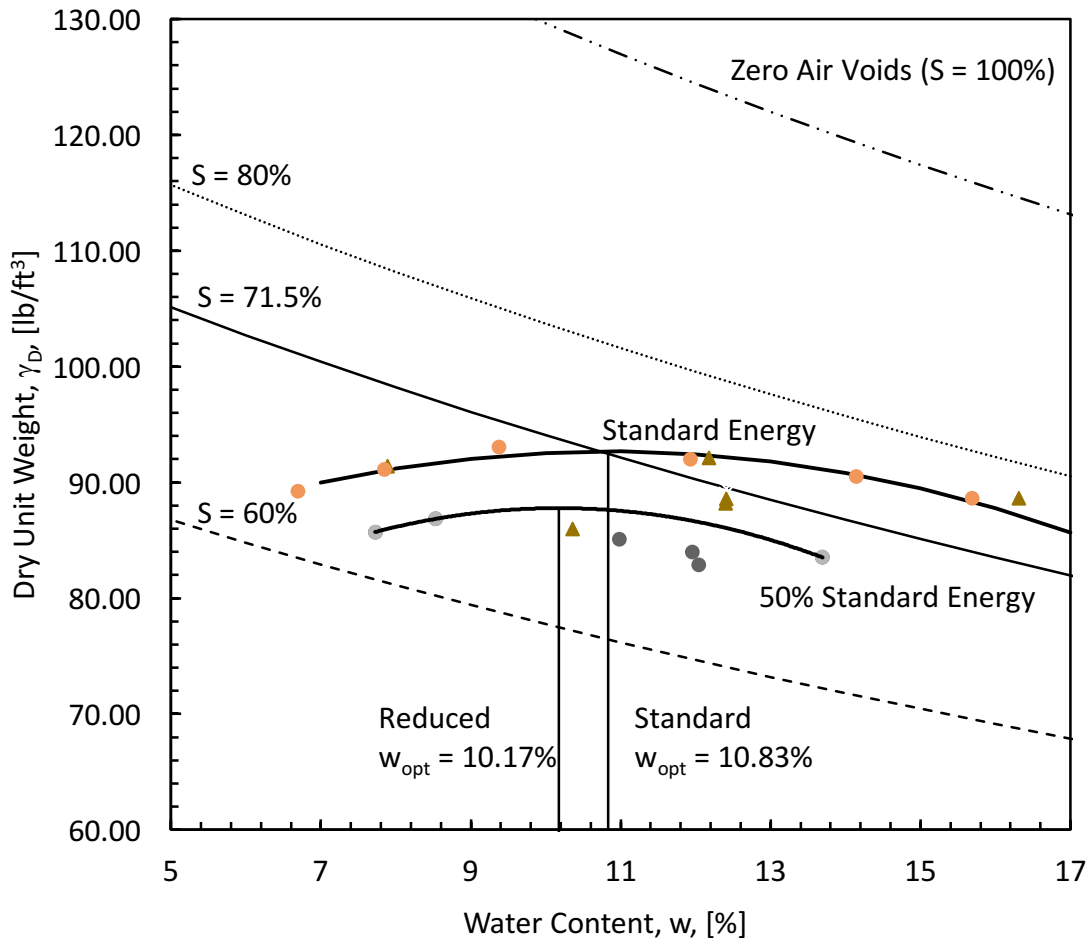


Figure 6. Proctor curve for 50 percent Proctor compaction energy.

Hydraulic Conductivity

The hydraulic conductivity for the centrifuged specimens was computed using Equation 3. Over the course of two weeks, hydraulic conductivity data were collected from the centrifuge

apparatus, as described in the methods and materials section. Ninety data points were collected for the six specimens that consisted of 15 hydraulic conductivity values per specimen.

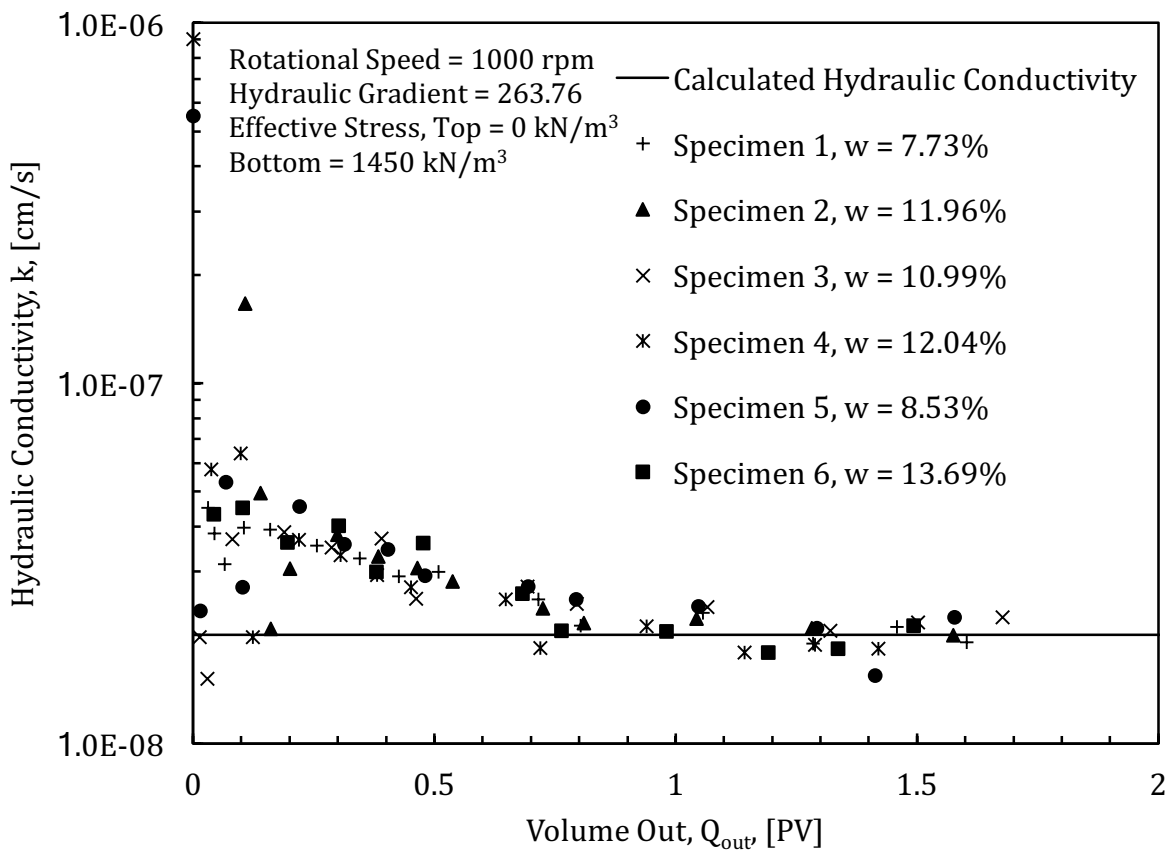
The requirements that were used for validating that the hydraulic conductivity data were adequate included: 1) collecting two pore volumes of flow out of the specimen and 2) maintaining a Q_{in}/Q_{out} ratio between 0.75 and 1.25. For this research, both requirements were not met due to the underestimation of time required to collect two pore volumes of flow and due to stresses being too high and the permeability being too low. For the six 50 percent reduced Proctor energy specimens, two pore volumes of flow was approximately 90g of water. At the measured hydraulic conductivity values, two pore volumes of water would take approximately nine days to permeate through the specimen using the centrifuge technique. The hydraulic conductivity of all six specimens as a function of volume of water that was collected from the bottom of the specimen, Q_{out} , is reported in Figure 7. The calculated hydraulic conductivity and volume ratio as a function of Q_{out} for each of the six specimens is also reported in the Appendix. The calculated hydraulic conductivity values for each specimen can be found in Table 3. The values calculated for hydraulic conductivity in this research compare closely to the values calculated for the same kaolinite soil by Zhao and Coffman (2016). Hydraulic conductivity values calculated by Zhao and Coffman using the CRS test ranged from 1E-07 to 1E-08 cm/s. The volume ratio requirement as a function of Q_{out} , for all specimens is reported in Figure 8. The volume ratio presented in Figure 8 was observed to become more precise as a function of increasing Q_{out} .

Table 3. Hydraulic conductivities for 50 percent reduced Proctor energy specimens.

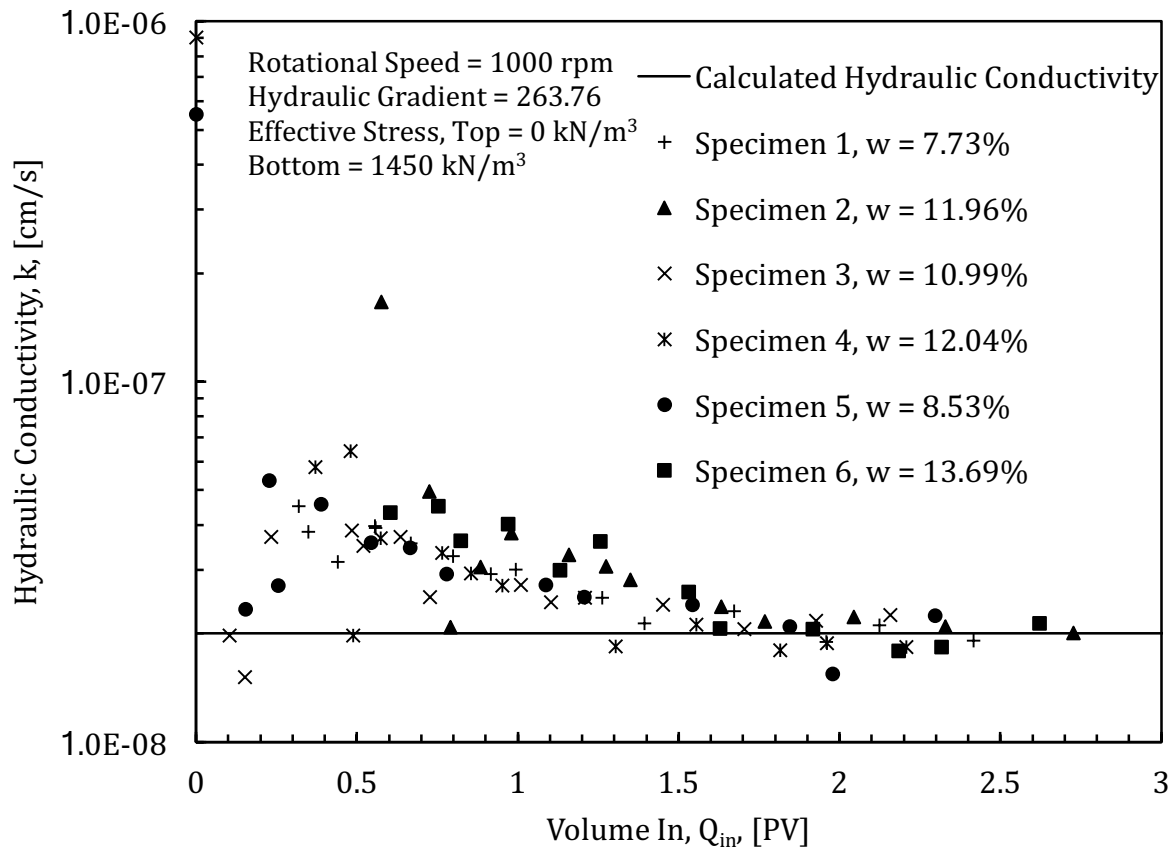
Specimen	Hydraulic Conductivity, k [cm/s]
1	1.90E-08
2	2.18E-08

3	2.10E-08
4	1.85E-08
5	2.00E-08
6	1.80E-08

The same relationship that was observed with volume ratio was observed with hydraulic conductivity values as they approached two pore volumes of flow (Figure 7 and Figure 8). For unsaturated soils, the hydraulic conductivity will increase as saturation increases to the point of saturated hydraulic conductivity. The asymptotic horizontal line in Figure 7, represented the quasi steady state saturated hydraulic conductivity of the specimens. Hydraulic conductivity value of individual the specimens can be found in the Appendix.

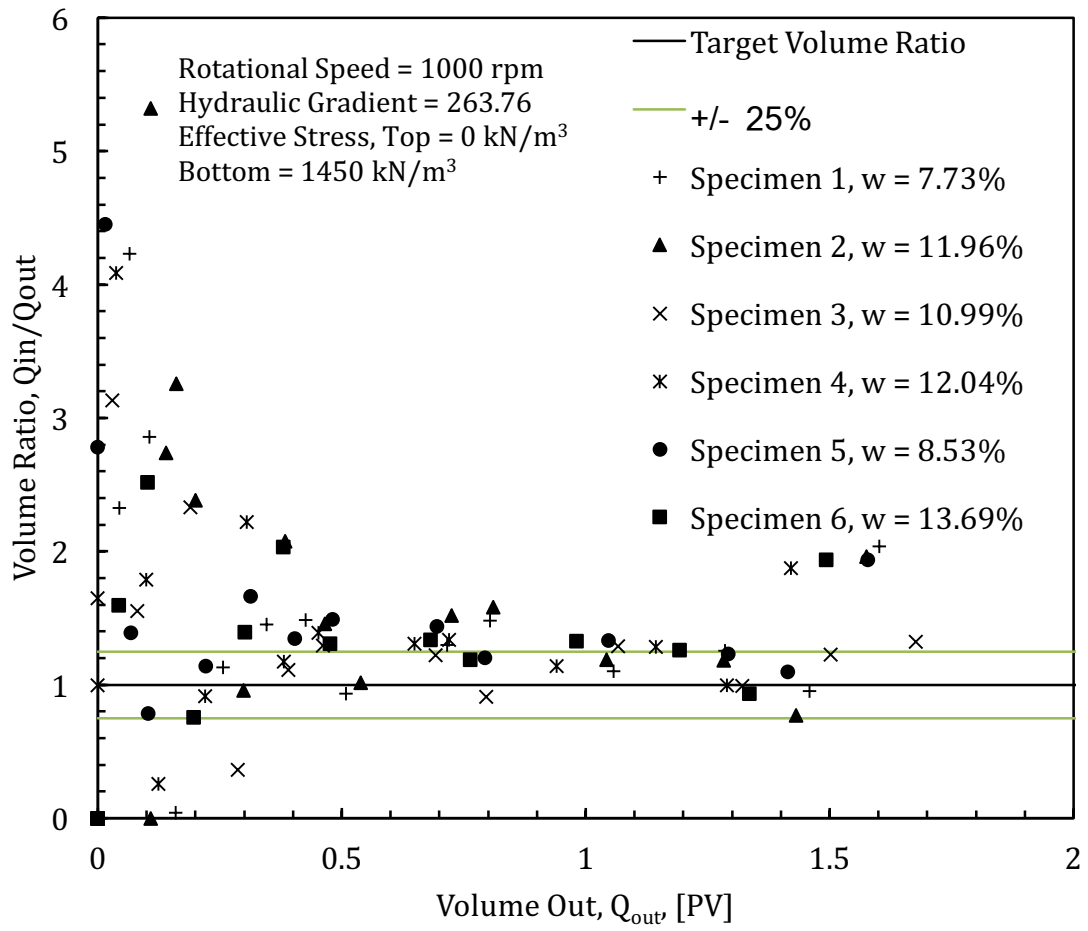


(a)

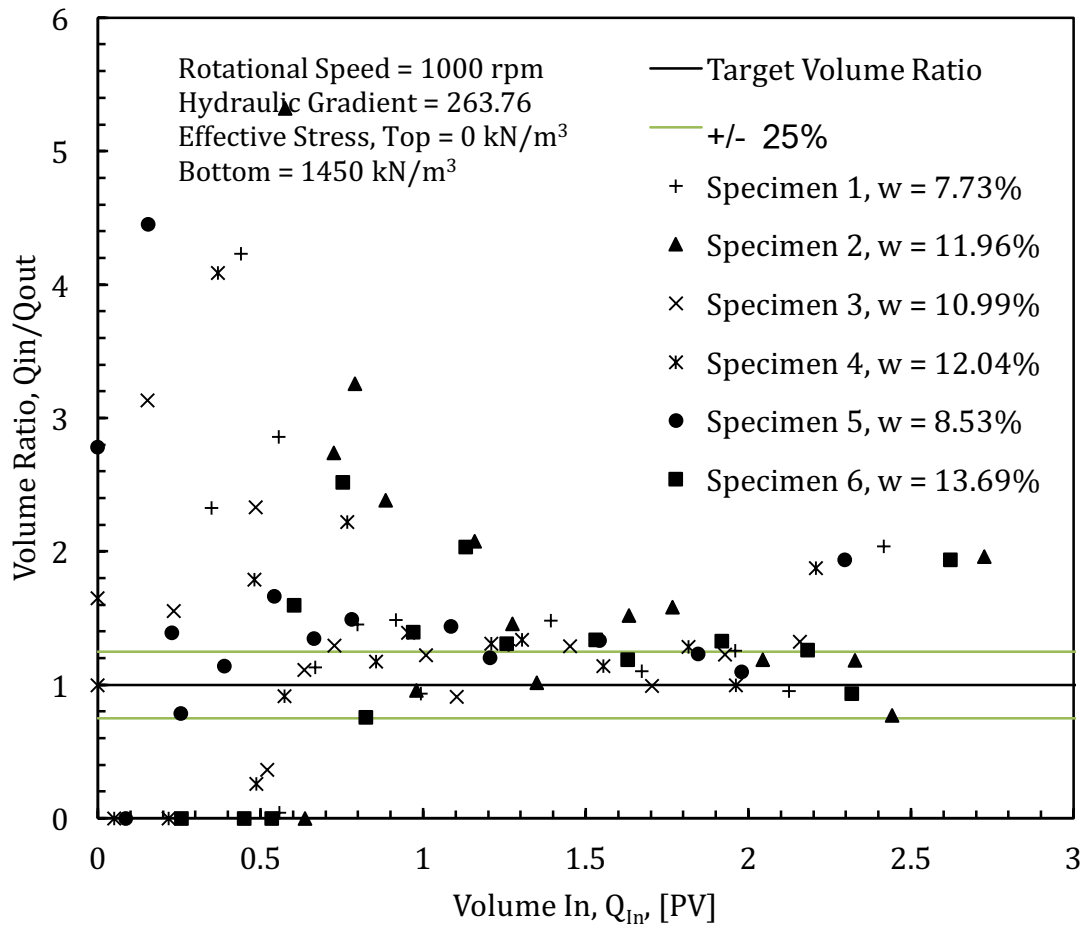


(b)

Figure 7. Hydraulic conductivity as a function of Q_{out} for all six 50 percent reduced Proctor energy specimens.



(a)



(b)

Figure 8. a) Volume ratio as a function of Q_{out} for all six 50 percent reduced Proctor energy specimens and b) Volume ratio as a function of Q_{in} for all six 50 percent reduced Proctor energy specimens.

Future Research/Lessons Learned

Many obstacles were encountered in the testing methods that were presented in this research. Recommended resolutions to these obstacles are reported in this section. The obstacles included 1) compaction technique, 2) centrifugation technique, and 3) volume calculations.

Compaction Technique

The amount of compaction that was used in this research was calculated adequately using Equation 1 and should have theoretically provided accurate results. However, it was recommended that more specimens should be created to validate the accuracy of this compaction method at additional water content levels (wetter preparation). Further research performed using the exact hammer and compaction mold/setup that were used in this research may provide more explanation for the low dry unit weight values and the location of the optimum water content estimation.

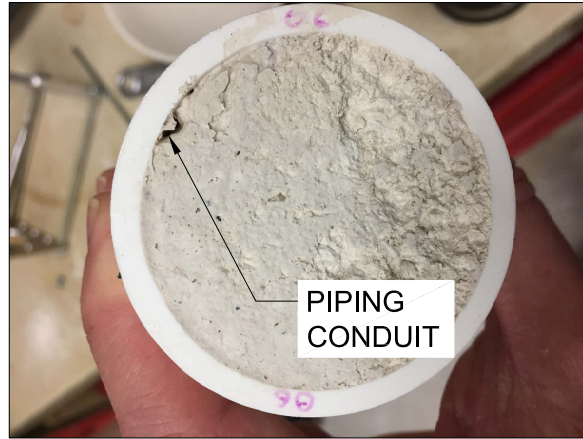
An improved compaction setup is recommended. Instead of using a PVC funnel as the collar for compacting the final lift, a similar diameter PVC pipe attached with a gasket or a PVC coupler is recommended. The use of a gasket or coupler would allow the last lift of the specimen to be compacted in a comparable way to a traditional standard Proctor test. This modification to the device should keep the hammer from making contact with the edges of the collar, thereby preventing energy loss before the hammer reaches the specimen. The dry unit weight and water content values should have been verified before beginning centrifugation. Centrifugation time will not be wasted if the Proctor curve is verified prior to beginning centrifugation.

Piping During Centrifugation

Specimen numbers three (3) and five (5) underwent piping due to centrifugation as reported in the first centrifugation cycle (Table 1). Piping in the specimen occurred when the force from centrifugation created a conduit for water to flow through the specimen. Despite two specimens undergoing piping, after 1) adding additional water to the top of the specimens and 2) restarting the centrifugation process, the soil specimens appeared to have consolidated and refilled the channel that was created during the piping events. Therefore, it was not observed to

be necessary to recreate or re-compact a specimen after piping occurred. However, the piping/reconsolidation event may have affected the soil specimen and the soil fabric. It is believed that after the specimens underwent piping and reconsolidation, the specimens were not the same fabric as the initial 50 percent reduced Proctor energy specimens.

After secondary research was conducted on standard Proctor specimens, piping was observed in three of the six samples while being centrifuged at a rotational velocity of 380 rpm (Figure 8). This observation lead to the conclusion that piping can occur under most rotational velocities. It was observed during this research that every specimen that underwent piping was supported by a bronze porous disk instead of a porous stone. Therefore, further research is recommended to investigate the use of a bronze porous disk with smaller pores that will create more head loss through the specimens. Further research is also recommended on the use of a Mariotte tube in the top of the apparatus. The Mariotte tube would allow a smaller gradient through the specimen because the water level would be closer to the soil (Boga et al., 2012).



(a)



(b)



(c)

Figure 8. Photographs of a specimen that underwent piping.

Determining Time of Centrifugation

The amount of time that the specimen underwent centrifugation was a function of 1) the amount of water stored on top of the specimen, 2) the saturation of the specimen, and 3) the hydraulic conductivity of the specimen. For use in this research, the first four centrifugation cycles were closely monitored to ensure that the top of the specimen did not dry out during centrifugation. The specimens should be centrifuged for the longest amount of time for which water will remain stored on top of the specimen. After four cycles of centrifugation, a ratio was computed to determine the length of time necessary for the majority of the water to permeate into the specimen. According to observations made during this research, this length of time was observed to be between 12 and 36 hours to ensure consistency in the technique and readability of the data collection. Based on this research, the number of variables used throughout the centrifugation process should be reduced. Therefore, the amount of time for each centrifugation cycle should be constant. In this research, the methods of determining the time of centrifugation were inadequate because the piping/reconsolidation stress lead to lower values of hydraulic conductivity, which led to the lack of data. In future research, the use of the ratio between centrifugation time and Q_{in} will allow the catchment of two pore volumes of flow to be collected in one third the amount of time when compared to alternative testing techniques.

Centrifugation Technique

Further research is necessary to determine the effects of a faster rotational speed on the specimen. Assuming the specimen does not change, and piping does not occur, an increased rotation speed should theoretically push the same amount of water through the specimen in a shorter amount of time. Therefore, a shorter amount of time being required to saturate the specimen may provide more data in a shorter amount of time. However, an increase in rotational

speed will increase the gradient across the specimen. The effective stresses at the top and bottom of the specimen will also increase which will reduce the hydraulic conductivity.

Secondary research was also conducted to determine the ideal centrifugation speed. Additional specimens were centrifuged to meet the gradient requirements outlined in ASTM D5084 (2016). Based on ASTM D5084 (2016) the gradient not exceed 40 for the hydraulic conductivity values that were measured in this research project. During the secondary research, specimens were centrifuged at 380 rpm which induced a gradient of 38 on the specimens. Therefore, to ensure complete adherence to ASTM D5084 (2016), the specimens should be centrifuged at 380 rpm. However, ASTM D5084 (2016) also states that if hydraulic conductivity values remain the same for gradients both exceeding and meeting the requirement, that the hydraulic conductivity value is acceptable.

Calculating Amount of Water Volume into the Specimen

In this research, the amount of volume in to the specimen, Q_{in} , was computed by measuring the change in height of the water stored on top of the specimen. The change in height directly related to the change in volume of water on top of the specimen which was assumed to have permeated into the specimen. However, errors may have occurred during the measurement and data collection. Poor quality data may have been obtained by using calipers to measure from the top of the aluminum cage to the water surface location. Therefore, it is recommended to weigh the specimen and apparatus without the PVC catchment cup before and after centrifugation cycles to calculate the change in weight of the apparatus. By using this method, the water that has left the specimen and entered the PVC catchment cup should be neglected, so the change in weight should be directly related to the change in volume of water that went into the specimen.

The previously recommended practice of calculating Q_{in} by weight was used for only one cycle of data collection, with results reported in Table 4. The variance in data retrieved by both methods was quite noticeable and may drastically reduce the amount of error in future research. However, the use of collecting volume by weight in the early centrifugation cycles, when the specimen was unsaturated, resulted in no net change, or zero Q_{in} because the water was collecting in the pore spaces of the specimen. Also, as observed in Table 4, the volume ratio while using volume by weight method is much closer to 1.0 than when using the volume by height method. Therefore, it is recommended to use both methods in the early centrifugation cycles and then switch to the volume by weight method after saturation was achieved (after one pore volume of flow has flown through the specimens).

Table 4. Comparison of methods of measuring Q_{in} of the specimen.

Volume In, [g]						
	1	2	3	4	5	6
By Height	13.53	13.86	10.53	12.14	14.61	13.75
By Weight	7.75	9.44	9.07	7.37	9.21	9.85

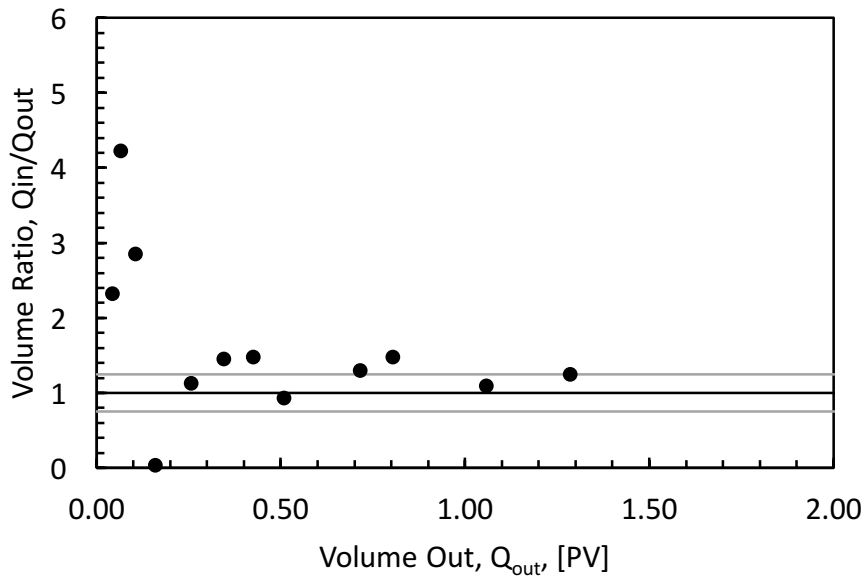
Conclusion

Six 50 percent reduced Proctor energy specimens were created and centrifuged for 15 sub-interval tests at 1000 rpm over the duration of 200 hours. Due to poor compaction techniques, an inadequate Proctor curve was developed and thus a placement window was not created. However, through the use of the centrifuge, hydraulic conductivity values were collected in one third the amount of time when compared to alternative testing techniques. To improve this research, it is recommended to 1) validate the Proctor curve before centrifugation, 2) centrifuge specimens at an acceptable gradient, and 3) observe the early centrifugation cycles to ensure more efficient work.

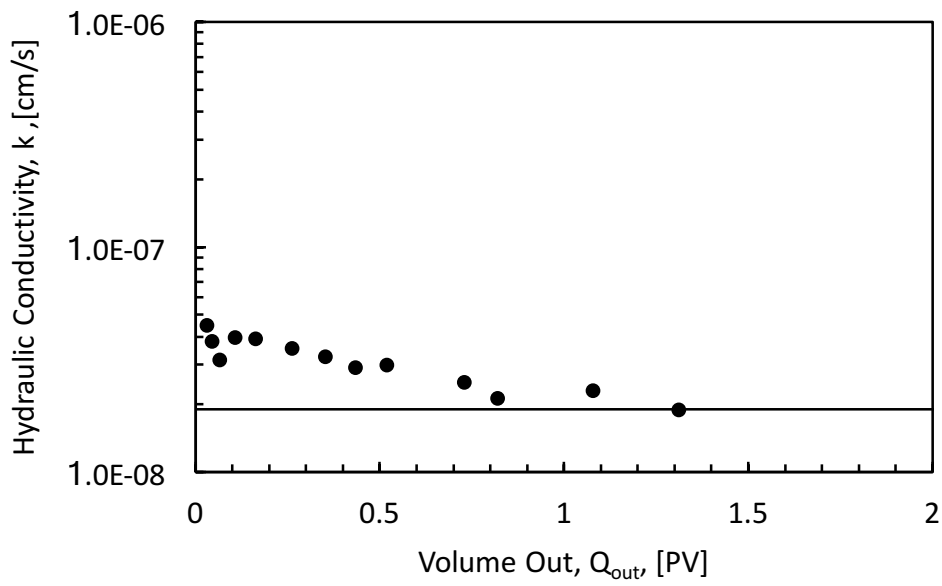
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Appendix

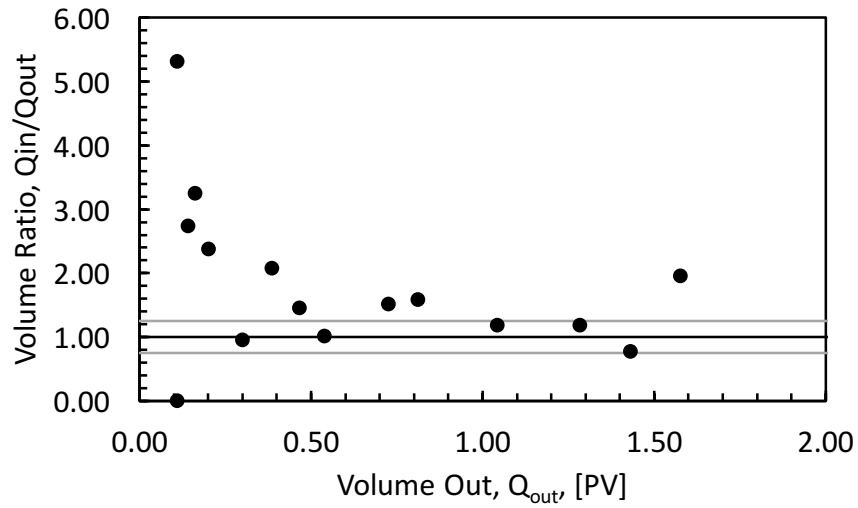


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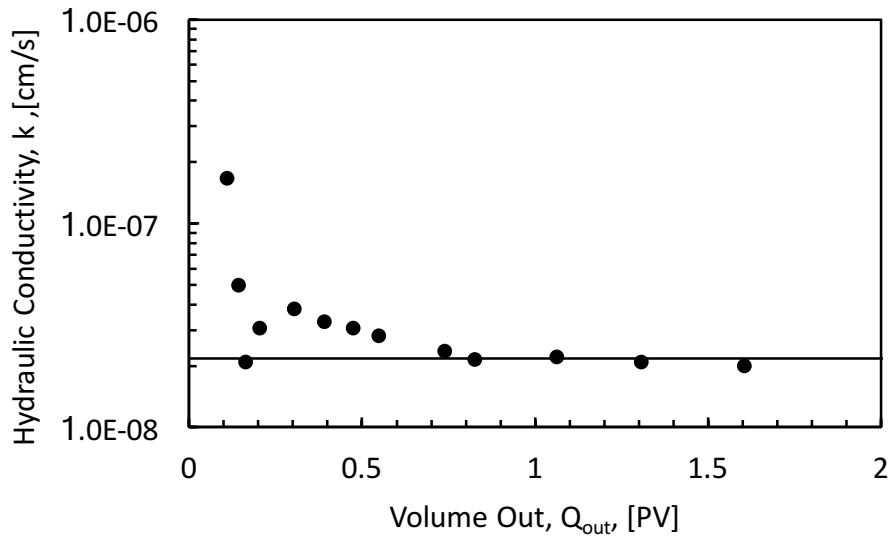


(b)

Figure A1. Hydraulic conductivity data from Specimen 1.

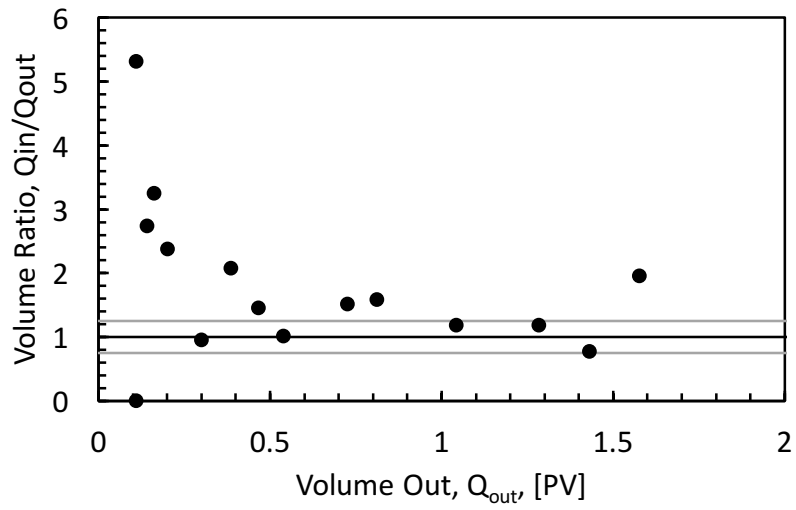


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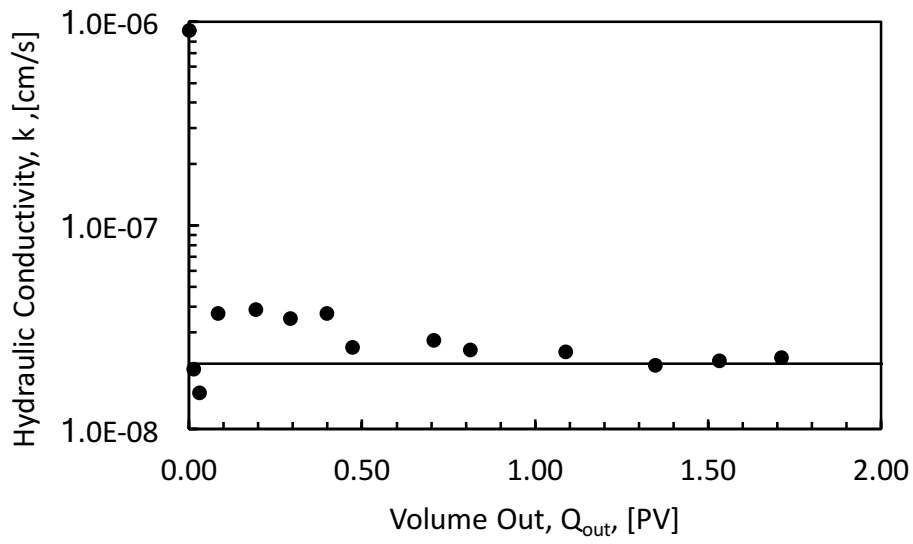


(b)

Figure A2. Hydraulic conductivity data from Specimen 2

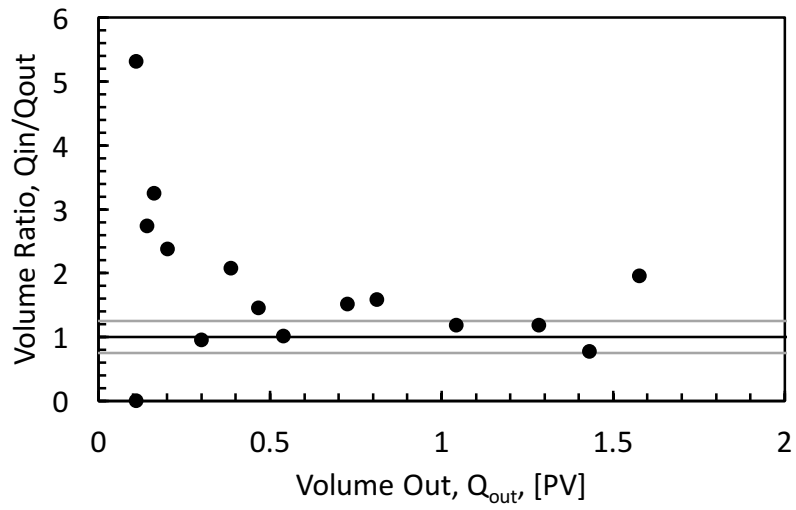


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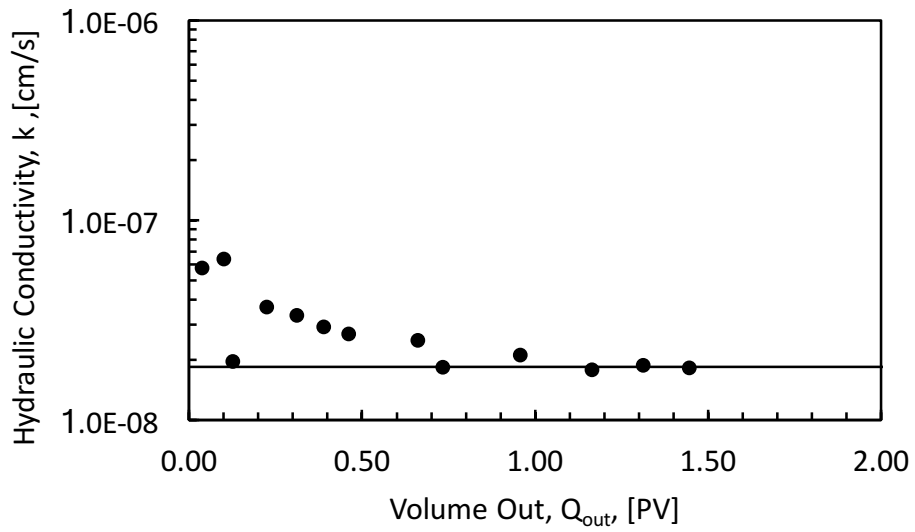


(b)

Figure A3. Hydraulic conductivity data from Specimen 3.

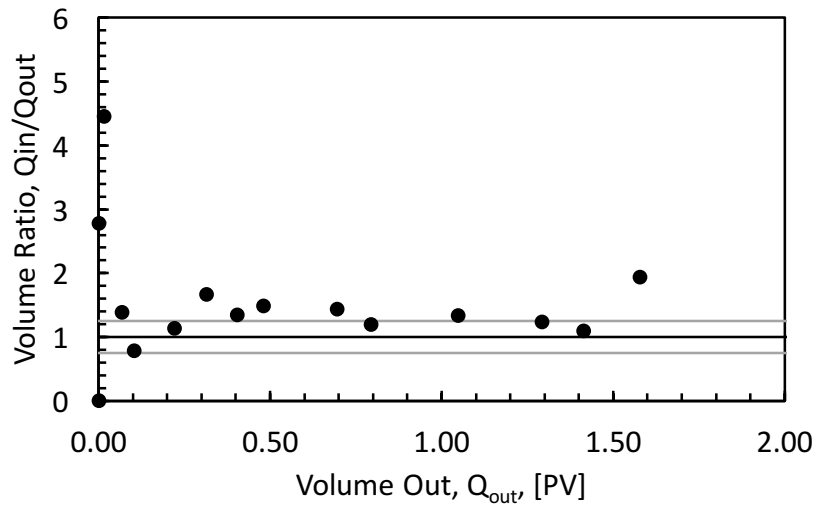


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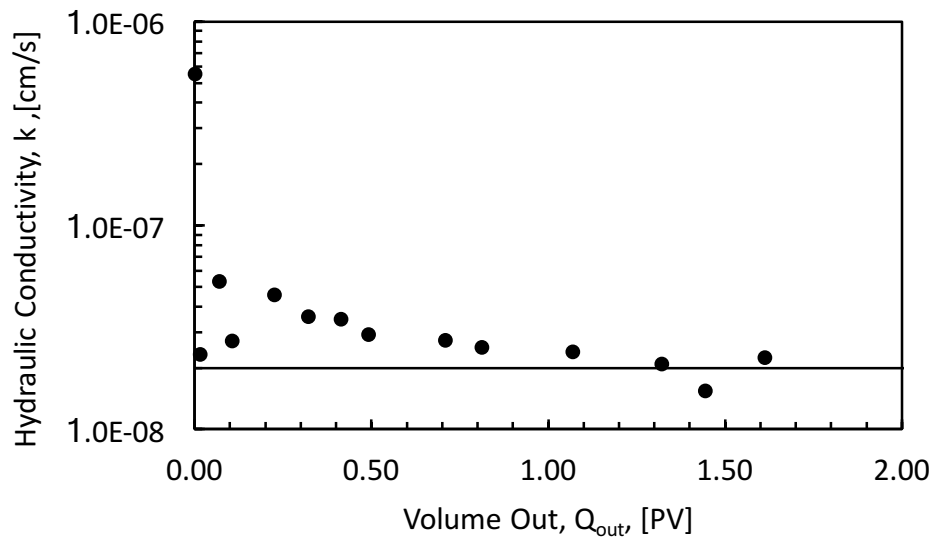


(b)

Figure A4. Hydraulic conductivity data from Specimen 4.

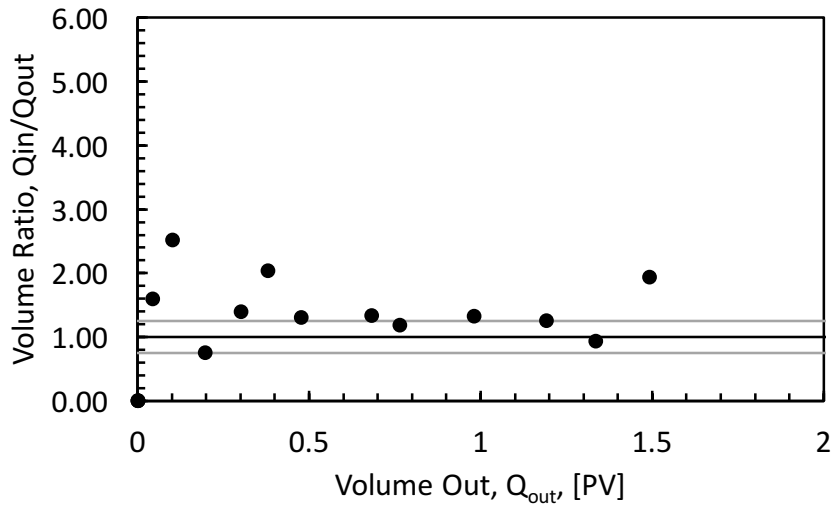


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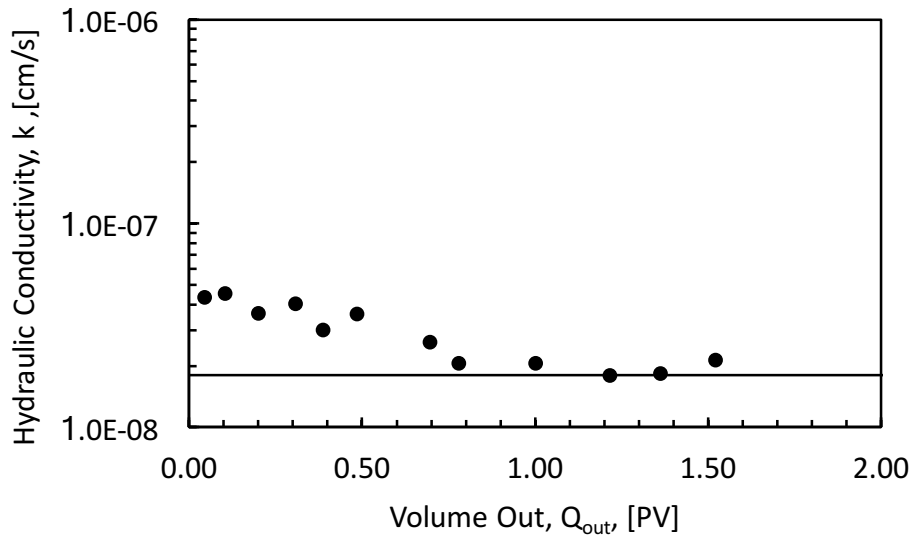


(b)

Figure A5. Hydraulic conductivity data from Specimen 5.



(a)



(b)

Figure A6. Hydraulic conductivity data from Specimen 6.

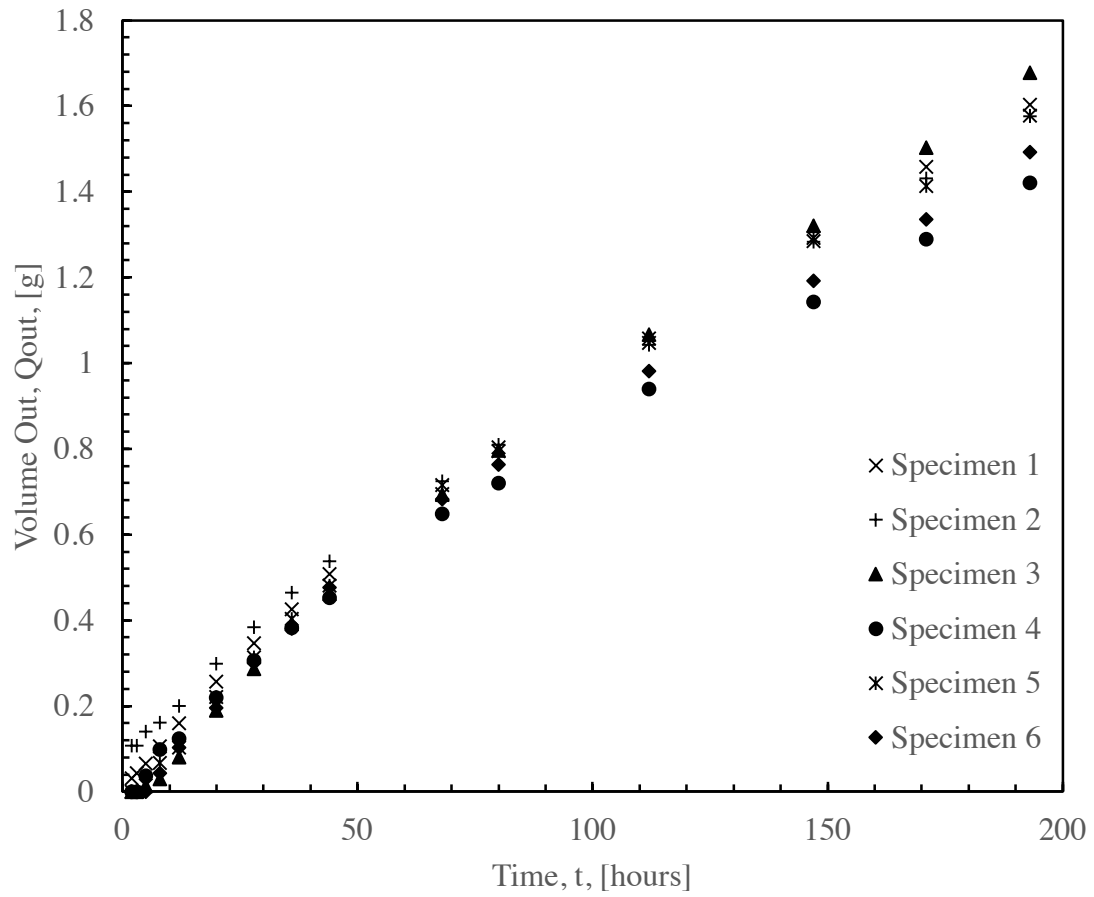


Figure A13. Volume exiting the sample as a function of centrifugation time.

Table A1. Reduced Proctor energy hydraulic conductivity data.

Test Number	Time [hrs]	Volume Ratio, Q_{in}/Q_{out}						Hydraulic Conductivity, k					
		[-]						[cm/s]					
1	2	10.36	5.32	1.65	-	2.78	-	4.51E-08	1.66E-07	9.04E-07	-	5.53E-07	-
2	3	2.33	-	0.99	-	-	-	3.83E-08	-	2.72E-06	-	-	-
3	5	4.23	2.74	7.50	4.09	4.45	-	3.15E-08	4.96E-08	1.98E-08	5.78E-08	2.33E-08	-
4	8	2.86	3.25	3.13	1.79	1.39	1.60	3.98E-08	2.09E-08	1.51E-08	6.40E-08	5.31E-08	4.33E-08
5	12	0.04	2.38	1.55	0.26	0.79	2.52	3.92E-08	3.06E-08	3.70E-08	1.97E-08	2.72E-08	4.52E-08
6	20	1.13	0.96	2.33	0.92	1.14	0.76	3.55E-08	3.80E-08	3.86E-08	3.68E-08	4.56E-08	3.62E-08
7	28	1.45	2.08	0.36	2.22	1.66	1.40	3.27E-08	3.30E-08	3.50E-08	3.34E-08	3.58E-08	4.02E-08
8	36	1.48	1.46	1.11	1.17	1.35	2.03	2.92E-08	3.07E-08	3.71E-08	2.93E-08	3.46E-08	3.00E-08
9	44	0.93	1.01	1.29	1.39	1.49	1.31	3.00E-08	2.82E-08	2.52E-08	2.71E-08	2.92E-08	3.60E-08
10	68	1.30	1.52	1.22	1.31	1.44	1.34	2.52E-08	2.37E-08	2.73E-08	2.52E-08	2.73E-08	2.61E-08
11	80	1.48	1.58	0.91	1.34	1.20	1.19	2.13E-08	2.16E-08	2.44E-08	1.84E-08	2.52E-08	2.06E-08
12	112	1.10	1.19	1.29	1.14	1.33	1.33	2.30E-08	2.22E-08	2.40E-08	2.11E-08	2.40E-08	2.05E-08
13	147	1.25	1.18	0.99	1.28	1.23	1.26	1.90E-08	2.09E-08	2.06E-08	1.79E-08	2.09E-08	1.79E-08
14	171	0.95	0.77	1.23	1.00	1.10	0.94	2.11E-08	1.70E-10	2.17E-08	1.88E-08	1.55E-08	1.83E-08
15	193	2.04	1.96	1.32	1.87	1.94	1.94	1.91E-08	2.00E-08	2.25E-08	1.83E-08	2.24E-08	2.13E-08

Test Number	Time [hrs]	Volume in, Q_{in}						Volume out, Q_{out}					
		[PV]						[PV]					
1	2	0.32	0.58	0.00	0.05	0.00	0.26	0.03	0.11	0.00	0.00	0.00	0.00
2	3	0.35	0.64	0.00	0.22	0.09	0.45	0.04	0.11	0.00	0.00	0.00	0.00
3	5	0.44	0.72	0.10	0.37	0.15	0.53	0.07	0.14	0.01	0.04	0.02	0.00
4	8	0.56	0.79	0.15	0.48	0.23	0.60	0.11	0.16	0.03	0.10	0.07	0.04
5	12	0.56	0.89	0.23	0.49	0.26	0.75	0.16	0.20	0.08	0.12	0.10	0.10
6	20	0.67	0.98	0.48	0.57	0.39	0.82	0.26	0.30	0.19	0.22	0.22	0.20
7	28	0.80	1.16	0.52	0.77	0.54	0.97	0.35	0.38	0.29	0.31	0.31	0.30
8	36	0.92	1.27	0.64	0.85	0.67	1.13	0.43	0.46	0.39	0.38	0.40	0.38
9	44	0.99	1.35	0.73	0.95	0.78	1.26	0.51	0.54	0.46	0.45	0.48	0.48
10	68	1.26	1.63	1.01	1.21	1.09	1.53	0.72	0.73	0.69	0.65	0.69	0.68
11	80	1.39	1.77	1.10	1.31	1.21	1.63	0.80	0.81	0.80	0.72	0.79	0.76
12	112	1.67	2.04	1.45	1.56	1.54	1.92	1.06	1.04	1.07	0.94	1.05	0.98
13	147	1.96	2.33	1.70	1.82	1.85	2.18	1.29	1.28	1.32	1.14	1.29	1.19
14	171	2.12	2.44	1.93	1.96	1.98	2.32	1.46	1.43	1.50	1.29	1.41	1.34
15	193	2.42	2.73	2.16	2.21	2.30	2.62	1.60	1.58	1.68	1.42	1.58	1.49