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Hydraulic conductivity testing of cement-bentonite mixes for use in annular well seals

Amy Lynn Norval

HYDRAULIC CONDUCTIVITY TESTING OF CEMENT-BENTONITE MIXES FOR

USE IN ANNULAR

WELL SEALS

by

AMY LYNN NORVAL

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Dr Katherine Grote, Advisor

Dr Leslie Gertsch

Dr. David Rogers

ABSTRACT

Grout is the material used in the annulus of water supply and monitoring wells to prevent movement of water from adjacent formations or from the land surface into the well. Grout is critical for preventing cross-contamination of aquifers through a borehole when a single well penetrates multiple aquifers and for protecting aquifers from surface contamination. The composition and emplacement of grout is regulated in most states, with standard mixes of bentonite and cement being the most widely used types of grout. Despite widespread adoption of grout regulations, surprisingly little literature is available to describe the effectiveness of different grout mixtures.. This study investigates the effectiveness of three bentonite-cement mixes (3%, 6%, and 12% bentonite by weight) and cement grout without bentonite. The study tests the hydraulic conductivity of each mixture as a function of grout composition and bonding of grout to the well casing. Results show that as the ratio of bentonite is increased the hydraulic conductivity decreased, however between 3% and 6% bentonite the hydraulic conductivity begins to increase.

ACKNOWLEDGEMENTS

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Thank you to Danny Flynn at Flynn Drilling, Melissa Grace at AgruAmerica, and Anna Saindon at Geotechnology, Inc., respectively, for donating the bentonite, geotextile material, and advice which were crucial to the success of this project.

I would like to thank my parents for their support, my mom for her help in acquiring and setting up my tanks and my brothers Skyler and Aaron for weighing out and mixing cement with me late at night.

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1. INTRODUCTION

Water wells are created by boring a hole into the ground and placing a casing of a smaller diameter into the hole. Portions of this casing are perforated, allowing water to enter the borehole and be brought to the surface, while other portions are non-perforated. The space left between the outside of the borehole and the well casing is referred to as the annular space. In the portions of the aquifer used for water extraction, , a high permeability material will be placed between the perforated casing (well screen) and outside of the borehole; this materials is known as the filter pack. There are many references which address methods for optimizing filter pack materials for water extraction wells and for monitoring wells. Zones which are not intended for water extraction must be filled with a low permeability material such as grout. Grout restricts the movement of water and contaminants from both the horizontal and vertical direction, thus preventing cross-contamination of aquifers through a borehole. Contamination can infiltrate vertically from surface water into aquifers or horizontally when a single well penetrates multiple aquifers allowing for contamination of an aquifer to spread to underlying aquifers. In the case of monitoring wells, where the purpose is to characterize the aquifer chemistry, extent of contamination, or groundwater head, grout serves to isolate a formation of interest, thus allowing measurements of head at different elevations; multi-level head measurements are needed to understand vertical flow within or between aquifers. Grout is thus essential both for maintaining the integrity of the water supply wells and for accurate characterization of groundwater conditions.

The composition of the grout in the annular space is regulated by each state's environmental regulation agency, which in Missouri is the Department of Natural Resources (DNR). State regulations specify the composition of the grout and the minimum required length of annular space to be filled with grout based on the well application. These requirements can vary depending on regional geology, known contamination of a geologic formation, or geo-hazards such as sinkholes. Grouting along the entire annulus from the screened interval to the surface is not always required in Missouri, and in some regions of the state, as little as 20 feet of grout is required. The grouting material used is of great importance, particularly in situations in which the required length of grout is short.

Grouting materials are selected based upon their ability to restrict flow. Hydraulic conductivity is a measure of how easily water passes through a media and is presented in terms of length per time, where higher values of hydraulic conductivity allow water to move through a material more quickly. A hydraulic conductivity of 10^{-6} cm/s is considered to be low and can be deemed impervious for grouting applications. For projects where it is imperative that water not pass through a material, it is naturally desirable to seek the lowest hydraulic conductivity possible.

Commonly, the grout material selected is pure Portland cement, which can cure underwater, and once set, is resistant to breakdown. Portland cement is desirable because it is made of very fine grained, almost dust-sized, particles of silica and lime. These materials bond chemically when saturated, resulting in a low hydraulic conductivity. A number of additives have been used with Portland cement to increase the strength, decrease the permeability, or control the curing time. One such additive is Bentonite clay, which is believed to decrease the permeability of cement-bentonite mixture. To install monitoring wells in Missouri, drillers are required to use bentonite as an additive to cement up to 6% by weight. Bentonite is a swelling clay which expands to up to 10 times its original volume in the presence of water, filling any available space. The current theory is that once hydrated, bentonite does not dry out. Therefore, it should fill any open pore spaces permanently. Despite the frequent and required use of bentonite, relatively few studies are available in the literature quantifying its effectiveness as a sealant. In this research, we seek to better understand how bentonite affects the hydraulic conductivity of grout and how it may affect the seal between grout and the casing material.

2. PREVIOUS WORK

Literature regarding the hydraulic conductivity of cement-bentonite mixtures is limited. It is possible that a great deal of research has been conducted, particularly by the petroleum industry, but that the studies are not published for proprietary reasons. In 2004, a study was performed in Nebraska to observe the behavior of in-situ cement, bentonite and cement-bentonite grouts over a two-year period of time (Lackey et al, 2009). The objective of this study was to determine how grout mixtures with varying percentages of solid materials performed under various hydrological and/or geologic conditions. Wells were installed using clear polyvinyl chloride (PVC) casing and observed using down-hole camera methods during the placement of the materials. A second survey, 16 months later, revealed that the integrity of the grout had been compromised by cracks and voids. This initial study prompted the creation of the Nebraska Grout Task Force (NGTF), which sought to test, in a similar manner, all of the state approved grouts, including bentonite slurry, bentonite chip, geothermal bentonite slurry, and cement-based grouts. The study consisted of the installation, between 2002 and 2004, of 63 monitoring wells in five sites across Nebraska with varying geological and hydrological settings. The grout structure was surveyed by downhole camera 90 days after installation, then dye was placed in the monitoring wells. The wells were again inspected after 24-hours. Initial dye testing occurred between 2004 and 2006, and a secondary test was performed in 2007 to assess the stability of the grout.

The footage obtained by the down-hole camera survey was analyzed for cracking, voids, and detachment from the well casing in foot long intervals. A rating ranging from

1 to 3 was assigned to each foot a of well, with 1 being very good, 2 showing cracks, and 3 showing voids or detachment. The ratings were averaged for the entire length of the well, as shown in Table 2.1. The cement-bentonite grout (the composition of which was not stated) was rated in the top 25% of the grouts studied.

Table 2.1 Nebraska Grout Task Force Overall Average Visual Ratings

Grout type	Visual rating (All installations)
Bentonite chip	1.3
Neat cement with 6 gallons of water	1.4
Cement with bentonite	1.6
Cement with sand	1.6
Bentonite slurry >20%	1.8
Neat cement with 7 gallons of water	1.8
Bentonite slurry =20%	2.0
Concrete	2.0
Bentonite slurry <20%	2.3
Bentonite geothermal-sand ~60%	2.7
Bentonite geothermal ~20%	2.8

In the dye testing phase of the investigation, a yellow dye was placed into the well and a down-hole survey was performed 24 hours later to find the deepest point of penetration. The results were presented as the average percentage of the saturated zone penetrated by dye and are presented in the following table (Table 2.2). The cement-bentonite grout drops from being in the top 25% of the visual rankings to ~50% in the dye penetration testing, with the dye penetrating an average of 48% of the unsaturated zone. Within the subcategory of cement-based grouts, the cement with bentonite exhibited the worst performance. During the 2007 dye testing, no dye penetration was observed in the wells with cement-based grout. The reason for this has not yet been

Table 2.2 Nebraska Grout Task Force Overall Average Percentage of Unsaturated Zone Penetrated by Dye

Grout type	Average percentage
Cement with sand*	24
Neat cement with 7 gallons of water*	37
Concrete*	40
Bentonite chip (Pilger & Trenton wells)	40
Neat cement with 6 gallons of water*	44
Cement with bentonite*	48
Bentonite slurry >20%	65
Bentonite geothermal-sand ~60%**	67
Bentonite slurry =20%	75
Bentonite geothermal ~20%**	86
Bentonite slurry <20%	87

* Based on maximum depth of dye in one- and 24-hour videos.
** Water level estimated from water table well

determined, but the NGTF hypothesized that either the red dye used in the second dye test was more difficult to detect, thus yielding faulty data, or that the precipitation of calcium may have sealed any detachment from the casing. The NGTF concluded that drilling and installation methods, hydrological and geological conditions, and grout composition all play an important role in the performance of the annular seal and called for a closer examination of installation practices (Lackey et al, 2009).

In a second study, researchers studied cement and bentonite grout mixtures in a laboratory setting (Edil et al, 1992). In this study, Sealing Characteristics of Selected Grouts for Water Wells, the authors concluded that the "structural stability" of the grout was perhaps more important than the permeability of the material itself. In their experiment, performed on neat cement, cement-bentonite, powder bentonite (Volclay), and granular bentonite (Benseal), the well grouts were evaluated using a well model in the laboratory. The experimental apparatus was a tank 15 ft x 6 ft wide and 6 ft deep, and four 8 inch PVC pipes were placed vertically into the model. The model was then filled with sand and saturated to simulate an aquifer. Lastly, a 4 inch outer diameter steel well casing was installed concentrically within the empty PVC pipes.

The four annular spaces created between the casing and the PVC were then filled with the four different grouts described above (one well for each mix) using tremie methods for the neat cement and powder bentonite and direct pouring of the cement-bentonite and granular bentonite mixes. Samples of each grout were also collected and placed into 2 inch diameter cylindrical molds for permeability testing in a flexible wall permeameter after curing. Following grout placement, the PVC pipes were removed, allowing the grout to come into contact with the sand. Infiltrometers (short sections of 8 inch PVC pipe) were installed around each of the annular seal at the grout sand interface to a depth of 1 foot below the surface, but were not filled with water during the curing process.

Cracking to various degrees was observed in all of the grout mixes within the two week curing period. At the end of the curing period, the infiltrometers were filled with water. Red dye was added to the infiltrometer at 10 weeks (8 weeks since grout placement) to trace the fluid flow paths that may have developed. Infiltrometer testing was concluded at the end of week 19. In the discussion of the results, the authors state that “infiltration rate tended to slow down after some time. However, the replenishment of water caused an increase in the infiltration rates…” An increase in the infiltration rate with an increase in the hydraulic head should have been expected. Increasing the column of water on top of the grout increases the pressure that is exerted by the water thereby causing fluid to move more quickly through the pore spaces or cracks. Likewise a decrease in hydraulic head would lead to a decreased rate of infiltration. The hydraulic conductivities calculated throughout the course of the experimentation were then averaged which further obscures the true hydraulic conductivities of the grout materials. The averaged results of the experimentation are presented in the table below (Table 2.3).

Table 2.3 Infiltration Rates in Well Model Experiment from Edil et al, 1992

Well designation *Sealant*	*#1* *Benseal®*		*#2* *Neat cement*		*#3* *Bentonite-Cement*		*#4* *Volclay®*	
	Δh/Δt*	q**	Δh/Δt	q	Δh/Δt	q	Δh/Δt	q
2-10 weeks	2.2	4.9	4.5	10.0	8.1	17.9	226.9	503.0
10-19 weeks (After adding dye)	3.4	7.5	4.5	10.0	32.3	71.6	403.2	894.0
Finite element program		3.0		3.0		9.0		3.0

* In $cm/sec \times 10^{7}$.
** In $cm^3/sec \times 10^{-5}$.

After the conclusion of testing, the grouts were removed an investigated for dye traces. In the cement-bentonite grout, dye was found at the PVC infiltrometer grout interface to the bottom of the infiltrometer (approximately 1 foot) and 6 inches of infiltration between the grout and steel well casing interface.

The authors concluded that given the infiltration along the grout casing interfaces and the cracking observed during the curing period, the permeability of the grout materials may be more controlled by the “structural stability” of the grout,(Edil et al, 1992).

In 2014, the Missouri DNR performed an unpublished qualitative experiment on well grouts. A well was drilled on their property in Rolla, MO, and the well was cased with clear PVC to allow a borehole camera to image the placement of various approved grouts. One of the grouts placed was a 50/50 cement-bentonite mix, and it was observed in the well that the two materials did not create a homogenous mixture (Justin Davis, MDNR Employee). It is not clear whether the large proportion of bentonite used in this experiment is responsible for the heterogeneity, but a propensity to not mix would create different zones within the grout that might lead to vastly different permeabilities for each zone.

3. METHODOLOGY

This experiment was designed to investigate how the cement-bentonite grout composition affects hydraulic conductivity and how it affects the seal between the grout and the casing. Three different cement-bentonite mixtures were tested, and , tests were also performed using pure cement as an annular seal. To test how the cement-bentonite ratio affects the seal with the casing, the surface area of the grout:casing interface was varied for each cement-bentonite mixture. The expectation was that if poor seals were forming between the grout and the casing, the hydraulic conductivity of the grout would increase as the area of the grout:casing interface increased. The increased hydraulic conductivity in this circumstance would be attributed to failure of the grout to create an effective seal to the well casing, which would create a micro-annular space and provide a conduit for fluid.

3.1 CEMENT AND BENTONITE MIXTURES

When deciding what mixtures of cement and bentonite to use in this study, 100 percent cement (neat cement) was chosen as a baseline for comparison to the cement-bentonite grouts. It is also important to test neat cement because it is the most commonly used grout. The quantity of bentonite to add to the cement was based upon current requirements by the Missouri DNR, where drillers must add up to 6% bentonite. To provide a range of bentonite-cement mixtures that are in line with current requirements, we tested mixtures where the bentonite was 3%, 6%, and 12% of the grout mixture, as determined by dry mass.

3.2 ADHERENCE OF GROUT TO THE CASING

To test the seal between the grout and well casing, the surface area of the casing was varied for different experiments. All experiments were conducted in a rectangular tank 11 in. wide by 20 in. long. Some tanks were filled only with grout, while other tanks had vertically installed PCV pipes of 1 in diameter which were set in the tank prior to adding grout. . To change the surface of the grout:casing interface, the number of pipes in each tank were varied; tests were run with 3 pipes and with 9 pipes, and we expected to observe an increase in the apparent hydraulic conductivity as the number of pipes increased.. If little or no difference in hydraulic conductivity was observed in tanks with no pipes or several pipes , this would indicate that adherence of the grout to the casing is generally good.

The decision to test the adherence of grout to only PVC pipes and not to include testing on steel well casing was made based on the limitations of time and budget. PVC was chosen over steel because of PVC's increasing dominance as a casing material in the field. A coding system using the parameters to be tested was established to identify the variables in each trial. The coding system will consist of the percentage of bentonite to be tested, either B0 (0% bentonite), B3 (3% Bentonite), etc.,, paired with the number of pipes used in the trial, where P0 designates zero pipes, P3 is three pipes, etc. The combinations tested are presented in Table 3.1.

Table 3.1 Coding System

		Percent Bentonite (by weight)			
		0	3	6	12
Number of Pipes	0	B0P0	B3P0	B6P0	B12P0
	3	B0P3	B3P3	B6P3	B12P3
	9	B0P9	B3P9	B6P9	B12P9

3.3 PERMEAMETER TESTING APPARATUS

Different experimental apparatuses were considered prior to construction of our final design. Measurements of hydraulic conductivity are generally performed in a permeameter for specimens that are anticipated to have low hydraulic conductivities. There are two types of permeameters, rigid-wall and flexible-wall. Rigid-wall Permeameters (ASTM D5856-15) are used where expected hydraulic conductivities are less than or equal to 10^{-5} m/s, meaning water travels less than 1 meter in a day's time under a unit gradient (0.864 m/ day). Rigid-wall permeameters use specimens which have been compacted inside the test apparatus and vacuum sealed, allowing only water to pass in and out of the material. Flexible-wall permeameters (ASTM D 5084-10) are used for specimens with expected hydraulic conductivities less than or equal to 10^{-6} m/s, around 0.1 meter in a days time under a unit gradient (0.0864 m/day). Samples used in a flexible-wall permeameter are also compacted. However, they are compacted outside of the testing apparatus, and after compaction they are placed inside the permeameter. The walls of the permeameter are then made to inflate, squeezing the sides of the specimen. To use a flexible-wall permeameter, the specimen must be fully saturated prior to compaction. Both of these permeameters attest a small diameter of material and are meant to test loose materials. In our study, grout cannot be compacted, and both rigid-wall and flexible-wall permeameters had no mechanism for incorporating pipes within the sample, so these permeameters were considered to be inappropriate for our experiment.

A study was performed by the American Society for Testing and Materials (ASTM) on the discrepancy between hydraulic conductivity values reported for in-situ field testing versus laboratory testing. Field testing generally involves a large area, whereas lab testing is often confined to only a few inches in diameter. Testing was performed in the field and using permeameters in the laboratory on compacted clay liners, which are similar to grout in that they have low hydraulic conductivities and have a macro-structure that may not be captured in testing a small sample. The diameter of the permeameter and the thickness of soil tested were increased until the field results could be replicated. This experiment found that the ideal sample for lab testing was 11.8 inches in diameter and 5.9 inches thick to acquire data that closely matched the values reported by in-situ testing (Benson et al, 1994).

Like clay liners, cement-bentonite grout also has a macro-structure, and it would be most representative to perform large-scale tests. The macro-structure includes not only any cracks which may occur, but also its expected heterogeneous texture. Cement-bentonite grout is mixed by first combining Portland cement and water and then adding bentonite granules. The mixture is then poured into the annular space around the well casing using one of several different approved methods. The goal of mixing these materials is to provide a homogenous product, but it is uncertain whether the bentonite truly mixes with the cement. Based on the results of the MDNR and ASTM studies,, large-scale testing is the most appropriate method.

Large diameter permeameters that met the requirements of this experiment are not commercially available, so it was necessary to construct the experiment apparatus. The following sections discuss the procedures used to construct the experimental apparatus and to select which materials and processes were optimal for this experiment.

Our experimental apparatus allowed water to be added above a layer of grout, to drain freely through the grout, and then to be collected when drainage was complete. The testing apparatus chosen for this experiment was a pre-fabricated rectangular glass tank chosen to ensure structural stability throughout experimentation. New tanks were used for each of the twelve scenarios listed in Table 3.1.

Each tank has a single hole which was drilled into the bottom using a 1/4" diamond bit hole saw and a power drill. This hole allowed for collection of drainage water which passed through the grout and into the bottom open portion of the tank. A hose was attached to the hole on the outside of the tank to control when the water was drained. The drainage hose was clipped to the top of the tank so that gravity prevented the tank from draining until an appropriate time. Before pouring grout into the tank, plastic risers were placed on bottom of the tank to create an open chamber below the grout which allowed for water collection over the entire area of the tank.

To allow water to drain through the grout while providing a surface upon which to pour grout, we constructed a drainage layer atop the risers using a wire mesh and a geotextile. The wire mesh was a strong, stiff sheet, and it allowed for water to flow freely through it. The sheet's primary purpose was to lend support to the geotextile which lies above it, and so the sheet must be relatively stiff. The geotextile was supplied by AgruAmerica and has a minimum apparent opening size of 0.150mm. The geotextile allowed water to pass through freely, but prevented grout particles from passing through during the placement and curing of the grout as well as during testing. The geotextile liner was sealed to the sides of the tank using silicone caulk. This seal prevented the migration of water along the sides of the tanks and held the geotextile in place during the placement of the grout. A small layer of sand (0.5-1.0 in thick) overlaid the geotextile to prevent grout from passing through the geotextile while it was being poured. Typically, in a commercially available permeameter, a porous stone is used of this function. Since there were no porous stones of this size commercially available, the geotextile in combination with the wish mesh sheet served the same purpose as a porous stone. The drainage layer (sand, geomembrane, and wire mesh) in each tank ranged from 0.75-1.25" thick.

Because the bottom portion of the tank was sealed off from the atmosphere, a release valve or pipe between the bottom chamber of the tank to the atmosphere was needed to allow air to escape as water permeated through the grout. Without this pipes, the pressure in the bottom chamber would have increased until no water would have passed into the drainage space, rendering the experiment ineffective.. Release pipes were installed using small diameter plastic pipes (5.5 mm) that were sealed into the corners and ended just below the geotextile in the bottom portion of the tank, allowing for air to leave this portion of the tank and ensuring free drainage of water while minimizing evaporation from this chamber.

Once the drainage layer was in place, tanks without pipes were ready for grout. The tanks which had pipes required additional preparation. Sections of PVC pipe 2 inches in diameter (the minimum diameter allowed by current MDNR regulations) and 12 inches tall were prepared. The bottom of the pipe was sealed using silicone to prevent any migration of water through the pipe, and the pipes were then filled with cement. After curing, the top of each pipe was also sealed with silicone. This ensured that the pipes did not transmit water, therefore altering results, and gave the pipes more weight, which made them more stable during placement of grout. After tanks with and without pipes were prepared, they were partially filled with water to a depth of 6 inches. Grout was poured through this standing water. In the field, grout is often poured through water as the water flows into the borehole from the surrounding formation. When placing grout through water, a tremie pipe is required. A tremie pipe is simply a small diameter pipe inserted into the annual space of the borehole. Grout flows through the tremie pipe to the bottom of the borehole, and the tremie pipe is raised as each section of the annular space is filled with grout. Thus, the tremie pipe ensures good grout placement in the annular space along the entire grouted length of the borehole. The minimum length of the grout column in the borehole according to MDNR regulations in 30 feet; full length grouting of the borehole is not required for most settings. The thickness of grout for this experimental design was between 6 and 7 inches. Since a long column of grout was not required, no tremie pipe was used.

Grout was mixed according to common practice, as outlined by the MDNR regulations. Amounts of grout sufficient for testing needs were measured out and mixed with the appropriate amount of the water using a paddle attachment for a power drill in a 5 gal bucket.

After grout was poured into each tank, additional water was added as needed to bring the water level up to the top of the release pipes. The top of the tank was covered with a thin clear plastic membrane to limit the effects of evaporation. Completed tanks are pictured in Figure 3.1. After the grout was poured, the tanks were left for a period of two week to allow for curing of the grout mixes, as was done in Edil et al., 1992.

After grout curing time was complete, the drainage hose was released so that water in the lowermost chamber of the tank drained. During the draining of the tanks, the plastic was removed from the tops of the tanks, which allowed air to move into the tank and down the release pipes, so water could drain from the lower chamber. After the initial draining, the plastic was replaced.

3.4 QUALITY CONTROL EXPERIMENTATION

Two pre-experiments were performed before tanks were completed. The purpose of each pre-experiment was to better understand the materials that would be used during experimental trials and to better ensure their success.

3.4.1 Pre-Experiment 1. Pre-experiment 1 was performed to determine whether or not plastic wrap would be sufficient to eliminate or minimize the effects of evaporation at the top of the tank. Two identical tanks were filled with water to approximately the same height, and the water levels were marked. One tank was then

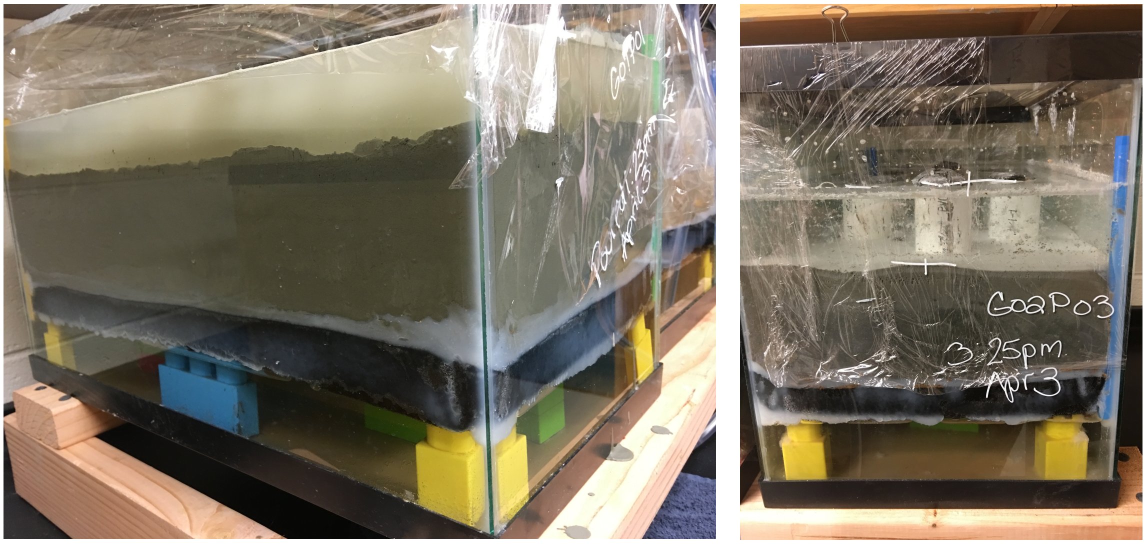


Figure 3.1 Tanks After Placement of Grout
Left tank is without pipes and right tank is with nine pipes

covered by plastic wrap and the other was left open for comparison as shown in Figure 3.2. Tanks were left to sit for a period of 14 days, after which water levels were re-measured. In the covered tank, no noticeable water loss was observed, however in the

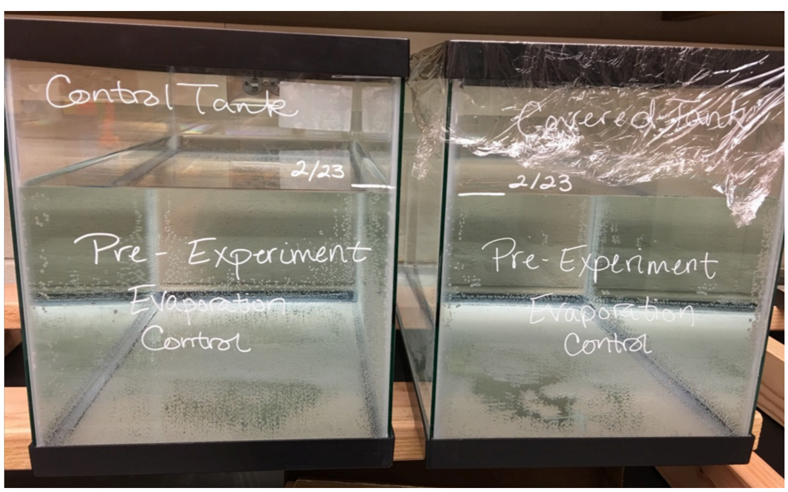


Figure 3.2 Pre-Experiment 1 Set Up
Control Tank (left) and experimental tank covered
in plastic wrap (right)

control tank, a water loss of 1.25" was recorded (see Figure 3.3). From this experiment it was determined that plastic wrap can be used to eliminate water loss due to evaporation.

3.4.2 Pre-Experiment 2. Pre-Experiment 2 involved the selection of the geotextile material to line the bottom of the drainage layer. Having a geotextile that will

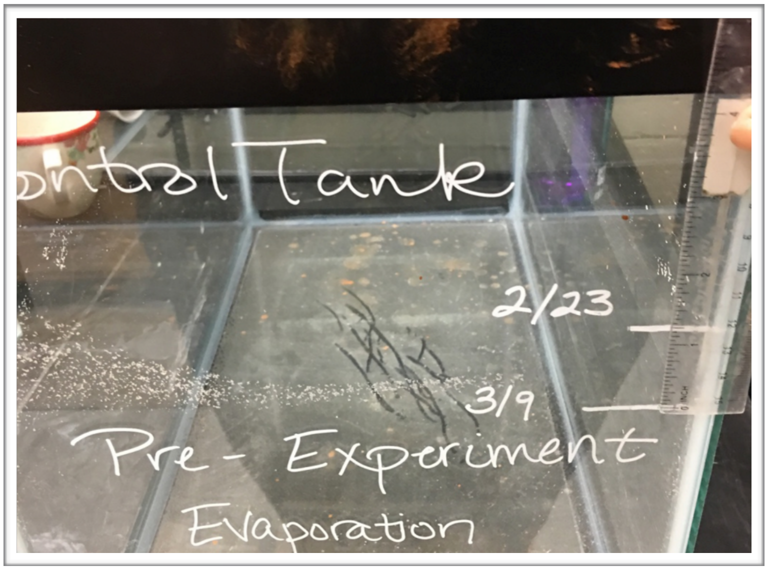


Figure 3.3 Pre-Experiment 1 Results
Appreciable drop in the water level in the uncovered tank shown

not pass grout during pouring is essential because the bottom chamber must be empty to allow for drainage during the permeability testing. AgruAmerica donated several samples for testing, as well as donating the Geotextile chosen in this experiment to line all of the tanks. A summary of the materials tested can be found in Table 3.2.

In order to meet the purposes of this experiment, the geotextiles needed to resist the passing of a majority of the grout and needed to resist clogging that would impair the flow of water. To test their properties, a piece of geotextile was fixed to the bottom of a 3" diameter section of PVC using silicone as seen in Figure 3.4.

Table 3.2 AgruAmerica Geotextile Properties

	Agrutex 061	**Agrutex 081**	**Agrutex 101**
Mass/Unit Area oz/sy	6	8	10
Apparent Opening Size US Sieve (mm)	70 (0.212)	80 (0.180)	100 (0.150)
Hydraulic Conductivity cm/sec	0.25	0.30	0.29

PVC pipe sections were placed into tanks of water and grout was poured into the pipe. Pouring was recorded so that leaked amounts could be compared. Figures 3.5 and 3.6 depict some of the images captured from those recordings.Information gathered was of a qualitative nature only. It was observed that a much smaller plume of grout passed through the bottom of the Agrutex 101 geotextile. This was anticipated as the Agrutex 101 had the smallest apparent opening size.

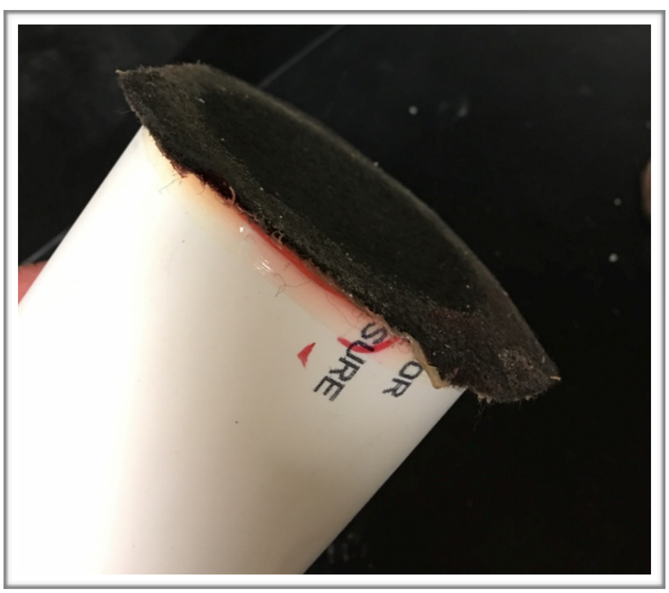


Figure 3.4 Pre-Experiment 2 PVC

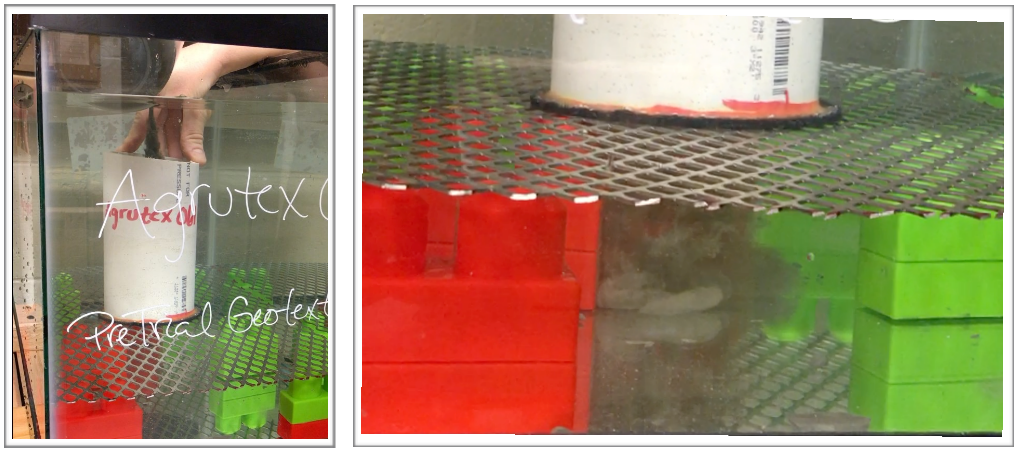


Figure 3.5 Pre-Experiment 2 Agrutex 061

During experimentation, the PVC pipe for the Agrutext 101 was pulled out of the water, at which point all of the material passed through the geotextile. This discovery reinforced the need to make sure that the geotextile was fixed firmly in place in the experimental tanks and that flow would not be induced through the tank so that materials

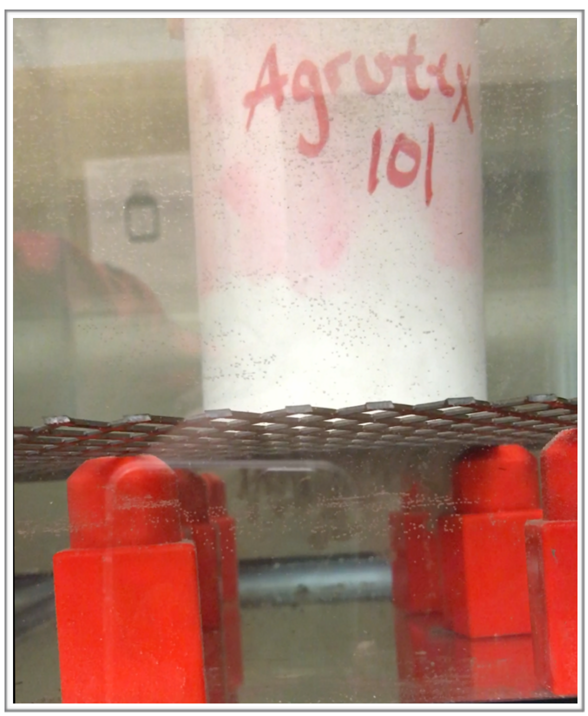


Figure 3.6 Pre-Experiment 2 Agrutex 101

would not be carried through the geotextile. As a result of Pre-Experiment 2, Agrutex 101 was chosen as the geotextile material for the drainage layers in the experimental apparatuses.

4.EXPERIMENTATION

Two sets of tanks were constructed, designated as Set 1 and Set 2. Set 1 had one tank for each of the scenarios described in Table 3.1 for a total of twelve tanks. The Set 2 tanks were similar, but lacked the neat cement control tanks, therefore totaling only nine tanks. The two sets provided redundancy and the ability to collect more data in a short amount of time. . Tanks were constructed according to the specifications set forth in the Apparatus Construction section of this study. It should be noted that each of the experiments were started at different times, as each grout was measured and mixed separately. The same volume of material was mixed for each tank, and the entire grout mixture was used regardless of the number of pipes in the tank. All the tanks were cured in a temperature controlled environment for quality control.

The following observations were made during the placement of grout:

1. Grout was poured into the approximate center of the tank and allowed to flow laterally to fill the space. It was observed that as the percentage of bentonite was increased, it became more difficult for the grout to flow laterally. In the 12% bentonite mix, the grout did not flow laterally and this grout had to be pushed into the empty space to uniformly fill the bottom of the tank.
2. Even small increases in the percentage of bentonite greatly affected the ability to pour the mix. The 3% bentonite mix was noticeable thicker than the neat cement, and the 12% bentonite did not pour in a continuous stream, but rather in clumps.

3. The apparent grout level was marked on the tank immediately following the pour. In some of the 3% and 6% bentonite tanks and in one of the neat cement tanks, the grout appeared to settle. In the 12 percent bentonite tanks, no settlement was observed.

After placement of grout and covering of the top of the tank, grout was allowed to cure for a period of 14 days. There are no requirements in the Well Specification and Regulations from MDNR on how long grout must be allowed to cure. Well installation generally occurs on a short time line, and sealing of the top of the well may immediately follow grout installation. A period of 14 days was chosen to ensure that the cement would be fully cured before a gradient would be produced across the grout during draining of the tank. At the end of the curing period, the bottom chamber of the tank was drained. After the drainage of the open chamber was accomplished, the drainage tubes were again elevated to prevent drainage out of the open chamber during the test.

As time progressed, water migrated through the pore spaces, and potentially through cracks that may have formed in the grout, and into the bottom chamber. The volume drained was represented by a drop in the water level above the grout. The water level was periodically measured and the time recorded to determine the loss in head over time, which would be used to calculate the hydraulic conductivity. Water was allowed to accumulate until the bottom chamber was nearly full, at which time the bottom would be drained and water would be added to the top of the tank, the water level noted, and the experiment would start over again. If the bottom of the tank became full, then any last measurements taken without free drainage would be invalid, as the exact gradient through the grout was no longer known.

It was expected that each grout would have differing hydraulic conductivities, so some grout mixtures would take longer than others to fill the empty chamber at the bottom of the tank. This was found to be true in this experiment. In the time required for some tanks to have a significant water loss, other tanks had shown substantial water loss and been refilled, sometimes multiple times. To ensure high-quality data, tanks in which the bottom chamber was half-full were drained and refilled to repeat the experiment within a reasonable amount of time. If the chamber at the bottom of the tank was allowed to fill to capacity, the gradient was lowered, thus producing false low permeability data.

5.RESULTS

The data collected from the tanks consisted of water level readings as a function of time, as well as measurements regarding the grout thickness. This information was used in the following equation to calculate the hydraulic conductivity (K) as shown in Equation 1.

$$K=(Z/t)*\ln(h_1/h_2) \qquad \text{Equation 1}$$

Where: K = hydraulic conductivity

Z = thickness of grout

h_1 = initial water level reading

h_2 = final water level reading

t = time elapsed between readings

The hydraulic conductivity was calculated after the start or restart of the experiment, after the initial two readings, between each reading and as a cumulative hydraulic conductivity until the restart of the tank. Data tables for each tank are presented in the Appendix.

A few of the tanks did not function properly; the water level in the Set 1 tank with 12% bentonite with 3 pipes drained within 1 day, indicating that the seal between the grout and the tank was likely compromised. After a few months, a crack developed down the side of one of the control tanks, neat cement with no pipes, at which point usable data could no longer be collected from this tank.

6. RESULTS DISCUSSION

6.1 CONTROL TANKS: NEAT CEMENT

It was predicted that the neat cement (control) would have a consistent permeability over time, as indicated by Edil et al., and that the permeability would not vary with the number of pipes, based on the low dye penetration observed in the Nebraska Grout Task Force study. However a graph of the data (Figure 6.1) shows variable hydraulic conductivities. It was surprising to note that the neat cement tank with

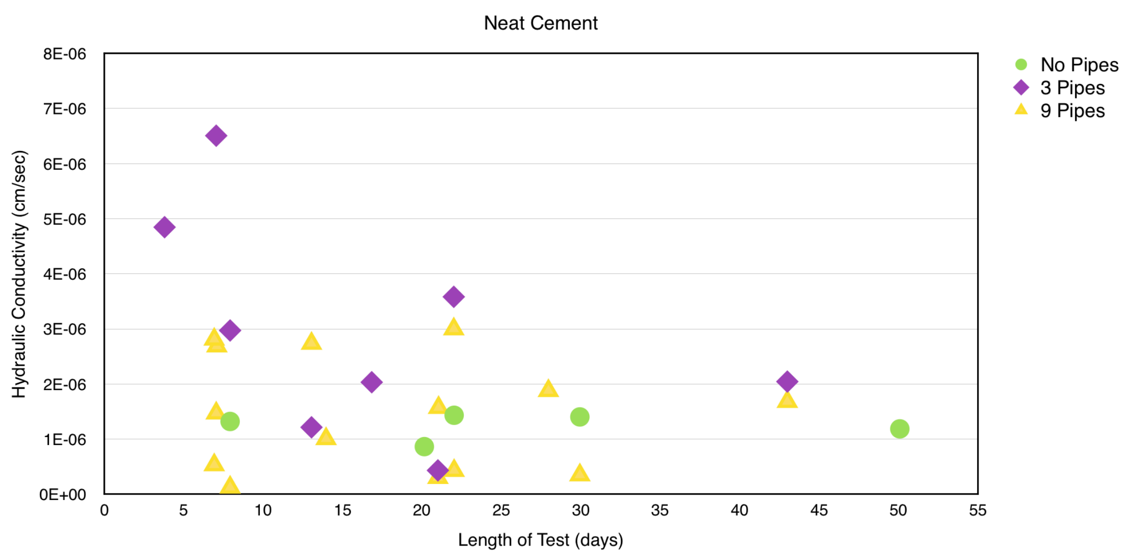


Figure 6.1 Neat Cement: Hydraulic Conductivity vs Length of Test

3 pipes exhibited a higher hydraulic conductivity than the tanks with no pipes or 9 pipes. An approximately 5 month gap in data collection falls in the middle of the testing period. It was hypothesized that the hydraulic conductivity of the grout may change over time, either due to mineralization precipitated out of the water, yielding lower hydraulic conductivities, or dissolution of grout materials or the formation of cracks leading to

higher hydraulic conductivities. A graph of the hydraulic conductivity over time is shown in Figure 6.2. The hydraulic conductivity of the tanks with 3 and 9 pipes showed little variation from the data collected at the beginning of the testing period. As stated earlier, the neat cement tank with zero pipes developed a crack over time that caused failure of the tank, thus the relationship between the hydraulic conductivity and the passage of time could not be established.

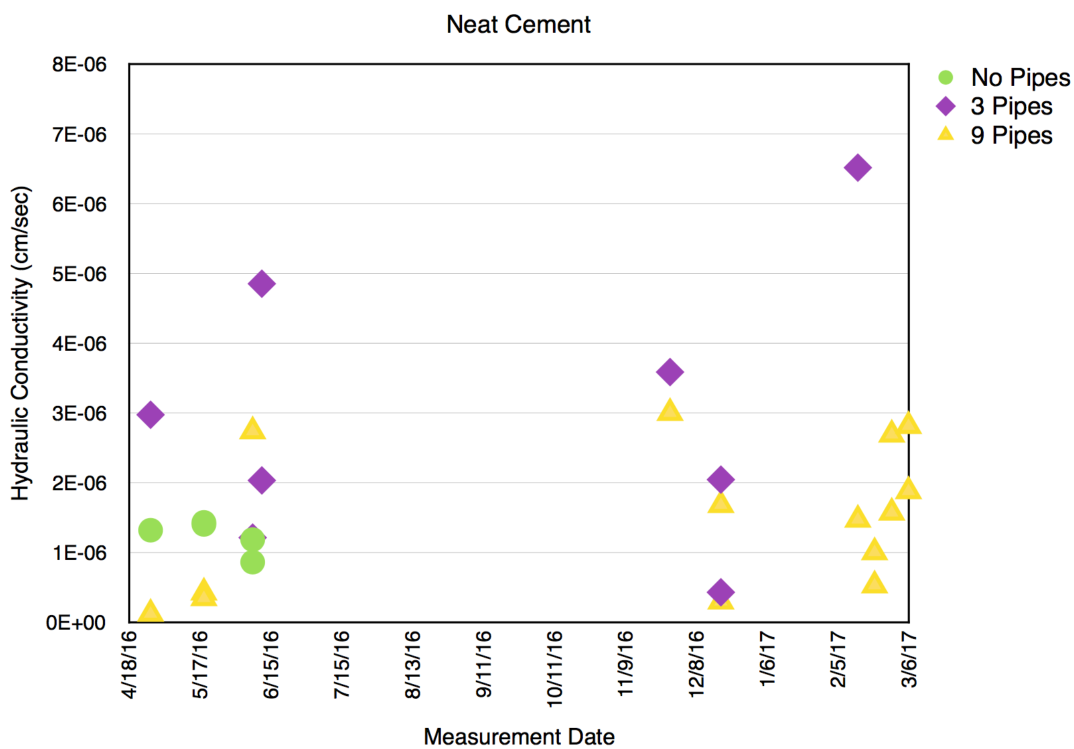


Figure 6.2 Neat Cement: Hydraulic Conductivity Over Time

Trends in the data were difficult to establish, it is hypothesized that since the control tanks were the first to be constructed and poured, the tanks may have had construction problems that the benefit of experience eliminated in the other tanks. It is possible that construction of additional tanks may yield stronger trends, however research regarding the hydraulic conductivity of cement grout is more widely available. The data collected in this study gave hydraulic conductivities expected for cement grouts.

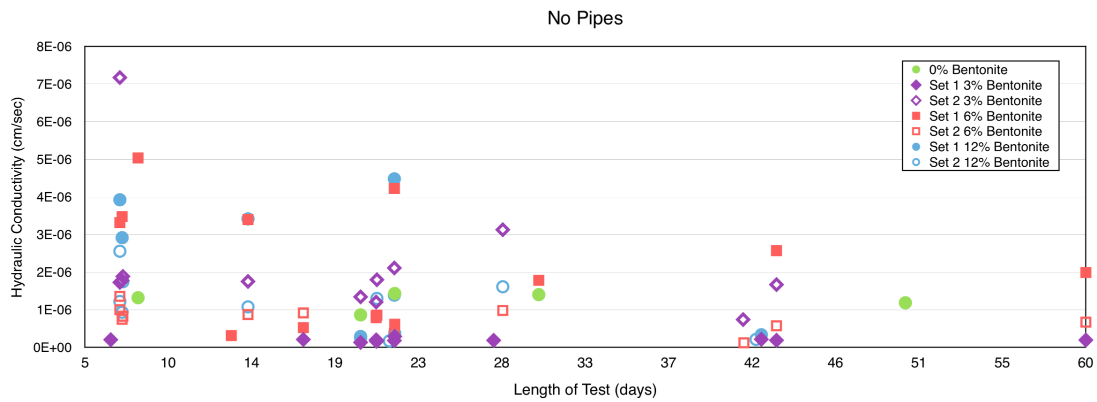
6.2 ALL TANKS WITH NO PIPES

The data from the tanks containing no pipes has been plotted in the following graphs (Figures 6.3). The data appears to be scattered with few strong trends. The neat cement tank, represented as 0% Bentonite appears to have a hydraulic conductivity greater than the majority of the Set 1 3% Bentonite data and the Set 2 6% Bentonite data.

Edil et al concluded that the structural stability of the grout may be a contributing factor to the hydraulic conductivity in the long term (Edil et al, 1992). If the interface between the well casing, whether PVC or steel, did not seal at pouring or was pulled away by shrinkage of the grout curing curing, then pathways for flow may be created. With that in mind, it was anticipated that in the tanks with no pipes, the hydraulic conductivity would remain constant over the passage of time. However, based on the graph of the data over the test period, some of the tanks experienced significant increases in the hydraulic conductivity. Significant increases were observed in the Set 2 3%, Set 1 and 2 6%, and Set 1 and 2 12% Bentonite tanks. As mentioned previously, the neat cement tank with no pipes developed a crack, so data after the time gap is not available.

6.3 ALL TANKS WITH 3 PIPES

The data from all the tanks with 3 pipes has been plotted in the following graphs (Figure 6.4). The original hypothesis that increasing the ratio of Bentonite would lower the hydraulic conductivity was supported in data from the 3 pipe tanks, as well as the



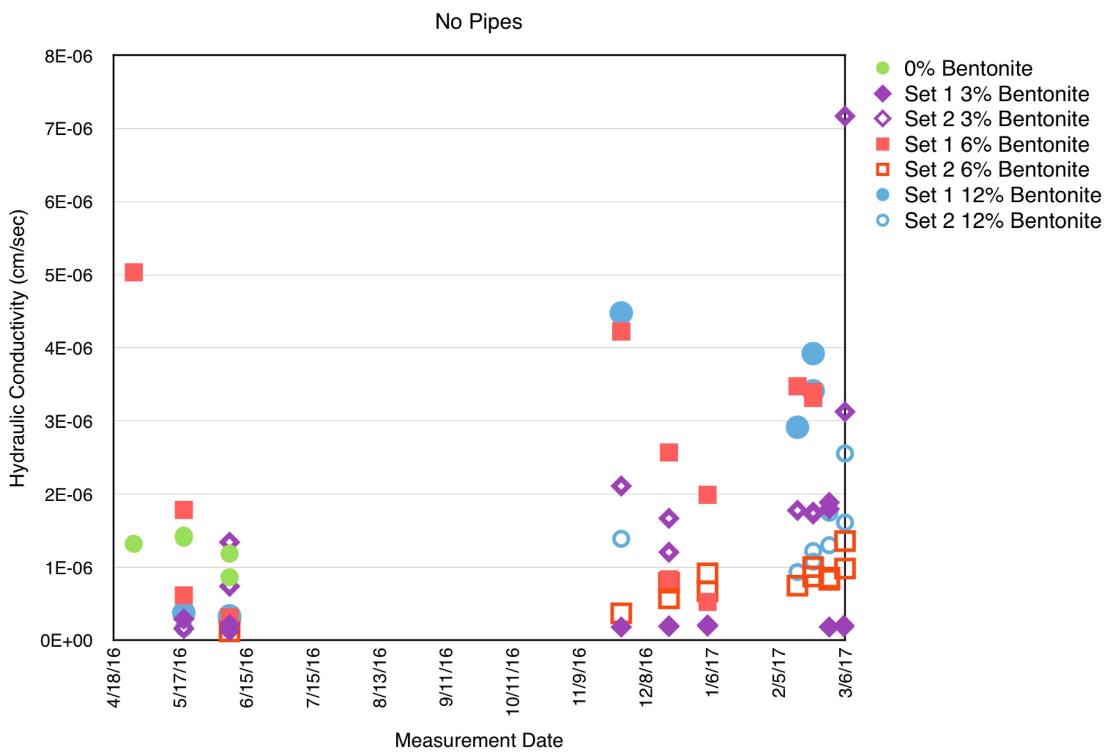


Figure 6.3 All Tanks with No Pipes

hypothesis that the hydraulic conductivity would remain fairly consistent throughout the passage of time. The hydraulic conductivities of the 3% and 6% bentonite are very close and the 12% bentonite was found to have higher permeabilities on average. This may indicate that the benefit of adding bentonite to cement may diminish with increasing percentage.

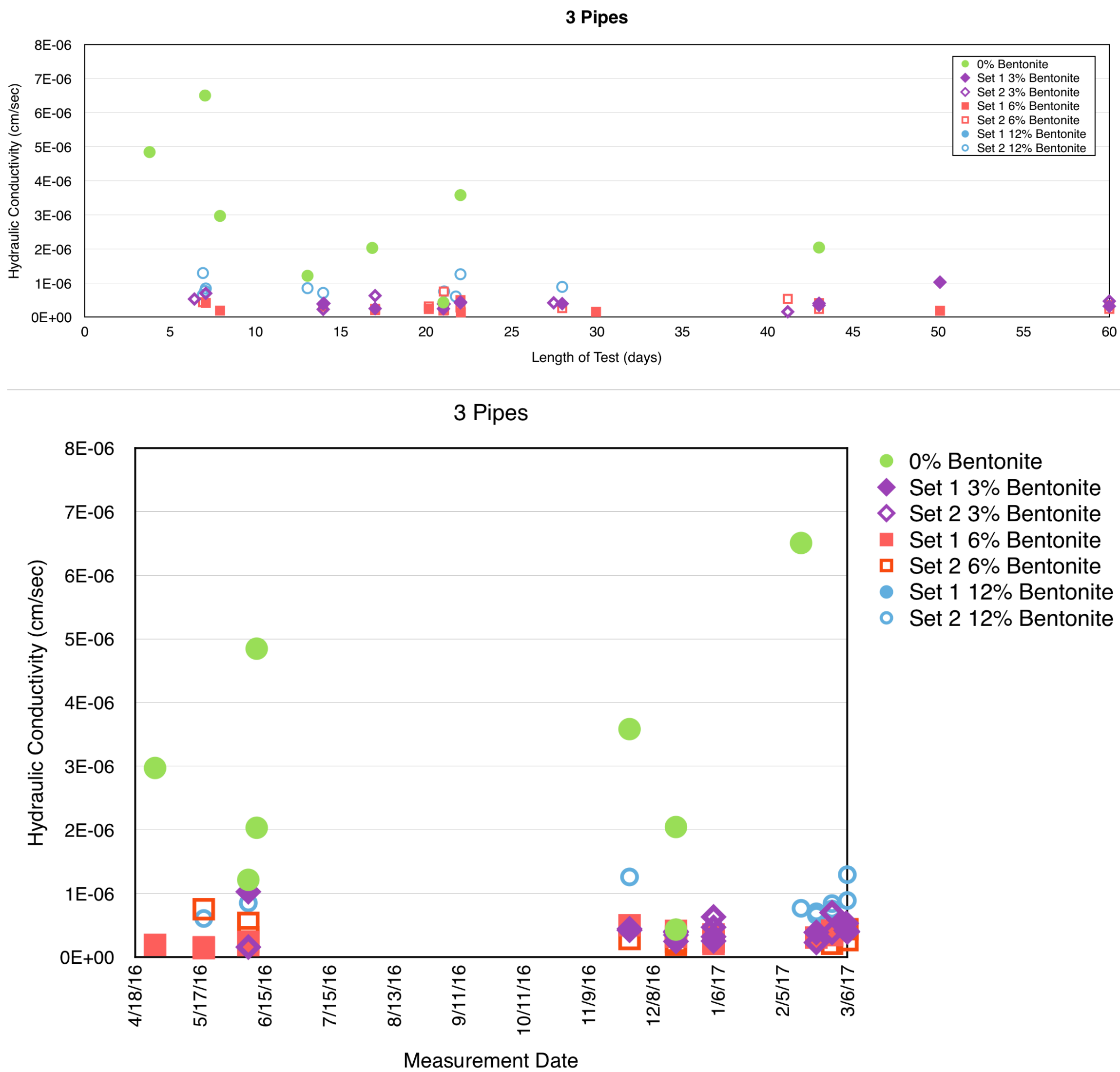


Figure 6.4 All Tanks with 3 Pipes

6.4 ALL TANKS WITH 9 PIPES

The data from all the tanks with 9 pipes has been plotted in the following graphs (Figure 6.5). As in the tanks with no pipes, some of the cement-bentonite grouts yielded higher hydraulic conductivities than the neat cement, in this case Set 1 6% and Set1 and 2

12%. The graph showing the hydraulic conductivity over time shows an increase for the Set 2 3%, Set 1 6% and Set 2 12% and a decrease in the Set 1 12% tank. No other tanks

in the data set showed a decrease in the permeability over time. The cause of this decrease is unknown but could be a result of a crack that was sealed over time by the hydration of bentonite or the precipitation of mineralization to close a crack.

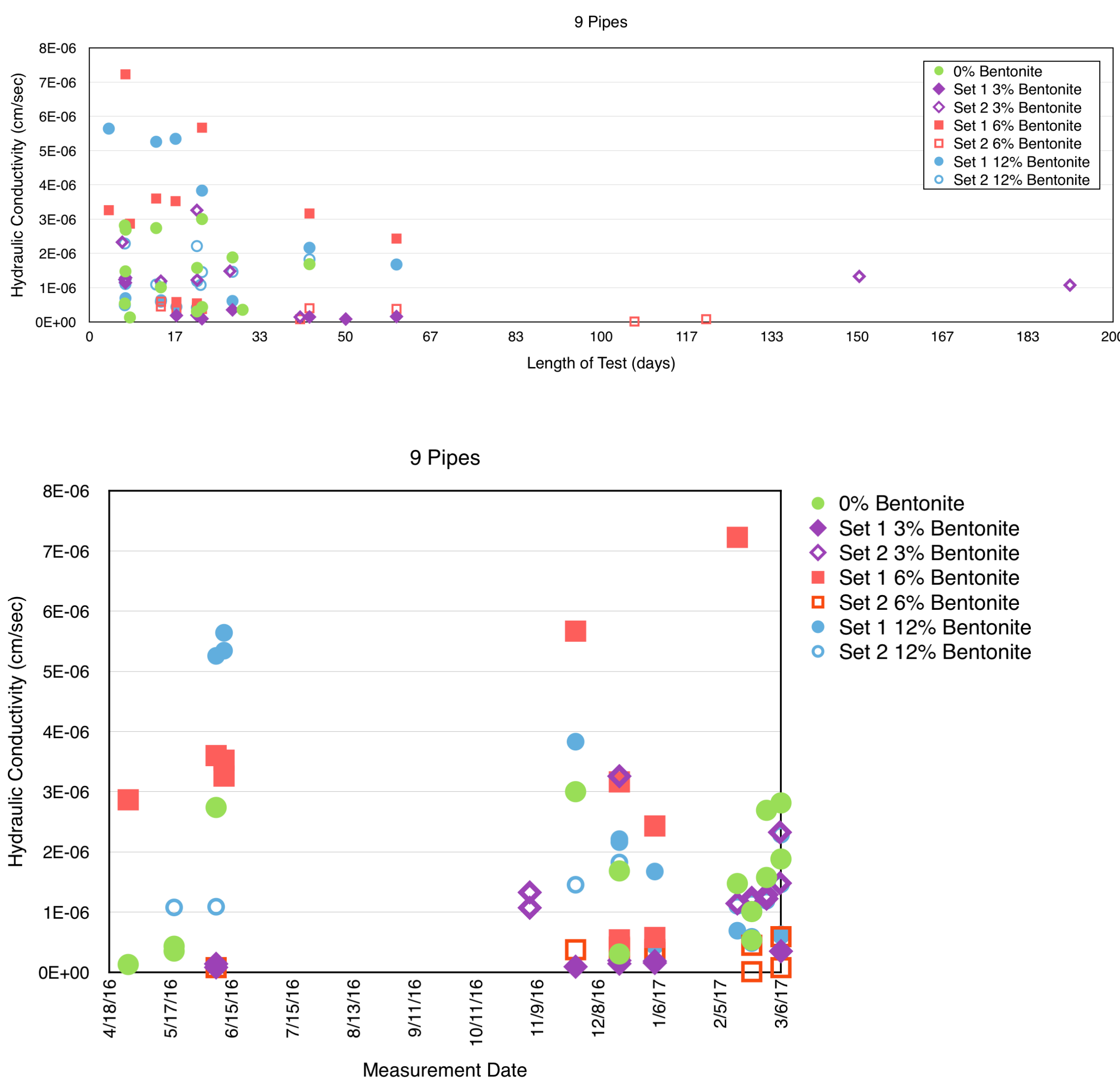


Figure 6.5 All Tanks with 9 Pipes

6.5 AVERAGED HYDRAULIC CONDUCTIVITIES

It was observed that between the two sets of tanks, (cement-bentonite grout mixes only) Set 1 tanks gave on average higher hydraulic conductivities than the Set 2 tanks. Both sets of tanks were stored in temperature controlled environments and water level readings were performed at the same time. Again, a possible source of discrepancy could be in the construction of the tanks. Set 2 was constructed and poured last and had the benefit of experience. The average hydraulic conductivities for all the tanks are presented in the following table (Table 6.1).

According to the averages, all of the grout mixes, regardless of the inclusion of pipes, meet the requirements for impermeability of 10^{-6} cm/sec or less. The averages for the combined cement-bentonite tanks have been plotted as a function of the number of

Table 6.1 Average Hydraulic Conductivities

	SET 1	SET 2	COMBINED
TANK	AVG K (CM/SEC)		
B0P0	1.24E-06	-	-
B0P3	2.95E-06	-	-
B0P9	1.47E-06	-	-
B3P0	1.99E-07	2.04E-06	1.19E-06
B3P3	4.21E-07	4.31E-07	4.26E-07
B3P9	1.70E-07	1.42E-06	9.36E-07
B6P0	2.48E-06	7.76E-07	1.69E-06
B6P3	2.90E-07	3.39E-07	3.12E-07
B6P9	3.28E-06	3.08E-07	1.80E-06
B12P0	2.25E-06	1.13E-06	1.57E-06
B12P3	-	8.63E-07	8.63E-07
B12P9	2.13E-06	1.44E-06	1.82E-06

pipes and the percentage of bentonite which are included in the following graphs (Figures 6.6 and 6.7).

It was hypothesized that addition of bentonite would decrease the hydraulic conductivity due to the expansion of bentonite and its ability to hold on to moisture. The trend in the data suggests that the benefit of bentonite might be limited to a small

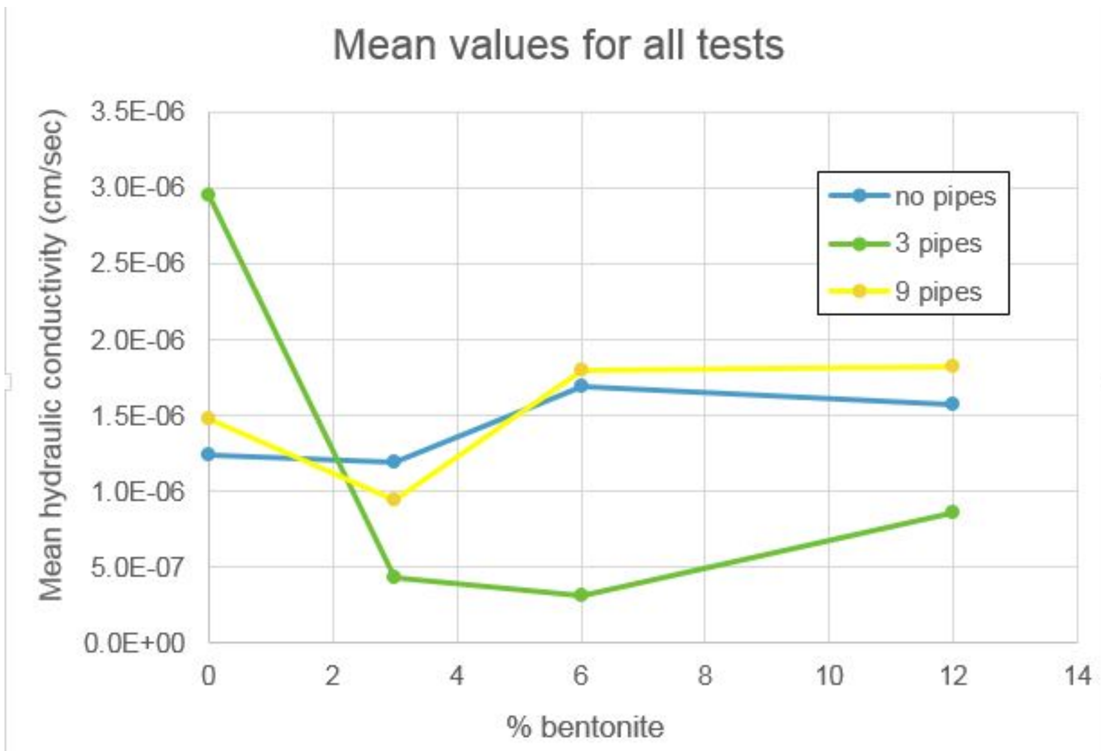


Figure 6.6 Average Values as a Function of the Percent Bentonite

percentage. Hydraulic conductivity was lowered between the 0 and 3% bentonite, however, rose between the 3 and 6% (with the exception of the 3 pipe tanks). In general, the addition of bentonite as an additive to cement to lower the hydraulic conductivity seem effective only when the percentage is less than 6% by weight. It was also observed during the initial pouring of the grout that the workability of the 6 and 12% bentonite

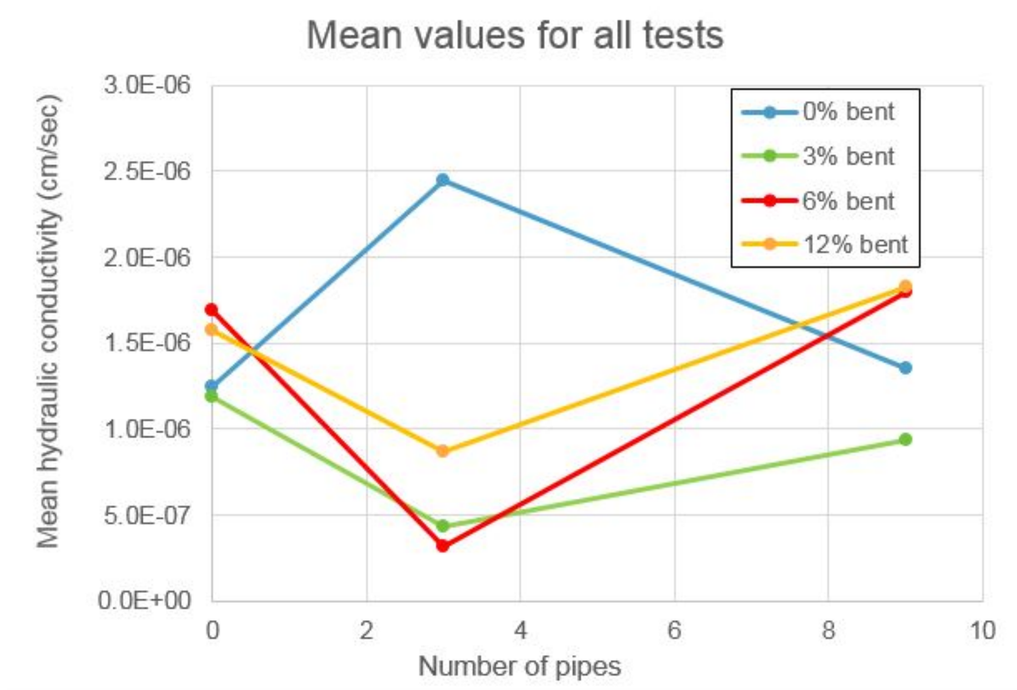


Figure 6.7 Average Values as a Function of the Number of Pipes

mixes was severely effected by the increase in bentonite. Both mixes gave an inconsistent texture and were difficult to pour. Based on these observations it is likely that pumping the grout with such high percentages of bentonite would be very difficult, possibly leading to poor seals.

The tanks with pipes were added to the study in order to determine whether or not a macro-structure was present which could control the hydraulic conductivity. It was assumed that, if present, the macro-structure would lead to increasing hydraulic conductivities as the number of pipes was increased. This was assuming that cracking would propagate around the grout and casing interface or that a micro-annulus would form created by the grout pulling away from or poorly adhering to the well casing. It was surprising to find that the tanks with 3 pipes had lower hydraulic conductivities than the tanks with zero or 9 pipes. It is possible that the crack are not generated around the casing, but that the length of the crack may have been limited by the installation of the pipe, this would explain the lowered hydraulic conductivity between no pipes and 3 pipes. The increase between the tanks with 3 pipes and those with 9 could be due to the micro-annulus. The micro-annulus may have been present in the 3 pipe tanks, however the flow pathways blocked may have been more significant in lowering the hydraulic conductivity, but in the 9 pipes the micro-annulus may have been significant enough to overcome the flow paths that were stopped. Further investigation into why the hydraulic conductivity decreased with additional pipes would be necessary in order to draw any conclusions.

The data collected also suggests that the hydraulic conductivity may increase with the passage of time. A more significant period of data collection may indicate hydraulic conductivities higher than the averages reported here. On the micro scale, fine particles initially blocking a flow path may become disturbed or pushed through the pore space over time causing an increase in the passage of water through the grout column. On the other hand the grout may experience a change in the macro-structure which may cause new flow pathways to be opened up.

7. CONCLUSIONS

In conclusion:

1. Macro structures may still be present within grout mixes that may contribute more significantly to the hydraulic conductivity than the composition of the material.
2. The benefit of bentonite as an additive to cement may decrease as the ratio is increased.
3. The hydraulic conductivity of the grout mix may increase over time, possible due to macro- or micro-structures within the grout.

Additional work should be done related to the macro- and micro-structure of the well grouts, perhaps centering on the nature of the grout matrix, whether or not the cement and bentonite bond and if a failure to bond creates a pathway for flow.

APPENDIX:

DATA TABLES FOR INDIVIDUAL TANKS

	S1B0P0								
	Top of grout measured from bottom of tank	18.6							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	12							
	Date	Reading	Head	Time Elapsed (sec)	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	25.5	6.9	START					
2	4/27/2016 10:00:00 AM	25	6.4	684000s	8	1.32E-06	684000s	8	1.32E-06
3	5/19/2016 10:30:00 AM	23.7	5.1	1902600s	22	1.43E-06	2586600s	30	1.40E-06
4	6/8/2016 2:00:00 PM	23.1	4.5	1740600s	20	8.63E-07	4327200s	50	1.19E-06
					AVG	1.20E-06		AVG	1.30E-06
					ST DEV	0.000000301		ST DEV	0.000000109

	S1B0P3								
	Top of grout measured from bottom of tank	16.3							
	bottom of geotextile measured from bottom of the tank	6.4							
	Thickness of Grout	9.9							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	26	9.7	START					
2	4/27/2016 10:00:00 AM	24.2	7.9	684000s	8	2.97E-06	684000s	8	2.97E-06
3	5/26/2016 1:00:00 PM	25.6	9.3	START					
4	6/8/2016 2:00:00 PM	24.4	8.1	1126800s	13	1.21E-06	1126800s	13	1.21E-06
5	6/12/2016 9:00:00 AM	23.2	6.9	327600s	4	4.85E-06	1454400s	17	2.03E-06
6	11/6/16	25.45	9.15	START					
7	11/28/16	20.9	4.6	1900800s	22	3.58E-06	1900800s	22	3.58E-06
8	12/19/16	20.55	4.25	1814400s	21	4.32E-07	3715200s	43	2.04E-06
9	2/6/17	25.1	8.8	START					
10	2/13/17	22.2	5.9	608400s	7	6.51E-06	608400s	7	6.51E-06
					AVG	3.26E-06		AVG	3.06E-06
					ST DEV	0.000002254		ST DEV	0.000001242

	S1B0P9								
	Top of grout measured from bottom of tank	16							
	bottom of geotextile measured from bottom of the tank	6.5							
	Thickness of Grout	9.5							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	27	11						
2	4/27/2016 10:00:00 AM	26.9	10.9	684000s	8	1.27E-07	684000s	8	1.27E-07
3	5/19/2016 10:30:00 AM	26	10	1902600s	22	4.30E-07	2586600s	30	3.50E-07
4	5/26/2016 1:00:00 PM	26.1	10.1						
5	6/8/2016 2:00:00 PM	23.3	7.3	1126800s	13	2.74E-06	1126800s	13	2.74E-06
6	11/6/16	25.75	9.75						
7	11/28/16	21.35	5.35	1900800s	22	3.00E-06	1900800s	22	3.00E-06
8	12/19/16	21.05	5.05	1814400s	21	3.02E-07	3715200s	43	1.68E-06
9	2/6/17	26	10						
10	2/13/17	25.1	9.1	608400s	7	1.47E-06	608400s	7	1.47E-06
11	2/20/17	24.8	8.8	597600s	7	5.33E-07	1206000s	14	1.01E-06
12	2/27/2017 14:00	23.4	7.4	612000s	7	2.69E-06	1818000s	21	1.57E-06
13	3/6/2017 12:00	22.2	6.2	597600s	7	2.81E-06	2415600s	28	1.88E-06
					AVG	1.57E-06		AVG	1.54E-06
					ST DEV	0.000001238		ST DEV	0.000000157

	S1B3P0								
	Top of grout measured from bottom of tank	16.3							
	bottom of geotextile measured from bottom of the tank	6.4							
	Thickness of Grout	9.9							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/27/2016 10:00:00 AM	25.5	9.2	START					
2	5/19/2016 10:30:00 AM	25	8.7	1902600s	22	2.91E-07	1902600s	22	2.91E-07
3	6/8/2016 2:00:00 PM	24.8	8.5	1740600s	20	1.32E-07	3643200s	42	2.15E-07
4	11/6/16	25.05	8.75	12996000s					
5	11/28/16	24.75	8.45	1900800s	22	1.82E-07	1900800s	22	1.82E-07
6	12/19/16	24.45	8.15	1814400s	21	1.97E-07	3715200s	43	1.89E-07
7	1/5/17	24.2	7.9	1468800s	17	2.10E-07	5184000s	60	1.95E-07
8	2/6/17	25.4	9.1	2811600s					
9	2/27/2017 14:00	25.1	8.8	1818000s	21	1.83E-07	1818000s	21	1.83E-07
10	3/6/2017	25	8.7	554400s	6	2.04E-07	2372400s	27	1.88E-07
					AVG	2.00E-07		AVG	2.06E-07
					ST DEV	0.000000047		ST DEV	0.000000039

	S1B3P3								
	Top of grout measured from bottom of tank	17.7							
	bottom of geotextile measured from bottom of the tank	6.4							
	Thickness of Grout	11.3							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	25.7	8	START					
2	6/8/2016 2:00:00 PM	23.1	5.4	4327200s	50	1.03E-06	4327200s	50	1.03E-06
3	11/6/16	24.65	6.95	START					
4	11/28/16	24.15	6.45	1900800s	22	4.44E-07	1900800s	22	4.44E-07
5	12/19/16	23.9	6.2	1814400s	21	2.46E-07	3715200s	43	3.47E-07
6	1/5/17	23.7	6	1468800s	17	2.52E-07	5184000s	60	3.20E-07
7	2/6/17 13:00	25.10	7.40	START					
8	2/20/17 12:00	24.80	7.10	1206000s	14	3.88E-07	1206000s	14	3.88E-07
9	3/6/2017 12:00	24.5	6.8	1209600s	14	4.03E-07	2415600s	28	3.96E-07
					AVG	4.60E-07		AVG	4.87E-07
					ST DEV	0.000000289		ST DEV	0.000000267

	S1B3P9								
	Top of grout measured from bottom of tank	18.5							
	bottom of geotextile measured from bottom of the tank	6.5							
	Thickness of Grout	12							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	25.6	7.1	START					
2	6/8/2016 2:00:00 PM	25.4	6.9	4327200s	50	7.92E-08	4327200s	50	7.92E-08
3	11/6/16	25.55	7.05	START					
4	11/28/16	25.45	6.95	1900800s	22	9.02E-08	1900800s	22	9.02E-08
5	12/19/16	25.25	6.75	1814400s	21	1.93E-07	3715200s	43	1.40E-07
6	1/5/17	25.1	6.6	1468800s	17	1.84E-07	5184000s	60	1.53E-07
7	2/6/17 13:00	25.90	7.40	START					
8	3/6/17 12:00	25.40	6.90	2415600s	28	3.48E-07	2415600s	28	3.48E-07
					AVG	1.79E-07		AVG	1.62E-07
					ST DEV	0.000000107		ST DEV	0.000000108

	S1B6P0								
	Top of grout measured from bottom of tank	16.7							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	10.1							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	25.7	9	START					
2	4/27/2016 10:00:00 AM	23.1	6.4	684000s	8	5.03E-06	684000s	8	5.03E-06
3	5/19/2016 10:30:00 AM	22.4	5.7	1902600s	22	6.15E-07	2586600s	30	1.78E-06
4	5/26/2016 1:00:00 PM	25.4	8.7	START					
5	6/8/2016 2:00:00 PM	25.1	8.4	1126800s	13	3.15E-07	1126800s	13	3.15E-07
6	11/6/16	25.45	8.75	START					
7	11/28/16	20.65	3.95	1900800s	22	4.23E-06	1900800s	22	4.23E-06
8	12/19/16	20.1	3.4	1814400s	21	8.35E-07	3715200s	43	2.57E-06
9	1/5/17	19.85	3.15	1468800s	17	5.25E-07	5184000s	60	1.99E-06
10	2/6/17	25.7	9	START					
11	2/13/17	24	7.3	608400s	7	3.48E-06	608400s	7	3.48E-06
12	2/20/17	22.7	6	597600s	7	3.31E-06	1206000s	14	3.40E-06
					AVG	2.29E-06		AVG	2.85E-06
					ST DEV	0.000001687		ST DEV	0.000001308

	S1B6P3								
	Top of grout measured from bottom of tank	17.2							
	bottom of geotextile measured from bottom of the tank	6.5							
	Thickness of Grout	10.7							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	25.4	8.2	START					
2	4/27/2016 10:00:00 AM	25.3	8.1	684000s	8	1.92E-07	684000s	8	1.92E-07
3	5/19/2016 10:30:00 AM	25.1	7.9	1902600s	22	1.41E-07	2586600s	30	1.54E-07
4	6/8/2016 2:00:00 PM	24.8	7.6	1740600s	20	2.38E-07	4327200s	50	1.88E-07
5	11/6/16	25.45	8.25	START					
6	11/28/16	24.75	7.55	1900800s	22	4.99E-07	1900800s	22	4.99E-07
7	12/19/16	24.35	7.15	1814400s	21	3.21E-07	3715200s	43	4.12E-07
8	1/5/17	24.15	6.95	1468800s	17	2.07E-07	5184000s	60	3.54E-07
9	2/6/17	26	8.8	START					
10	2/20/17	25.7	8.5	1206000s	14	3.08E-07	1206000s	14	3.08E-07
11	2/27/17 14:00	25.5	8.3	612000s	7	4.16E-07	1818000s	21	3.44E-07
					AVG	2.90E-07		AVG	3.06E-07
					ST DEV	0.000000121		ST DEV	0.000000120

	S1B6P9								
	Top of grout measured from bottom of tank	17.6							
	bottom of geotextile measured from bottom of the tank	6.4							
	Thickness of Grout	11.2							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/19/2016 12:00:00 PM	25.7	8.1	START					
2	4/27/2016 10:00:00 AM	24.4	6.8	684000s	8	2.86E-06	684000s	8	2.86E-06
3	5/26/2016 1:00:00 PM	25.5	7.9	START					
4	6/8/2016 2:00:00 PM	23.1	5.5	1126800s	13	3.60E-06	1126800s	13	3.60E-06
5	6/12/2016 9:00:00 AM	22.6	5	327600s	4	3.26E-06	1454400s	17	3.52E-06
6	11/6/16	25.45	7.85	START					
7	11/28/16	20.6	3	1900800s	22	5.67E-06	1900800s	22	5.67E-06
8	12/19/16	20.35	2.75	1814400s	21	5.37E-07	3715200s	43	3.16E-06
9	1/5/17	20.15	2.55	1468800s	17	5.76E-07	5184000s	60	2.43E-06
10	2/6/17	25.3	7.7	START					
11	2/13/17	22.8	5.2	608400s	7	7.23E-06	608400s	7	7.23E-06
					AVG	3.39E-06		AVG	4.07E-06
					ST DEV	0.000002459		ST DEV	0.000001732

	S1B12P0								
	Top of grout measured from bottom of tank	16.5							
	bottom of geotextile measured from bottom of the tank	6.5							
	Thickness of Grout	10							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/27/2016 10:00:00 AM	25.2	8.7	START					
2	5/19/2016 10:30:00 AM	24.6	8.1	1902600s	22	3.76E-07	1902600s	22	3.76E-07
3	6/8/2016 2:00:00 PM	24.2	7.7	1740600s	20	2.91E-07	3643200s	42	3.35E-07
4	11/6/16	25.05	8.55	START					
5	11/28/16	20.15	3.65	1900800s	22	4.48E-06	1900800s	22	4.48E-06
6	2/6/17	24.5	8	START					
7	2/13/17	23.2	6.7	608400s	7	2.91E-06	608400s	7	2.91E-06
8	2/20/17	21.8	5.3	597600s	7	3.92E-06	1206000s	14	3.41E-06
					AVG	2.40E-06		AVG	2.30E-06
					ST DEV	0.000001965		ST DEV	0.000001865

	S1B12P3								
	Top of grout measured from bottom of tank								
	bottom of geotextile measured from bottom of the tank								
	Thickness of Grout								
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	BROKEN TANK								

	S1B12P9								
	Top of grout measured from bottom of tank	17							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	10.4							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	5/26/2016 1:00:00 PM	24.6	7.6	START					
2	6/8/2016 2:00:00 PM	21.3	4.3	1126800s	13	5.26E-06	1126800s	13	5.26E-06
3	6/12/2016 9:00:00 AM	20.6	3.6	327600s	4	5.64E-06	1454400s	17	5.34E-06
4	11/6/16	24.25	7.25	START					
5	11/28/16	20.6	3.6	1900800s	22	3.83E-06	1900800s	22	3.83E-06
6	12/19/16	20.35	3.35	1814400s	21	4.13E-07	3715200s	43	2.16E-06
7	1/5/17	20.15	3.15	1468800s	17	4.36E-07	5184000s	60	1.67E-06
8	2/6/17	24.6	7.6	START					
9	2/13/17	24.3	7.3	608400s	7	6.88E-07	608400s	7	6.88E-07
10	2/20/17	24.1	7.1	597600s	7	4.83E-07	1206000s	14	5.87E-07
11	3/6/17	23.6	6.6	1209600s	14	6.28E-07	2415600s	28	6.07E-07
					AVG	2.17E-06		AVG	2.52E-06
					ST DEV	0.000002325		ST DEV	0.000002027

	S2B3P0								
	Top of grout measured from bottom of tank	16.4							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	9.8							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/28/2016 10:00:00 AM	23.2	6.8	START					
2	5/19/2016 10:30:00 AM	23	6.6	1816200s	21	1.61E-07	1816200s	21	1.61E-07
3	6/8/2016 2:00:00 PM	21.6	5.2	1740600s	20	1.34E-06	3556800s	41	7.39E-07
4	11/6/16	22.8	6.4	START					
5	11/28/16	20.65	4.25	1900800s	22	2.11E-06	1900800s	22	2.11E-06
6	12/19/16	19.8	3.4	1814400s	21	1.21E-06	3715200s	43	1.67E-06
7	2/6/17	23.1	6.7	START					
8	2/13/17	22.4	6	608400s	7	1.78E-06	608400s	7	1.78E-06
9	2/20/17	21.8	5.4	597600s	7	1.73E-06	1206000s	14	1.75E-06
10	2/27/2017 14:00	21.2	4.8	612000s	7	1.89E-06	1818000s	21	1.80E-06
11	3/6/2017 12:00	19.5	3.1	597600s	7	7.17E-06	2415600s	28	3.13E-06
					AVG	2.17E-06		AVG	1.64E-06
					ST DEV	0.000002107		ST DEV	0.000000885

	S2B3P3								
	Top of grout measured from bottom of tank	17.5							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	10.9							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/28/2016 10:00:00 AM	25.5	8	START					
2	6/8/2016 2:00:00 PM	25.1	7.6	3556800s	41	1.57E-07	3556800s	41	1.57E-07
3	11/6/16	25.25	7.75	START					
4	11/28/16	24.7	7.2	1900800s	22	4.22E-07	1900800s	22	4.22E-07
5	12/19/16	24.25	6.75	1814400s	21	3.88E-07	3715200s	43	4.05E-07
6	1/5/17	23.7	6.2	1468800s	17	6.31E-07	5184000s	60	4.69E-07
7	2/6/17	25.5	8	START					
8	2/20/17	25.3	7.8	1206000s	14	2.29E-07	1206000s	14	2.29E-07
9	2/27/2017 14:00	25	7.5	612000s	7	6.99E-07	1818000s	21	3.87E-07
10	3/6/2017	24.8	7.3	554400s	6	5.31E-07	2372400s	27	4.21E-07
					AVG	4.37E-07		AVG	3.56E-07
					ST DEV	0.000000199		ST DEV	0.000000115

	S2B3P9								
	Top of grout measured from bottom of tank	18.4							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	11.8							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/28/2016 10:00:00 AM	25.8	7.4	START					
2	6/8/2016 2:00:00 PM	25.5	7.1	3556800s	41	1.37E-07	3556800s	41	1.37E-07
3	11/6/16	20.05	1.65	12996000s	150	1.33E-06	16552800s	192	1.07E-06
4	11/28/16	23.35	4.95	START					
5	12/19/16	21.4	3	1814400s	21	3.26E-06	1814400s	21	3.26E-06
6	2/6/17	25.4	7	START					
7	2/13/17	25	6.6	608400s	7	1.14E-06	608400s	7	1.14E-06
8	2/20/17	24.6	6.2	597600s	7	1.23E-06	1206000s	14	1.19E-06
9	2/27/2017 14:00	24.2	5.8	612000s	7	1.29E-06	1818000s	21	1.22E-06
10	3/6/2017	23.6	5.2	554400s	6	2.32E-06	2372400s	27	1.48E-06
					AVG	1.53E-06		AVG	1.36E-06
					ST DEV	0.000000990		ST DEV	0.000000938

	S2B6P0								
	Top of grout measured from bottom of tank	16.6							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	10							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/28/2016 9:00:00 AM	26	9.4	START					
2	6/8/2016 2:00:00 PM	25.6	9	3560400s	41	1.22E-07	3560400s	41	1.22E-07
3	11/6/16	25.45	8.85						
4	11/28/16	24.85	8.25	1900800s	22	3.69E-07	1900800s	22	3.69E-07
5	12/19/16	23.75	7.15	1814400s	21	7.89E-07	3715200s	43	5.74E-07
6	1/5/17	22.85	6.25	1468800s	17	9.16E-07	5184000s	60	6.71E-07
7	2/6/17	25.6	9						
8	2/13/17	25.2	8.6	608400s	7	7.47E-07	608400s	7	7.47E-07
9	2/20/17	24.7	8.1	597600s	7	1.00E-06	1206000s	14	8.74E-07
10	2/27/17	24.3	7.7	612000s	7	8.28E-07	1818000s	21	8.58E-07
11	3/6/17	23.7	7.1	597600s	7	1.36E-06	2415600s	28	9.82E-07
					AVG	7.66E-07		AVG	6.50E-07
					ST DEV	0.000000378		ST DEV	0.000000286

	S2B6P3								
	Top of grout measured from bottom of tank	17.2							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	10.6							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/28/2016 10:00:00 AM	26.3	9.1	START					
2	5/19/2016 10:30:00 AM	25.2	8	1816200s	21	7.52E-07	1816200s	21	7.52E-07
3	6/8/2016 2:00:00 PM	24.8	7.6	1740600s	20	3.12E-07	3556800s	41	5.37E-07
4	11/6/16	25.25	8.05	START					
5	11/28/16	24.85	7.65	1900800s	22	2.84E-07	1900800s	22	2.84E-07
6	12/19/16	24.6	7.4	1814400s	21	1.94E-07	3715200s	43	2.40E-07
7	1/5/17	24.35	7.15	1468800s	17	2.48E-07	5184000s	60	2.42E-07
8	2/6/17	25.7	8.5	START					
9	2/27/17	25.4	8.2	1818000s	21	2.10E-07	1818000s	21	2.10E-07
10	3/6/17	25.2	8	597600s	7	4.38E-07	2415600s	28	2.66E-07
					AVG	3.48E-07		AVG	3.62E-07
					ST DEV	0.000000195		ST DEV	0.000000204

	S2B6P9								
	Top of grout measured from bottom of tank	17.5							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	10.9							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/28/2016 10:00:00 AM	25.8	8.3	START					
2	6/8/2016 2:00:00 PM	25.6	8.1	3556800s	41	7.47E-08	3556800s	41	7.47E-08
3	11/6/16	25.45	7.95	START					
4	11/28/16	24.95	7.45	1900800s	22	3.72E-07	1900800s	22	3.72E-07
5	12/19/16	24.45	6.95	1814400s	21	4.17E-07	3715200s	43	3.94E-07
6	1/5/17	24.15	6.65	1468800s	17	3.27E-07	5184000s	60	3.75E-07
7	2/6/17	25.8	8.3	START					
8	2/20/17	25.4	7.9	1206000s	14	4.46E-07	9201600s	107	7.47E-09
9	3/6/17	24.9	7.4	1209600s	14	5.89E-07	10411200s	121	7.51E-08
					AVG	3.71E-07		AVG	2.17E-07
					ST DEV	0.000000170		ST DEV	0.000000181

	S2B12P0								
	Top of grout measured from bottom of tank	16.2							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	9.6							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/27/2016 5:00:00 PM	25.3	9.1	START					
2	5/19/2016 10:30:00 AM	25	8.8	1877400s	22	1.71E-07	1877400s	22	1.71E-07
3	6/8/2016 2:00:00 PM	24.6	8.4	1740600s	20	2.57E-07	3618000s	42	2.12E-07
4	11/6/16	25.35	9.15	START					
5	11/28/16	23.15	6.95	1900800s	22	1.39E-06	1900800s	22	1.39E-06
6	2/6/17	24.9	8.7	START					
7	2/13/17	24.4	8.2	608400s	7	9.34E-07	608400s	7	9.34E-07
8	2/20/17	23.8	7.6	597600s	7	1.22E-06	1206000s	14	1.08E-06
9	2/27/17	23	6.8	612000s	7	1.74E-06	1818000s	21	1.30E-06
10	3/6/17	22	5.8	597600s	7	2.56E-06	2415600s	28	1.61E-06
					AVG	1.18E-06		AVG	9.56E-07
					ST DEV	0.000000835		ST DEV	0.000000565

	S2B12P3								
	Top of grout measured from bottom of tank	15.6							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	9							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/27/2016 5:00:00 PM	25.7	10.1	START					
2	5/19/2016 10:30:00 AM	24.5	8.9	1877400s	22	6.06E-07	1877400s	22	6.06E-07
3	5/26/2016 1:00:00 PM	25.5	9.9						
4	6/8/2016 2:00:00 PM	24.5	8.9	1126800s	13	8.51E-07	1126800s	13	8.51E-07
5	11/6/16	25.45	9.85						
6	11/28/16	23.15	7.55	1900800s	22	1.26E-06	1900800s	22	1.26E-06
7	2/6/17	25.5	9.9						
8	2/13/17	25	9.4	608400s	7	7.67E-07	608400s	7	7.67E-07
9	2/20/17	24.6	9	597600s	7	6.55E-07	1206000s	14	7.11E-07
10	2/27/17	24.1	8.5	612000s	7	8.41E-07	1818000s	21	7.55E-07
11	3/6/17	23.4	7.8	597600s	7	1.29E-06	2415600s	28	8.88E-07
					AVG	8.96E-07		AVG	8.34E-07
					ST DEV	0.000000275		ST DEV	0.000000208

	S2B12P3								
	Top of grout measured from bottom of tank	17							
	bottom of geotextile measured from bottom of the tank	6.6							
	Thickness of Grout	10.4							
	Date	Reading	Head	Time Elapsed	Time Elapsed (days)	K (cm/sec)	Time Elapsed for Trial	Time Elapsed (days)	K (cm/sec) since start
1	4/27/2016 5:00:00 PM	25.5	8.5	START					
2	5/19/2016 10:30:00 AM	24	7	1877400s	22	1.08E-06	1877400s	22	1.08E-06
3	5/26/2016 1:00:00 PM	26	9	START					
4	6/8/2016 2:00:00 PM	25	8	1126800s	13	1.09E-06	1126800s	13	1.09E-06
5	11/6/16	25.15	8.15	START					
6	11/28/16	23.25	6.25	1900800s	22	1.45E-06	1900800s	22	1.45E-06
7	12/19/16	21.25	4.25	1814400s	21	2.21E-06	3715200s	43	1.82E-06
8	2/6/17	25	8	START					
9	2/13/17	24.5	7.5	608400s	7	1.10E-06	608400s	7	1.10E-06
10	2/20/17	24	7	597600s	7	1.20E-06	1206000s	14	1.15E-06
11	2/27/17	23.5	6.5	612000s	7	1.26E-06	1818000s	21	1.19E-06
12	3/6/17	22.7	5.7	597600s	7	2.29E-06	2415600s	28	1.46E-06
					AVG	1.46E-06		AVG	1.29E-06
					ST DEV	0.000000502		ST DEV	0.000000264

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VITA

Amy Lynn Norval was born to Ed and Shari Norval August 26, 1991 in Springfield, MO. She attended Springfield Public Schools and graduated from Kickapoo High School in 2010. Amy received her bachelors in Geology from Missouri University of Science and Technology in 2014 with honors. During her graduate studies in Geological Engineering, Amy served the department as a grader, graduate teaching assistant, lead teaching assistant and course administrator. She began working at Geotechnology, Inc. in Memphis, Tennessee as a full-time geotechnical engineer in May 2016 .She received her MS in Geological Engineering in May 2017 from the Missouri University of Science and Technology.