Final Report

Cobble Systems Pervious/Permeable Pavements

Submitted by

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ECOSYSTEMS
PERMEABLE BINDING AGENT

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(NOTE: The following evaluation was done before *EcoSystems Permeable Binding Agent* left the R&D phase and is referred to as "Pervious Grout" in this study. The agent was used to bind aggregate as joint material in every test.)

Table of Contents

List of Figures

List of Tables

Project Description

The purpose of this study was to evaluate the performance of a pervious grout developed for use with permeable pavers by Cobble Systems. The evaluation of the field performance is for permeable pavement systems with modifications made to the filler stones. A binding agent is added to eliminate loss during the rejuvenation process. The testing on several pervious and permeable pavements was performed at the Stormwater Management Academy Research and Testing laboratory (SMART Lab), UCF, Orlando in Orange County, Florida. Presented in Figure 1 is a picture of the test area with eleven different pavement systems. Cobble Systems supplied the required materials and installed the pervious/permeable pavements at the research site. The company is located in Orlando, Florida and operates consultancy services for the design and installation of pervious/permeable pavements.

Figure 1: Project test areas

Scope of Services

The study intended to provide information on the infiltration rates of permeable/pervious pavements, including pervious grout and the effects of sediment loading and rejuvenation on the infiltration capacity. No previous study has been completed for this new pervious grout. Thus, the SMART Lab performed field evaluation services in general accordance with the standard methods previously used for the evaluation of infiltration rates of pervious pavements at the research center. Field evaluations were performed using the Embedded Ring Infiltrometer Kit (ERIK) discussed below and used at the SMART Lab. The purpose of this study was to obtain information concerning the efficiency of the Cobble Systems pervious grout used with permeable pavement systems in each of the following areas:

1. Evaluation of the infiltration rates of the eleven different permeable/pervious pavements under different surface clogging conditions using the short-ring ERIK

2. Evaluation of the infiltration rates of the eleven different permeable/pervious pavements under different surface clogging conditions using the long-ring ERIK

3. Verify how well the permeable grout performs under the various conditions that the system is subjected to in the testing protocol.

4. Determine the effectiveness of the vacuum sweeper truck on removing sediment to improve water filtration.

The pavement surface clogging conditions evaluated were: newly installed pavement; pavement surface loaded with sandy soil (AASHTO A-3) and the subsequent rejuvenated (vacuum sweeping) pavement surface; and finally, pavement surface loaded with silty-sandy soil (AASHTO A-2-4) and the subsequent rejuvenated (vacuum sweeping) pavement surface.

Background Information

Pervious and permeable pavements are a unique and effective means to reduce stormwater runoff. By capturing rainwater and allowing it to seep into the ground, pervious and permeable pavements are instrumental in recharging groundwater, reducing stormwater runoff, and meeting U.S. Environmental Protection Agency (EPA) stormwater regulations (Paul D. Tennis 2004). Permeable pavement systems are used in a variety of residential, commercial, and industrial applications but are confined to light duty traffic and infrequent use (Scholz and Grabowiecki 2006).

The limitations of these pavements come from the increase in void space in the pavement system, which reduces the amount of stress that can be applied onto the system before failure. The permeable and pervious pavements have voids in the system which allows water to flow into the system and reduce stormwater runoff. Over time soil particles enter the voids, which slow down the infiltration rate of the pavements and reduce the runoff reduction effectiveness. The two techniques used to remove these soil particles are pressure washing, and air or vacuuming sweeping (Mark Dougherty 2011). Both cleaning methods can increase infiltration rates by at least 200% when comparing the infiltration rates before and after the cleaning, with the largest improvement in pavement infiltration capacity resulting when the two cleaning methods are combined (LeFevre 2007).

The differences between the pervious and permeable pavements in this research are within the top layer of the system and the variations that come along with those alterations. The top layer of the permeable pavement consists of pavers and permeable grout between each paver. For the permeable paver, rainwater can only filter through the grout because the pavers are impervious. On the other hand, the porous pavements that do not have pavers are called pervious pavements. These pervious pavement systems are different types of #89 stone held together with a binder, and have more surface opening to allow water to flow through the system. The two different types of pavements are usually installed where there is a low traffic volume. The applications are: residential driveways, service and access driveways, roadway shoulders, crossovers, fire lanes, utility access, slope stabilization, erosion control bicycle, equestrian trails, and land irrigation (Scholz and Grabowiecki 2006).

Pervious/permeable pavement systems consist of multiple layers; an example is shown in Figure 2. The top layer is the pervious/permeable pavement layer, which can range in depth from two to twelve inches. For the permeable pavement system that uses brick pavers, the water moves through the system via the gaps in the joints of bricks. These gaps are traditionally filled with a filler stone to prevent transport of sediments and provide strength. The next layer in the system is a reservoir layer that will hold the rainwater as it infiltrates through the rest of the system. During the rain event, the top layer infiltration rate is typically faster than the infiltration rate of the parent earth which results in water accumulating in the reservoir layer. Therefore the reservoir layer needs to be large enough to account for the accumulation. A filter fabric is located below the reservoir layer to prevent migration of parent soil into the reservoir layer.

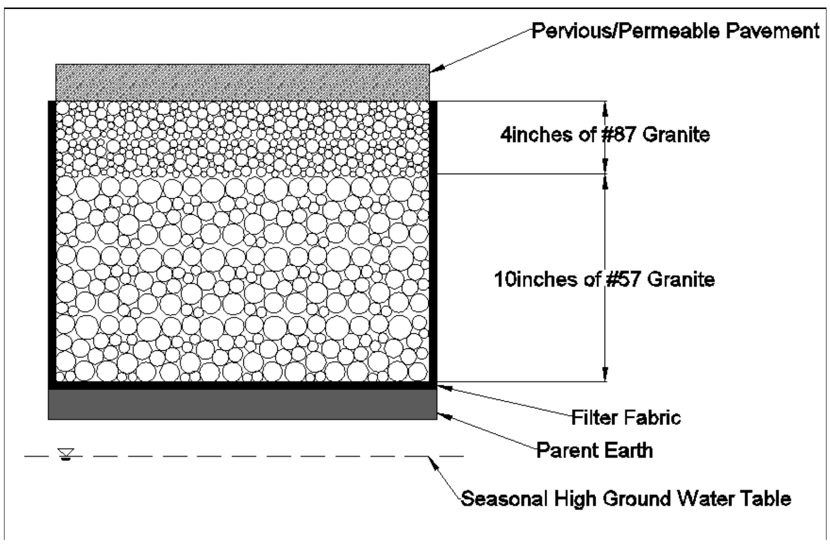

Figure 2: Pervious/Permeable Pavement Cross Section

The infiltration rates are measured using an embedded ring infiltrometer kit (ERIK). There are two different length embedded rings, namely long and short, which consist of PVC pipe embedded into the pavement system. The short pipe is intended to measure the infiltration of the surface layer and is installed such that the pipe goes through the pavement layer and terminates in the gravel sub base as shown in Figure 3. Since this pipe provides information on the surface infiltration rate for the pavement, the short ring ERIK is the best indicator to the degree of clogging and the need for maintenance. The long pipe, shown in Figure 3, is installed through the entire pavement system and imbedded 4 inches into the parent soil, which shows the infiltration rate of the whole system. This data gives information on the recovery time of the system.

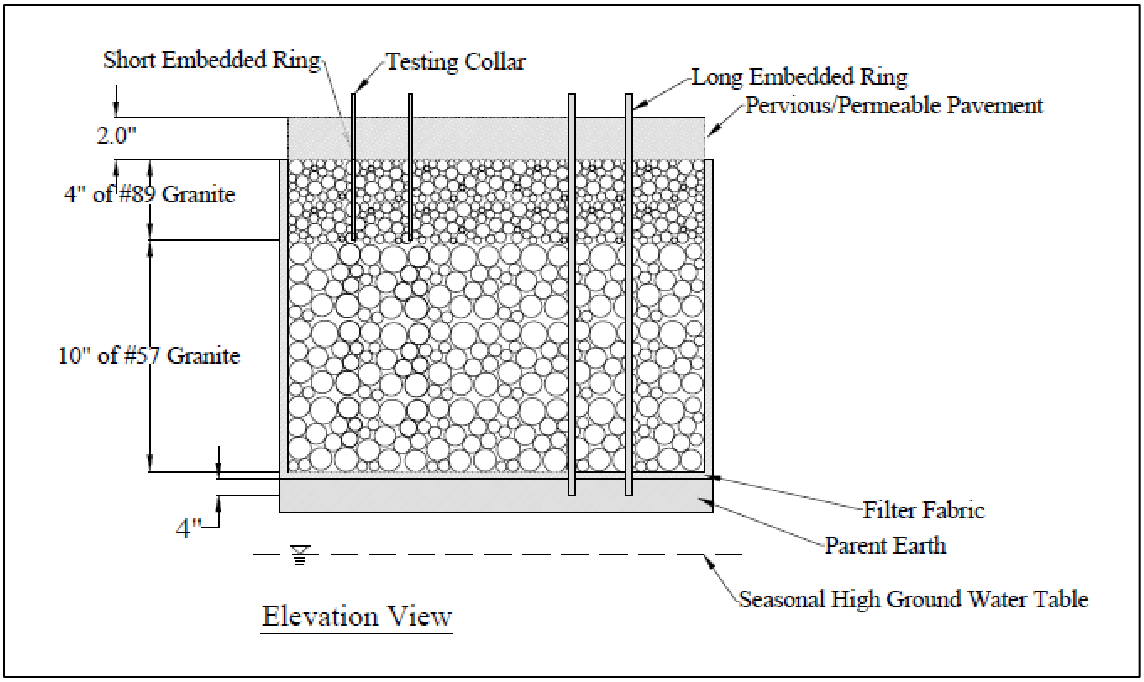

Figure 3: Short and Long Embedded Ring for Pervious Pavement System Example

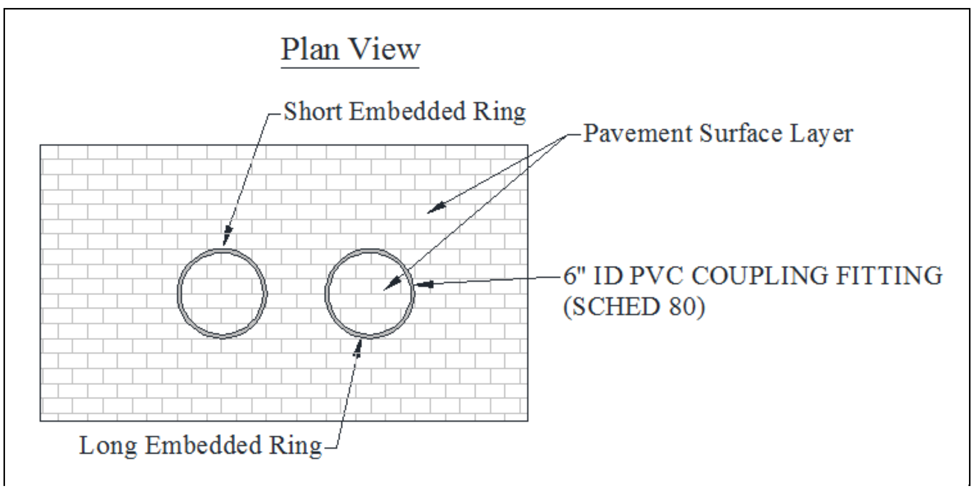

Figure 4: Plan View of Pavement

Permeable paver systems can be used as an infiltration practice for stormwater management. They have large openings at the joints that promote rapid passage of water and allow it to infiltrate into underlying soils. A reservoir of select pollution control media can also be added beneath the pervious pavers to remove pollutants. The family of porous pavements, already recognized as a best management practice by the Environmental Protection Agency

(USEPA, 1999), has the potential to become a popular alternative for dealing with stormwater runoff.

Embedded Ring Infiltrometer Kit (ERIK)

The Embedded Ring Infiltrometer Kit (ERIK) is used to measure the infiltration rate of the pervious/permeable pavements. The embedded ring restricts the water to only flow in a downwards direction giving a more accurate measurement of the true infiltration rate. This ERIK device was developed at the University of Central Florida (UCF) in Orlando and was designed to overcome any difficulties in obtaining infiltration measurements of pervious/permeable pavement systems using an efficient, accurate, non-destructive and repeatable, and economical approach (Manoj Chopra 2011).

The ERIK device was based on the Double Ring Infiltrometer and limits the need to keep two rings with a constant water head to just one ring. Figure 3 shows the length of both the short and long ring ERIK pipes. It can be seen that the short embedded ring goes through the surface layer and terminates in the rock reservoir layer while the longer embedded ring goes through the whole pervious/permeable system and is embedded 4 inches into the parent earth. This is done to isolate different parts of the pavement system, with the short ring isolating the surface layer while the long ring evaluates the entire system recovery.

To run an infiltration test the following steps and conditions must be achieved. First, equilibrium needs to be achieved prior to recording data for both the short ring and long ring tests. For the short ring ERIK, a constant head is maintained with a hose prior to adding water from the measurement reservoir (see Figure 5, Figure 6, and Figure 7 for illustration of measurement reservoir). Once a constant head is maintained, the rate of water addition is matched with the measurement reservoir and the timer is started when the water level passes the top mark. The time taken for the water level to move past each successive mark is recorded. Each mark in the 2 inch diameter measurement reservoir corresponds to a 0.5 inch drop in the 6 inch diameter embedded ring. This procedure is repeated 5 times to ensure a robust data set. With this data, the infiltration rate can easily be calculated.

For the long ring ERIK this means fully saturating the material contained in the pipe as well as maintaining a constant head. When water is initially added to the embedded ring, a head of water quickly forms but air will bubble out lowering the head level. The bubbles will cease once equilibrium is obtained. Water is added to maintain a constant head from a hose. At this point water is to be added from the measuring reservoir at a rate equal to the equilibrium saturation rate maintaining the constant head of 1 inch. Once the water level in the measurement reservoir passes the top mark, the stopwatch is started. The time it takes for the water level to move past each successive mark is recorded. Each mark in the 2 inch diameter measurement reservoir corresponds to a 0.5 inch drop in the 6 inch diameter embedded ring. This procedure is repeated 5 times to ensure a robust data set. With this data the infiltration rate is then calculated.

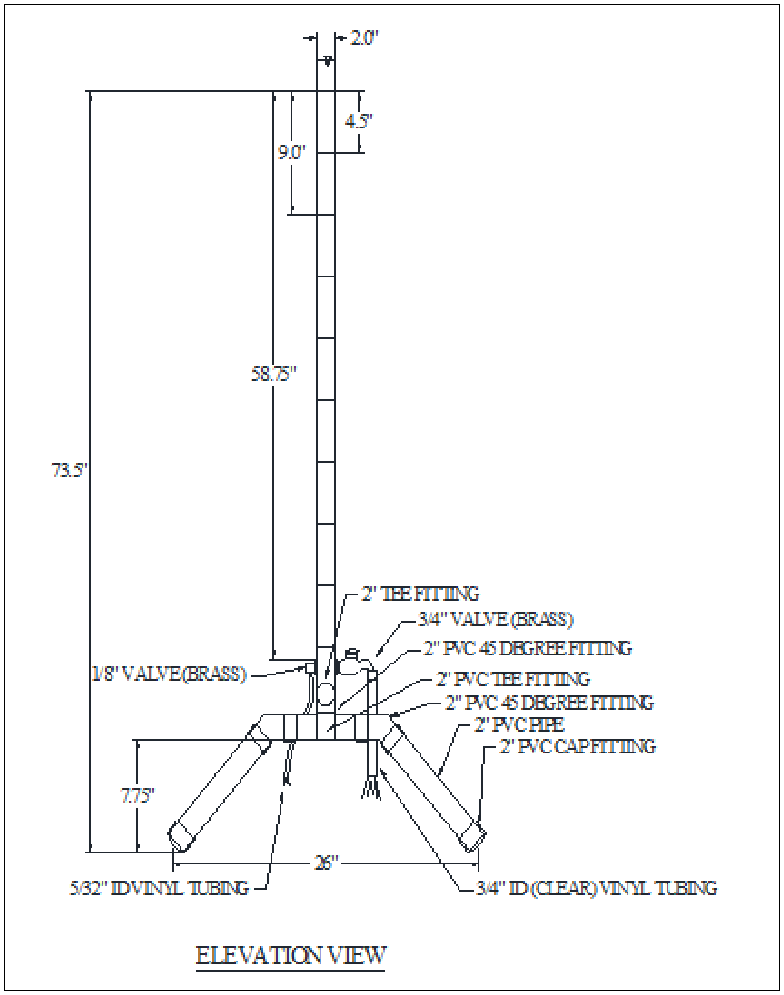

Figure 5: Elevation View of Measurement Reservoir for ERIK Device

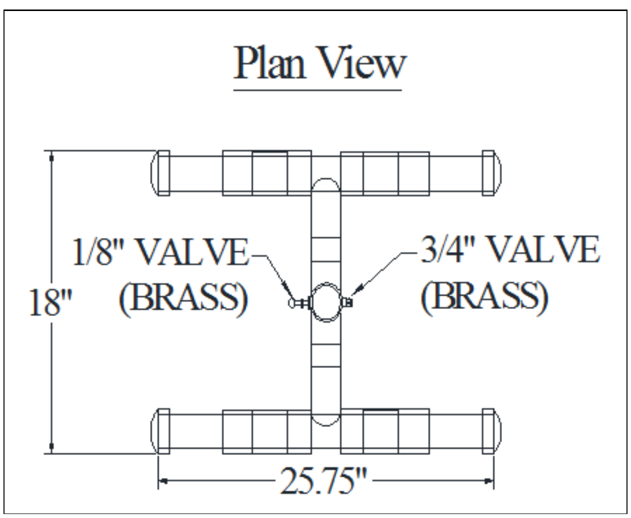

Figure 6: Plan View of Measurement Reservoir for ERIK Device

Figure 7: ERIK Testing in Progress

Reusable Grout

Permeable pavement systems typically consist of impervious brick pavers and filler stone (usually #89 granite chips but #89 limerock is also used). This filler stone is used to add strength and increase contact between bricks. The voids of the filler stone are typically 15-35% of the total volume of the coarse aggregate (Mary Vancura 2012). The use of filler stone is necessary but can be problematic when maintenance is performed on these systems and the filler stone is removed with the sediment (University of Maryland 2011). This represents an added cost to the owner and a drawback to these types of systems. The recommendation for the total frequency of the vacuum sweep is two times per year (Lake County Forest Preserves 2003). To address this issue a permeable grout was developed by Cobble Systems which uses a poorly graded sand or #89 stone with EcoSystems Grout™ (a two part epoxy binder) to make a permanent, pervious filler.

Pavement Installation and Setup

A total of 11 different pavement systems were installed by Cobble Systems at the University of Central Florida Stormwater Management Academy laboratory. The site prior to installation and after completing installation is shown in Figure 8 and Figure 9, respectively. A cross section of the pavement systems is shown above in Figure 2. Pavements 1-4 are types of pervious pavements that use the Cobble Systems binder with different stone aggregate and pavements 5-11 are permeable pavements with different pervious grout. There are eight different test pads separated by footers and stem walls with each test pad being around 9ft by 9ft. Three of these test pads are divided in half. The parent earth at the site is sandy soil, AASHTO type A-3.

Figure 8: Test area prior to installing pavements

Figure 9: Pavements after completely installed

Before the pavements could be installed, the parent earth needed to be excavated and the area for the footings was cleared as shown in Figure 10. Then, Figure 11 illustrates framing for the concrete and the #5 rebar in place. Connected onto of the footings are steel reinforced stem walls shown in Figure 11, which are used to section off the different pavements.

Figure 10: Test area with footings excavated

Figure 11: Steel reinforced stem walls being installed

After the footings and stem walls were formed, the parent earth was compacted. Filter fabric was then installed to separate the stone reservoir from the parent earth thus significantly limiting any interstitial mixing (Figure 12). A sub-base of #57 granite stone was installed and compacted in 4-inch lifts for the total height of the granite section being 10 inches (Figure 13).

Figure 12: Filter fabric installed

Figure 13: Granite installed over filter fabric prior to compaction

Two different size infiltration test pipes were installed for each pavement type, namely a short ring and a long ring. The short ring was installed in pavement surface terminating in the top two inches of the #57 granite layer and the long ring was installed through the entire system embedded 4 inches into the parent soil (See Figure 3). Next, 4 inches of #89 granite stone was installed and compacted on top of the #57 granite stone. The different pervious and permeable pavement surface layers where then constructed on top of the #89 granite stone. Figure 14 shows the pervious river rock surface layer being laid on top of the #89 granite stone and Figure 15 illustrates the porous grout being installed in one of the paver test pads. The completed installation of the pavements is shown in Figure 9 with each pavement numbered. Additional pictures of the instillation are located in the Appendix at the end of this report.

Figure 14: River Rock being installed

Figure 15: Ecosystems Grout being installed

Testing Program

The investigations were performed using four sections of permeable pavers at the SMART Lab. The total area of paved surface was about 3000 square feet. The test pad was divided into 11 sections. All sections were equipped with the ERIK to measure the rate of infiltration through the pavement. All sections were loaded with sediment to study the degree of clogging as well as the ability of the vacuum sweeper truck to rejuvenate the systems. The primary focus of the sediment loading section was to investigate the requirements for maintenance and the acceptable techniques to use for cleaning. Table 1 shows the parameters associated with each section to be tested.

Table 1: Permeable Paver Test Section Description

Section	Paver Type and Filler	Paver or Loose Laid
1	#8 River Rock with Binder	Loose Laid
2	#89 Granite with Binder	Loose Laid
3	#57 River Rock with Binder	Loose Laid
4	#20\30 Sand with Binder	Loose Laid
5	Old Castle with #20/30 Sand	Paver
6	Old Castle with #89 Granite	Paver
7	Cobble Systems Fan Pattern with #6\20 Sand	Paver
8	Cobble Systems Straight Pattern with #89 Granite	Paver
9	Cobble Systems Charleston Cobble Straight Pattern with #89 Granite	Paver
10	Cobble Systems Charleston Cobble Straight Pattern with #20\30 Sand	Paver
11	Cobble Systems Straight Pattern with #20\30 Sand	Paver

The pavements were installed 9/03/2010.

Protocol for Infiltration and Rejuvenation testing

The timeline for the five different conditions that these pavements were tested is as follows - On 9/3/2010 the pavements were installed, on 6/5/2011 they were all loaded with a sandy soil (AASHTO type A-3), on 2/22/12 the pavements were then rejuvenated with a vacuum sweeper truck, then on 6/4/2012 the pavements were loaded with a silty-sandy soil (AASHTO type A-2-4), after which they were rejuvenated again with a vacuum sweeper truck on 10/23/2012.

The first infiltration rates were measured right after the pavements were installed (Figure 9). To perform an ERIK test a small 6 inch testing collar is installed on the embedded PVC pipe with silicon to eliminate water from leaking. This test collar allows for a head of water to develop above the system, for this testing a 2 inch head was used. The test collar needs to be taken off and reinstalled before and after each infiltration test done so vehicles can travel over the pavements unobstructed. After about nine months, the pavements were loaded with a roughly 2 inch thick layer of sandy soil (A-3 soil) as shown in Figure 16. The sandy soil was loaded and compacted with a bobcat in addition to washing the soil into the pavement with a hose. This helped the soil particles enter the pavement system and increased the compaction capacity. Another round of infiltration testing was done to observe the effect of soil loading on the pavements.

Figure 16: Pavements post loading of sandy soil

A standard sweeper vacuum truck (Figure 17) was selected to rejuvenate the pavements and a method was adopted from previous research done at the Stormwater Management Academy. To increase the amount of particles being removed, water was added to saturate the pavements to allow the fine grained sediments to reach their liquid limit, become plastic and mobile, and then be removed by the sweeper truck shown in Figure 18 and Figure 19 (Manoj Chopra 2011). More infiltration tests (ERIK tests) were performed to observe the effects of rejuvenation on the pavement systems.

Figure 17: Sweeper truck cleaning the pavements

Figure 18: Saturating pavements to optimize soil particle removal

The next sediment loading regiment was with a silty-sandy soil (A-2-4). The sediment loading was performed using procedure as previously discussed with the sandy soil. More ERIK tests were completed to observe the reduction in infiltration due to the loading of the silty-sandy soil. Following those tests, the pavements were rejuvenated in the same way as previously shown, which is with a vacuum sweeper truck as shown in Figure 19 and Figure 20. ERIK tests were then performed to achieve data on how well the pavements were rejuvenated.

Figure 19: Saturating the pavements while the sweeper truck

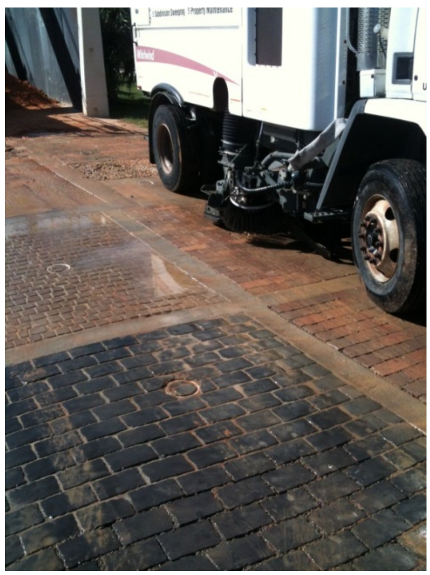

Figure 20: Sweeper truck removing silty-sand soil

Results for Short Ring Tests

Presented below in Figure 21 is a numbered layout of the pavements after they were installed. For the short-ring tests, the rings were installed flush with the pavement surface and imbedded 4 inches into the top layer of #89 granite stone.

Figure 21: Pavements after completely installed

Pavement systems 1 and 2 are loose laid pervious pavement systems. Both pavements had very high initial infiltration rates that ranged from 6023 in/hr to 3394 in/hr. They also behaved similarly when loaded with sediment and then rejuvenated (see Figure 32 and Figure 33 in the Appendix). The results for pavement system 1 are presented below in Figure 22 which gives an example of the trend for both pavements. The two pavements had a significant reduction in infiltration rate when loaded with a sandy soil resulting in infiltration rates ranging from 87.6 in/hr to 2.9 in/hr. The sweeper truck rejuvenation restored the infiltration rates to about one third of the initial rates for both pavements. After the pavements were loaded with the silty-sandy soil, the infiltration rates ranged from 4.5 in/hr to 0.4 in/hr. The final rejuvenation process restored the infiltration rates to about the same as after the first rejuvenation.

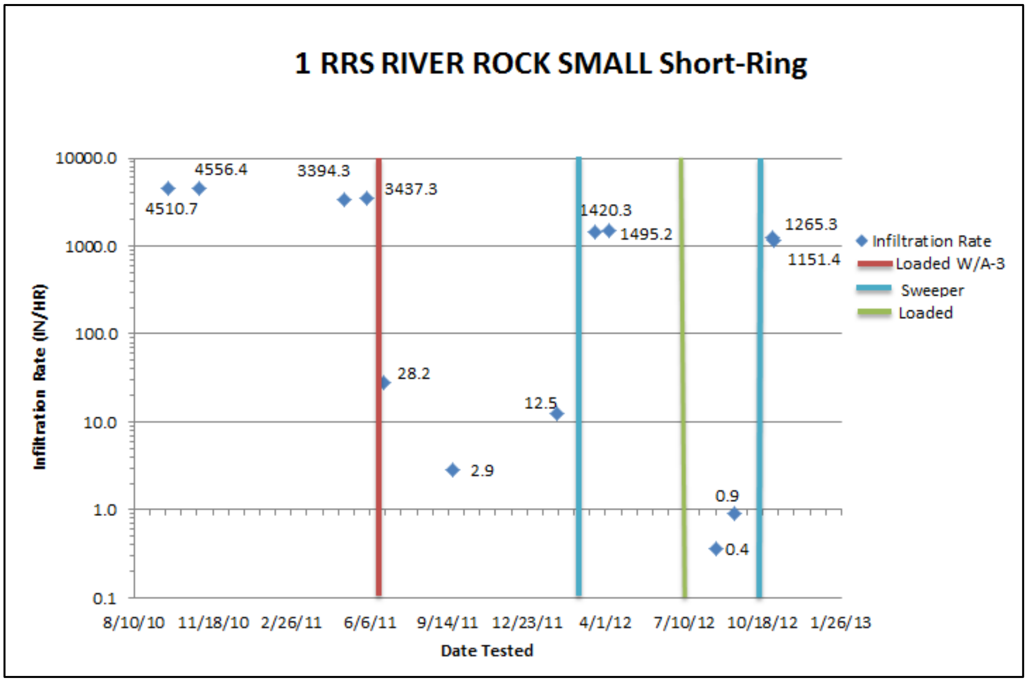

Figure 22: Infiltration Rate vs. Time for 1 RRS Short-Ring

Pavement 3, the loose laid large river rock section, had the highest initial infiltration rates compared to all the pavement systems examined. The infiltration rate for pavement 3 ranged from 10,400 in/hr to 7,810.5 in/hr (see Figure 23). This is due to the fact that larger stone was used for this pavement system resulting in large open voids. Once the sandy soil (A-3) was loaded on the surface, the infiltration rates decreased significantly to 69.9 in/hr and 38.5 in/hr. The vacuum sweeper truck was unable to rejuvenate the pavement due to the fact that more soil was imbedded into the system than any other pavement due to the large gaps between the large river rocks. This resulted in soil traveling deeper into the system than the vacuum could effectively remove. Once this pavement was loaded with soil it was visible in the pavement after each rejuvenation process. This corresponded with infiltration rates that are not significantly different from the rates after the loading of the sandy soil which is shown below in Figure 23. When the silty-sandy soil (A-2-4) was loaded, the infiltration rates were further reduced. The last rejuvenation attempt by the vacuum sweeper truck restored the infiltration rates to around the rates after the first rejuvenation, indicating that soil that traveled deeper into the system was unable to be removed.

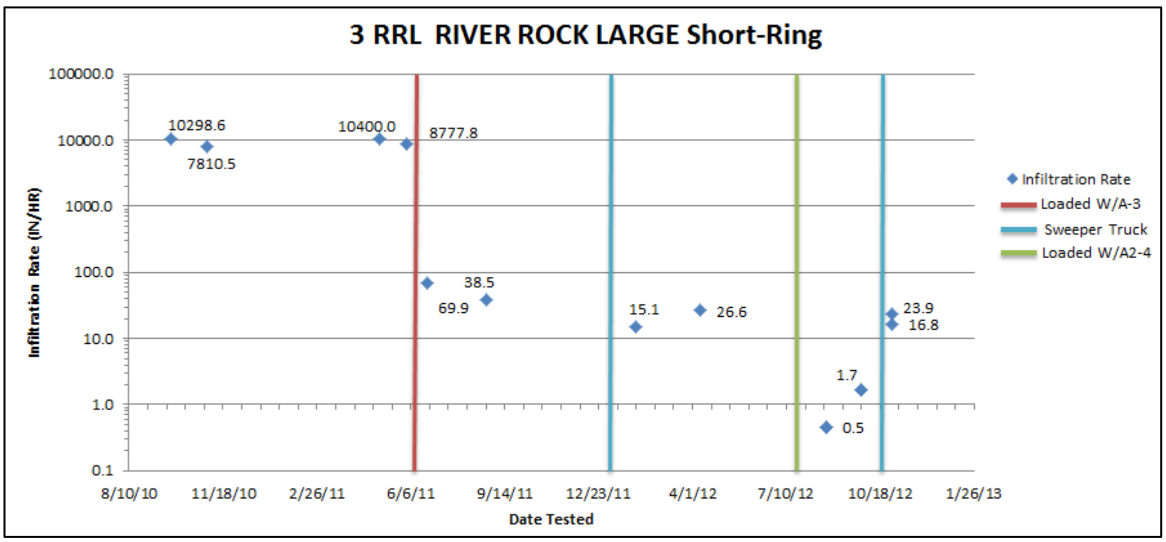

Figure 23: Infiltration Rates vs. Time for 3 RRL Short-Ring

Pavement 4, the loose laid sand system, had the lowest initial infiltration rates of the first four non-paver pervious pavements. The short-ring results are located below in Figure 24. This pavement had the same type of trend as the first two pavements where the infiltration rates decreased and increased respectfully when loaded with sediment and rejuvenated with a sweeper truck.

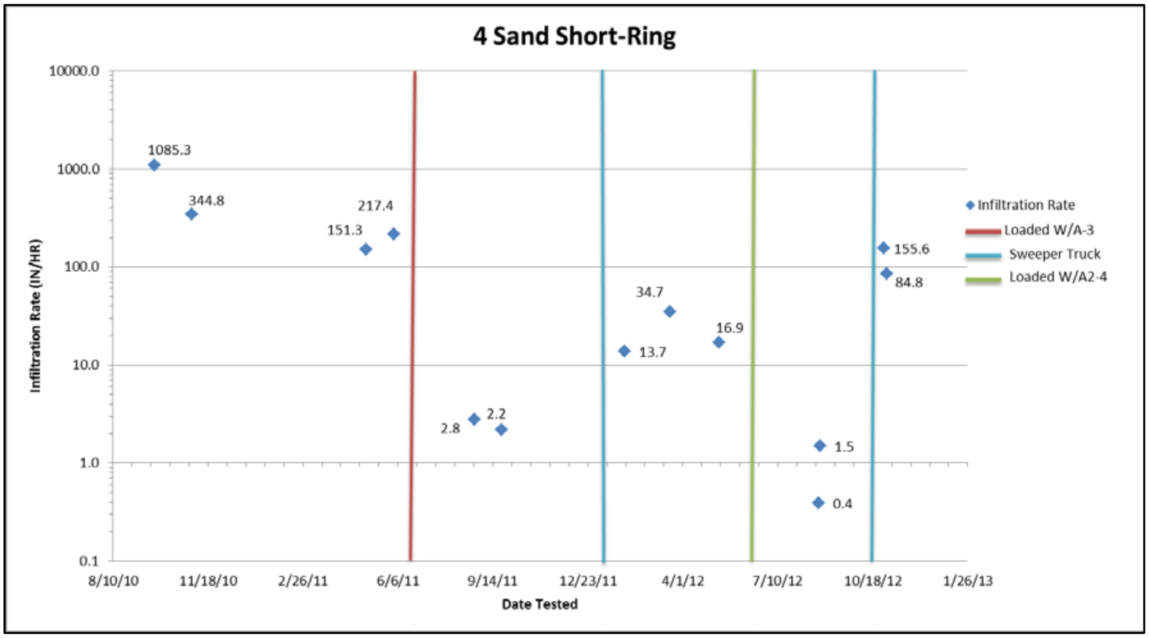

Figure 24: Infiltration Rates vs. Time for 4 Sand Short-Ring

Pavements 6, 8 and 9 are permeable pavers that have #89 granite stone grout. Pavement 6 had the highest initial infiltration rates of the three pavements, while pavement 8 had the lowest initial infiltration rates (see Figure 37, Figure 39, and Figure 40 in the Appendix). The infiltration rates ranged from 3300.8 in/hr to 1430.3 in/hr for these pavement systems. All three of the pavements had the typical trend of infiltration rates decreased and increased respectfully when loaded with sediment and rejuvenated with a vacuum sweeper truck. An example of the trend is presented below in Figure 25 for pavement 6. The three pavements were loaded with A-3 sandy soil resulting in an infiltration rate range of 8.9 in/hr to 0.9 in/hr for pavements 6 and 8. Pavement 9 infiltration rates decreased to a range of 53.7 in/hr to 29 in/hr. After the sweeper truck rejuvenated the pavements, pavement 6 increased to around one third of its initial infiltration rate. Pavements 8 and 9 rejuvenated to around one half of their initial infiltration rates. The pavements were then loaded with an A-2-4 silty-sandy soil, which resulted in a decrease of the pavements infiltration rates. The pavements showed an infiltration rate decrease to a range of 7.2 in/hr to 0.3 in/hr. The final rejuvenation resulted in the pavements infiltration rates to increase from loading conditions but none of them reached the same infiltration rate as after the first rejuvenation. Pavement 9 had the fastest final infiltration rate at 885.8 in/hr while pavement 8 had the lowest at 13.2 in/hr.

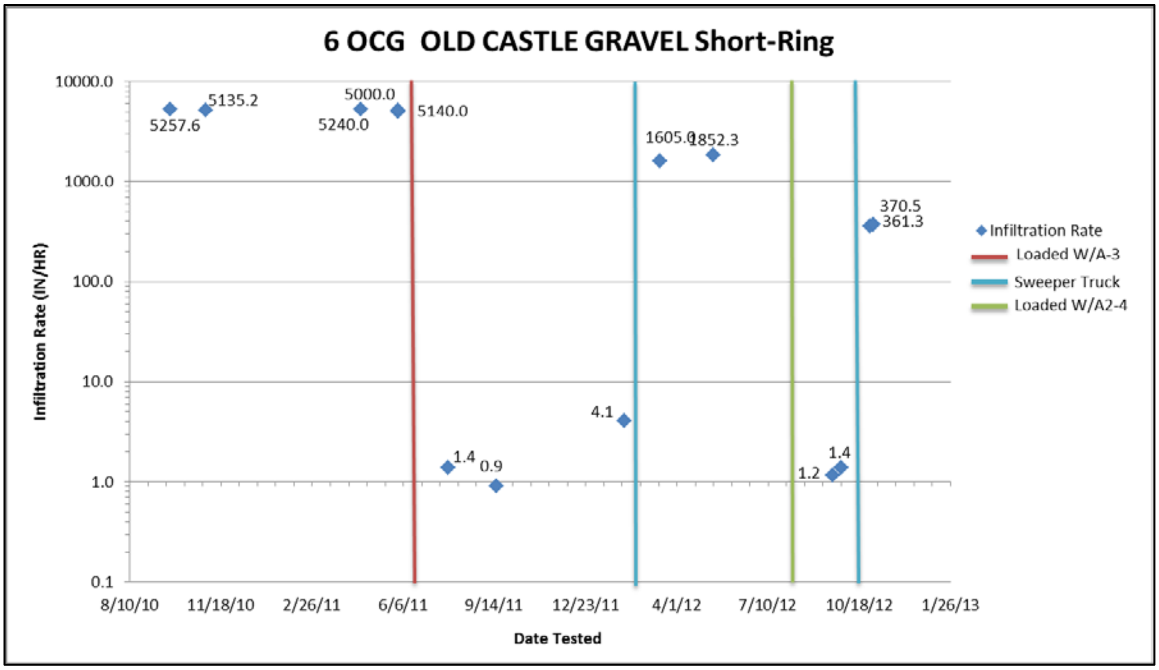

Figure 25: Infiltration Rates vs. Time for 6 OCG Old Castle Gravel Short-Ring

Permeable pavements 5, 7, 10, and 11 consist of pavers with sand grout. All of the pavements had their highest infiltration rates when they were initially installed. Also they all had the typical trend as seen on the pavements disused above (see Figure 36, Figure 38, Figure 41, and Figure 42 in the Appendix). Pavement 11 is shown below as an example in Figure 26. Pavement 5 was completely clogged after the first loading with A-3 sand, which means that no water would permeate through the pavement, thus the pavement acted like an impervious surface. Pavement 7 was affected by erosion from a dirt mound that was installed before the first loading, which resulted in the last two initial tests to have values of a loaded condition test. Pavements 10 and 11 had higher infiltration rates after the first rejuvenation for the A-3 soils than when compared to the rates after the last rejuvenation process for the A-2-4 soil type. Whereas, pavements 5 and 7 had the highest infiltration rates after the last vacuum sweeper truck rejuvenation than the first.

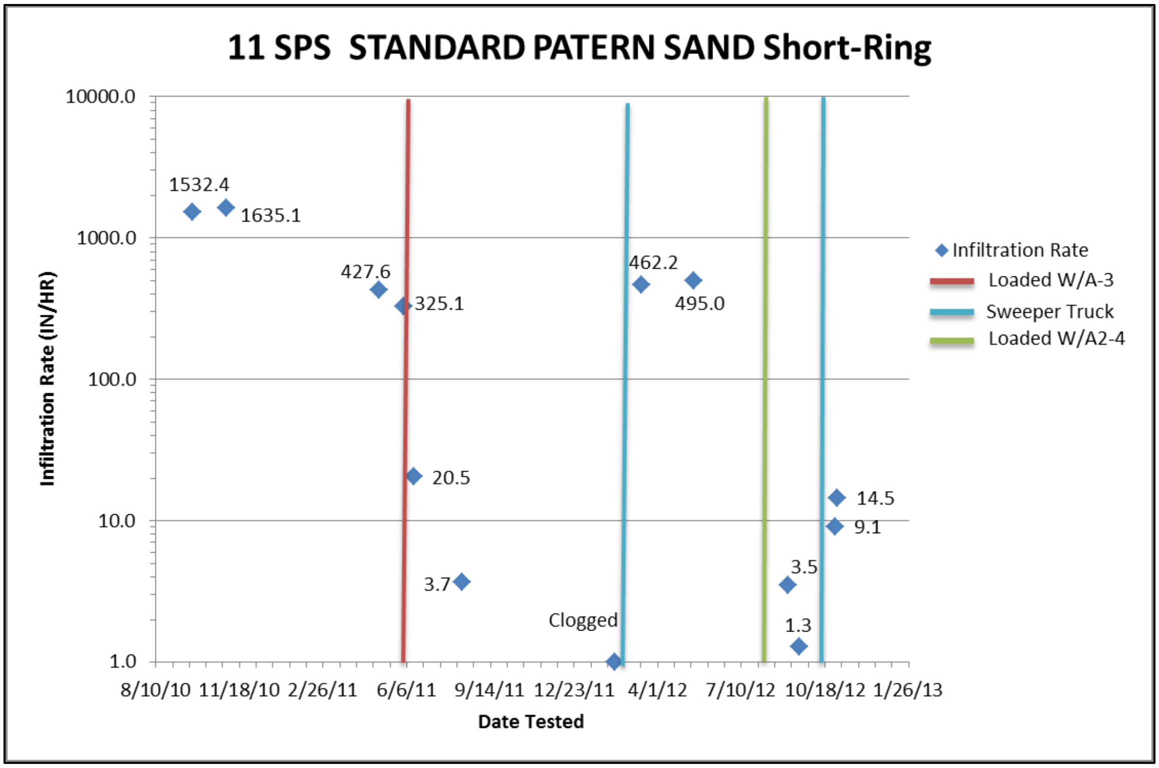

Figure 26: Infiltration Rate vs. Time for 11 SPS Short-Ring

Results for Long Ring Tests

The long-ring ERIK was installed flush with the pavement surface and embedded 4 inches into the parent earth. This results in infiltration rates significantly lower than the short-ring ERIK due to the permeability of the parent earth. For example, the initial infiltration rates for pavement 1 were around 4000 in/hr for the short-ring ERIK and around 25 in/hr for the long-ring ERIK. In Figure 21, the pavements are numbered to clarify which pavement is which.

Pavements 1 and 2 are loose laid stone systems. The two pavements had different trends with their results (see Figure 43 and Figure 44 in the Appendix). Pavement 1 had the typical trend where the infiltration rates would increase after being rejuvenated and decrease after being loaded with sediment as shown in Figure 27. Pavement 2 tests were not as consistent as other pavements, because some values for loading conditions were higher than the rejuvenated conditions.

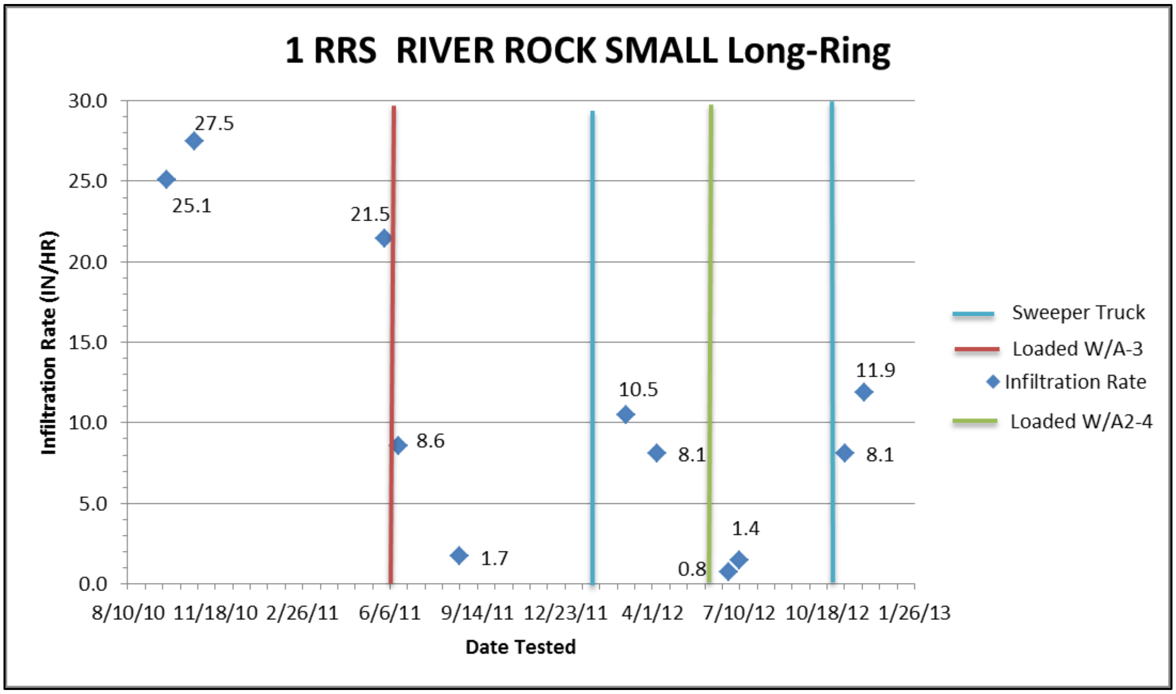

Figure 27: Infiltration Rate vs. Time for 1 RRS Long-Ring

Pavement 3 is a loose laid pervious pavement system that consists of large river rock. Despite the initial short-ring infiltration rates for this pavement being the fastest rates measured, the initial infiltration rates for the long ring ERIK were equivalent to the other initial long-ring infiltration rates. Once the surface was loaded with A-3 sandy soil, the infiltration rates dropped to an average of 1.3 in/hr (see Figure 28). The rejuvenation did not improve the infiltration rates significantly due to the low amount of sediment that was able to be removed. The subsequent loading of the A-2-4 silty sandy soil did not affect the infiltration rates measured. The final rejuvenation process did show an improved infiltration rate.

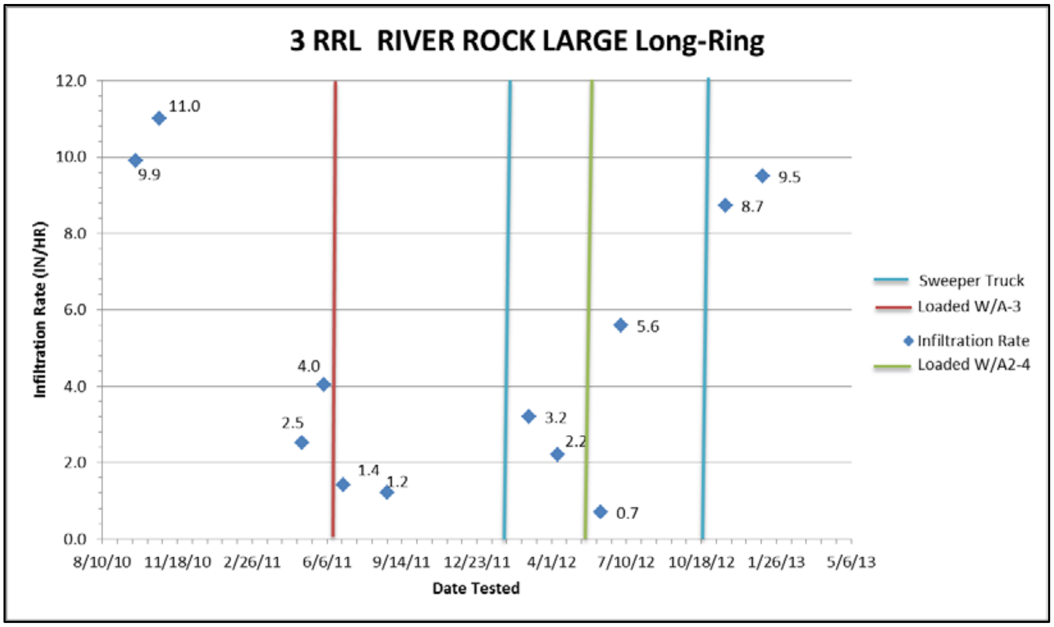

Figure 28: Infiltration Rate vs. Time for 3 RRL Long-Ring

Pavement 4 is a loose laid pervious pavement system that consisted of poorly graded sand bound together. The initial rates varied but were higher than when the pavement was loaded with A-3 sandy soil, which is shown in Figure 29. The pavement showed some slight increase of the infiltration rate after the initial rejuvenation. The system was then loaded with A-2-4 silty sandy soil resulting in the infiltration rates decreasing. The subsequent rejuvenation showed an increase in the measured infiltration rates.

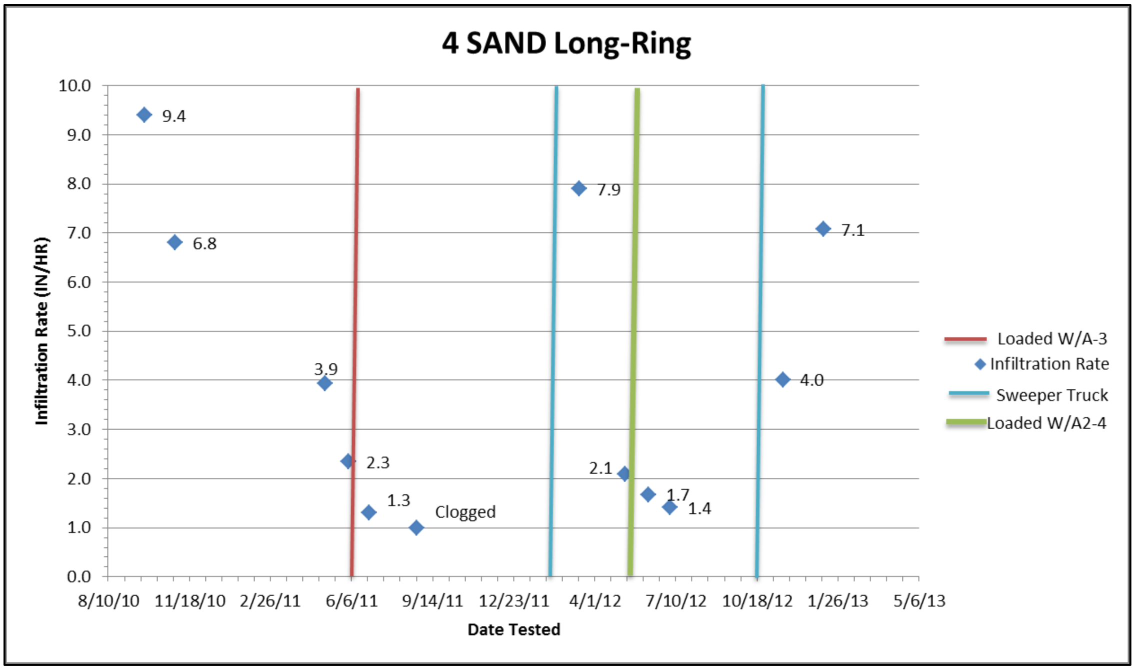

Figure 29: Infiltration Rate vs. Time for 4 Sand Long-Ring

Pavements 5, 7, 10, and 11 consisted of permeable pavers with sand grout. Below in Figure 30 is an example of a trend of one of these pavement systems. Pavement 7 was a very typical pavement, the infiltration rates would increase and decrease at each of the different phases. This was also true about pavement systems 5 and 11 (see Figure 47 and Figure 53 in the Appendix). Looking at the long ring ERIK results, pavement 10 had one of the slowest infiltration rates compared to any other pavement. The maximum infiltration rate was 1.9 in/hr and the lowest infiltration rate was 0.6 in/hr (see Figure 52 in the Appendix). Throughout the duration of testing for this pavement, the pavement's infiltration rates were fairly consistent with having minimal difference between each phase.

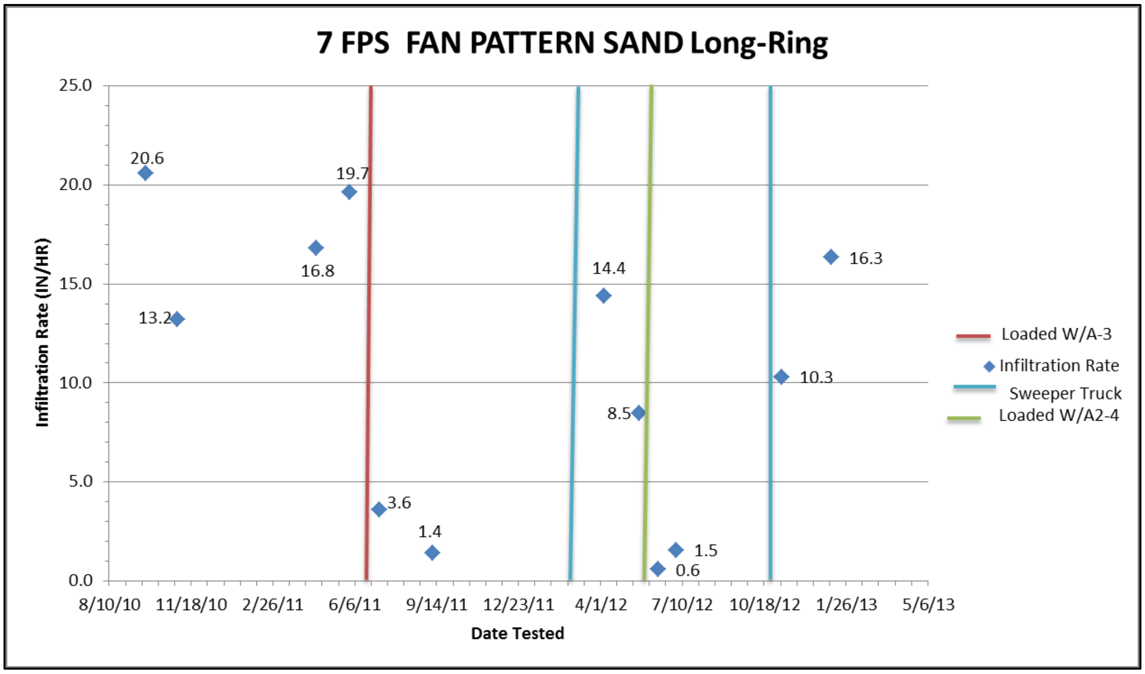

Figure 30: Infiltration Rates vs. Time for 7 FPS Fan Pattern Sand Long-Ring

Pavements 6, 8, and 9 are permeable pavers with #89 granite stone grout. Figure 31 shows the results for the long ring ERIK for pavement 6. Pavement 8 followed this trend (see Figure 50 in the Appendix). Pavement 9 had infiltration rates ranging rom 2 in/hr to 0 in/hr (see Figure 51 in the Appendix). The first rejuvenation process did improve the infiltraiton rates however, after the loading with the A-2-4 silty sandy soil the rejuvenation did not show any improvement.

Figure 48

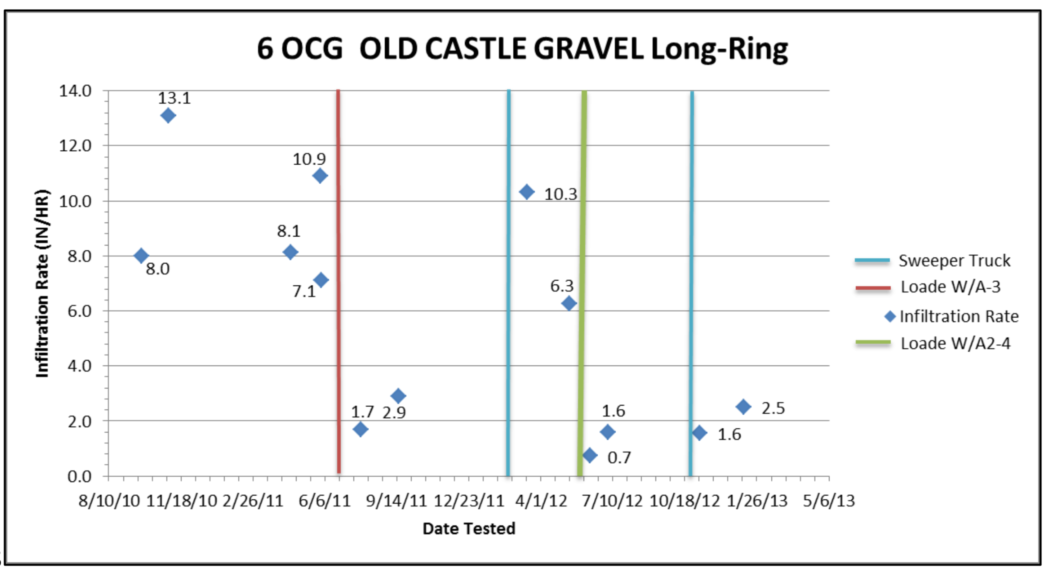

Figure 31: Infiltration Rates vs. Time for 6 OCG Old Castle Gravel Long-Ring

Observations and Conclusions

Observations

A few observations can be made from this research and are summarized here. First, it was observed that rejuvenation using a vacuum sweeper truck removed a significant amount of sediment from the pervious/permeable pavement systems. Additionally, it was observed that rejuvenation efforts never fully removed all soil particles from the different pavement systems. As a result, the infiltration rates never completely rejuvenated to the initial infiltration rates but were significantly improved in most cases.

An important observation was made about the condition of the pavements during the rejuvenation process. This had to do with the level of moisture in the sediments clogging the pervious/permeable pavements. It was observed that the rejuvenation process was most effective when the clogging sediments were either completely dry or completely saturated. If the pavements were vacuumed while the clogging sediments were somewhat moist, then the sediment particles tend to stick together and become difficult to remove. Since conditions where the clogging sediments are completely dry are unlikely to occur, it is recommended that these systems be rejuvenated under saturated conditions such as during a rain event. When the clogging sediment particles are within their liquid limit, they become suspended with the water which increases the efficiency of the vacuum sweeper truck because the water lubricates the sediment particles.

Pavement system 3, the large river rock loose laid pavement system, had the largest voids of all the systems examined. This resulted in the pavement initially outperforming the other pavements in regard to infiltration rate. The larger void space however, allowed more clogging sediment to enter the pavement system which made it harder for the vacuum sweeper truck to rejuvenate the pavement. Observing all the pavements after each of the loading events, it was clear that the large river rock pavement allowed the most soil into the sub-base storage reservoir. Due to the depth that the soil traveled into the large river rock pavement system, the vacuum sweeper truck was unable to remove all of the clogging sediment from the system. This resulted in a significant volume of soil left in the pavement and thus a reduction in the storage provided by the pavement system. Another issue with this pavement was that the river rocks would break off from the surface with normal wearing. This was due to the river rocks being large and having a rounded surface which reduced the surface area available for the rocks to attach to each other. Another factor that could have contributed to the large river rocks breaking free from the pavement surface may have been that the binder used was not strong enough to hold everything in place.

During the duration of the testing program, there was a mound of soil that was installed near the pavement systems 7 and 8. This mound of soil was constructed after some of the initial testing for pavement 7 was complete and after all of the initial tests were complete for pavement

8. When the mound of soil was installed, pavement 7 infiltration rates decreased significantly, which showed that it was being affected. This scenario showed how these pavements can be affected in the real world by poor site erosion and sediment control. Having the mound of soil so close to the pavement also limited the maneuverability of the sweeper truck which resulted in the embedded rings for pavement 8 to not be rejuvenated by the vacuum sweeper truck. Instead, a wet/dry vacuum was implemented to rejuvenate this pavement.

Conclusion

Short-Ring Infiltrometer

After the installation of the pavement systems, all of the virgin pavements were at their peak infiltration rate based on the short-ring ERIK results. The loading of the systems with the sandy (A-3) soil caused the pavements infiltration rates to decrease ranging between 87.6 in/hr to 0 (fully clogged). The pavements that were clogged after the first loading were pavements 5 and pavement 11. After the first rejuvenation was completed, pavements 1, 2, 5, 6, and 8-11 increased to a rate that was sufficient to conclude that the vacuum sweeper truck in fact rejuvenated the system. Pavements 4 and 7 rejuvenated but the infiltration rate increase was not as much as those listed above. Pavement 3, on the other hand, showed a decrease in its infiltration rate and therefore was not rejuvenated by the vacuum sweeper truck.

The second sediment loading event used a silty-sandy (A-2-4) soil which had a more significant effect on the permeable paver systems than the sandy soil did. This is due to the silt in the soil, which is a finer particle that can be lodged into smaller spaces resulting in more clogging than the A-3 sandy soil. The infiltration rates for all the pavement systems fluctuated from 7.2 in/hr to clogged, where the only one that was clogged was pavement 7.

After the second rejuvenation, pavements 1, 2 and 5 returned to around the same infiltration rate as they were after the first rejuvenation. Pavements 4 and 7, on the other hand, had an increase in their infiltration rates when compared to the rates after the first rejuvenation. This increase could have been due to pre-soaking the pavements an hour before the vacuum sweeper truck began rejuvenating the pavements, possible allowing more soil particles to reach their liquid limit and therefore be sucked out of the pavement. It could also be due to normal variation in infiltration rates due to differences in environmental conditions when the measurements were done. Pavements 6 and 8-11 decreased their infiltration rates when compared to the infiltration rates after the first rejuvenation. Pavement 8 had to be hand vacuumed with a wet/dry vacuum because the truck was unable to position itself over the short monitoring ring for that pavement. Pavement 3 returned to about the same infiltration rate as the rate after the first rejuvenation however that rate was less than after the first loading.

Pavements 6, 8-11 have very similar patterns in the results of their infiltration rates. All these pavements peak at the initial stage or new condition and have their slowest rates after being loaded with the two types of soil. The first rejuvenation for all of the pavements showed a significant increase in infiltration rate. The second rejuvenation also showed an increase in infiltration rate compared to the clogged condition however the rates were not as high as after the first rejuvenation. Pavement 7 had a large increase in infiltration rate from the second rejuvenation compared to the clogged condition. The rates went from clogged to an average of 428 in/hr.

Long-Ring Infiltrometer

The long-ring ERIK pipe is installed flush with the pavement surface and is embedded 4 inches into the parent earth. This causes the measured infiltration rates to be significantly slower due to the fact that the permeability of the parent earth is much less than the different pavement surface layers. The measured infiltration rates for the initial condition ranged from 27.5 in/hr to 0.7 in/hr for all of the systems examined. All eleven of the pavements have long-ring ERIKs installed into the system and were subjected to the same 5 different conditions stated above for short ring test, i.e. new, loaded with A-3 soil, rejuvenated, loaded with A-2-4 soil, and rejuvenated.

Pavements 1, 4, 5, 6, 7, and 11, behaved as expected showing a decrease in infiltration rates under the loaded conditions and an increase in infiltration rates after rejuvenation. Therefore, these pavements are able to sufficiently recover after the rejuvenation process. Pavement 2 and 3 had similar characteristics with a few infiltration rate values having conflicting results.

Pavements 8, 9 and 10 had some of the slowest infiltration rates, ranging from 2 in/hr to 0 in/hr. This caused the differences in each phases of the pavement to not be shown as clearly as other pavements with higher infiltration rates.

It should be noted that all of the long-ring results showed only minor decreases in infiltration rates under sediment loaded conditions and only minor increases after rejuvenation. This shows the importance of installing both the short-ring and long-ring ERIK, with the short-ring providing information about the degree of clogging of the surface layer and the long-ring providing information about the recovery of the system.

Bibliography

Axler, R., C. Kleist, G. Host, C.Hagley, M.Lonsdale, J. Reed, J. Schomberg, N. Will, J. Henneck, G. Sjerven, E.Ruzycki, T.Carlson, B. Munson, and C. Richards. *Pervious pavement.* 2009. http://www.lakesuperiorstreams.org/stormwater/toolkit/paving.html (accessed 8 7, 2012).

Elena Gomez-Ullate, Elena Castillo-Lopez, Daniel Castro-Fresno, Joseba Rodriguez Bayon. *Analysis and Contrast of Different Pervious Pavements for Management of Storm-Water in a Parking Area in Northern Spain.* Santander: Springer Science+Business Media B.V. 2010, 2010.

Hunt, William F. *Urban Waterways.* NORTH CAROLINA COOPERATIVE EXTENSION, 2011.

Lake County Forest Preserves. *Permeable Paver Research Summary.* February 2003. http://atfiles.org/files/pdf/PermPavers.PDF (accessed February 26, !013).

LeFevre, Jennifer. "Pervious Concrete is Popular Concrete." (NRMCA publication) 2007: 45-48.

Manoj Chopra, Erik Stuart, Mike Hardin, Ikenna Uju, Marty Wanielista. "Pervious pavement is a unique and effective means to address important environmental issues and support green, sustainable growth ." Final Report, Orlando, Florida, 2011.

Manoj Chopra, Erik Stuart, Mike Hardin, Ikenna Uju, Marty Wanielista. "Pervious Pavements-Installation, Operations and Strength Part 4: Flexipave (Recycled Rubber Tires) Systems." Final Report, Orlando, 2011.

Mark Dougherty, Michael Hein, Brent Martina, and Bruce Ferguson. "Quick Surface Infiltration Test to Assess Maintenance Needs on Small Pervious Concrete Sites." *JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING* (American Society of Civil Engineers), 2011: 553-561.

Mary Vancura, Kevin MacDonald, Lev Khazanovich. "Location and Depth of Pervious Concrete Clogging Material before and after Void Maintenance with Common Municipal Utility Vehicles." *Journal of Transportaion Engineering* (American Society of Civil Engineers), 2012: 332-338.

Masoud Kayhanian, Dane Anderson, John T. Harvey, David Jones, Balasingam Muhunthan. "Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots." *Journal of Environmental Management*, 2012: 114-123.

MMSD. *THE APPLICATION OF STORMWATER RUNOFF REDUCTION BEST MANAGEMENT PRACTICES.* Interm, Milwaukee: Stormtech, Inc., 2005.

NRMCA. *Pervious Concrete Pavement.* 2011. http://www.perviouspavement.org/ (accessed 8 8, 2012).

Oregan Environmental Council. *Stormwater Solutions: Turning Oregon's Rain Back into a Resource.* Porland : Oregan Enviromental Council, 2007.

Paul D. Tennis, Michael L. Leming, David J. Akers. *Pervious Concrete Pavements.* Final Report, Portland : Portland Cement Association, 2004.

Scholz, Miklas, and Pitro Grabowiecki. *Review of Permeable pavement systems.* Building and Environment, 2006.

University of Maryland. *Permeable Pavement Fact Sheet Information for Howard County, Maryland Homeowners.* August 13, 2011. http://mastergardener.umd.edu (accessed February 26, 2013).

Appendix

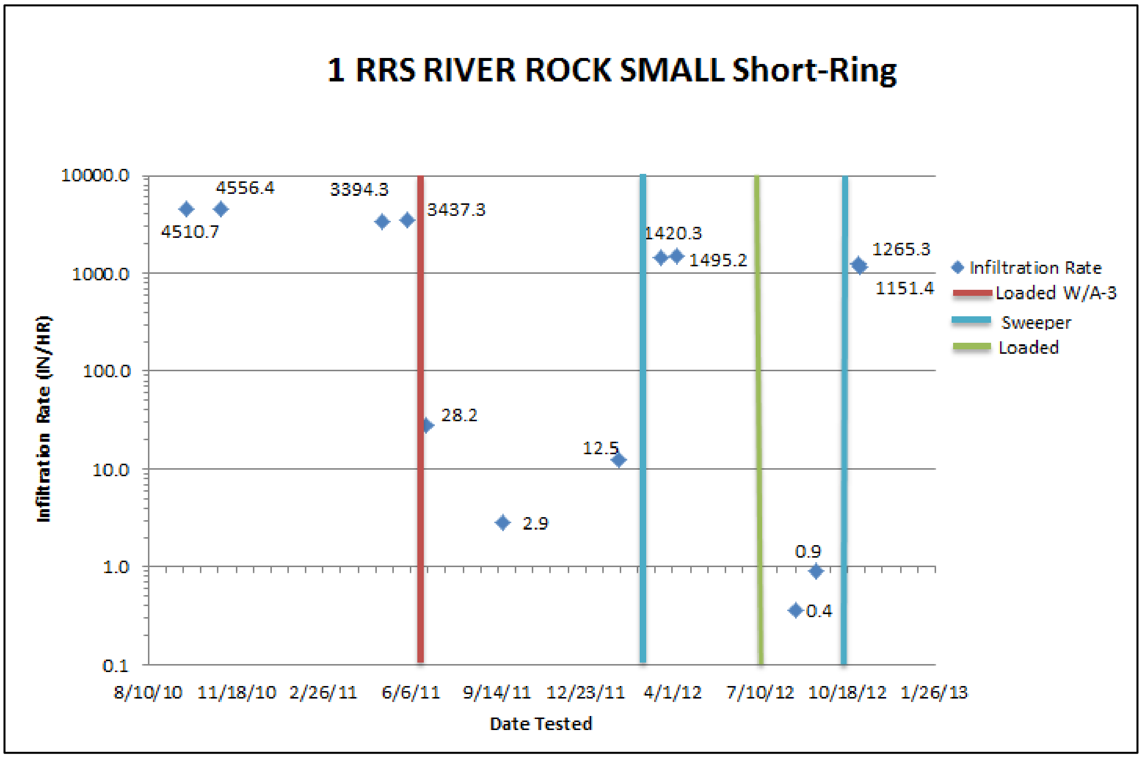

Figure 32: 1 RRS Short-Ring

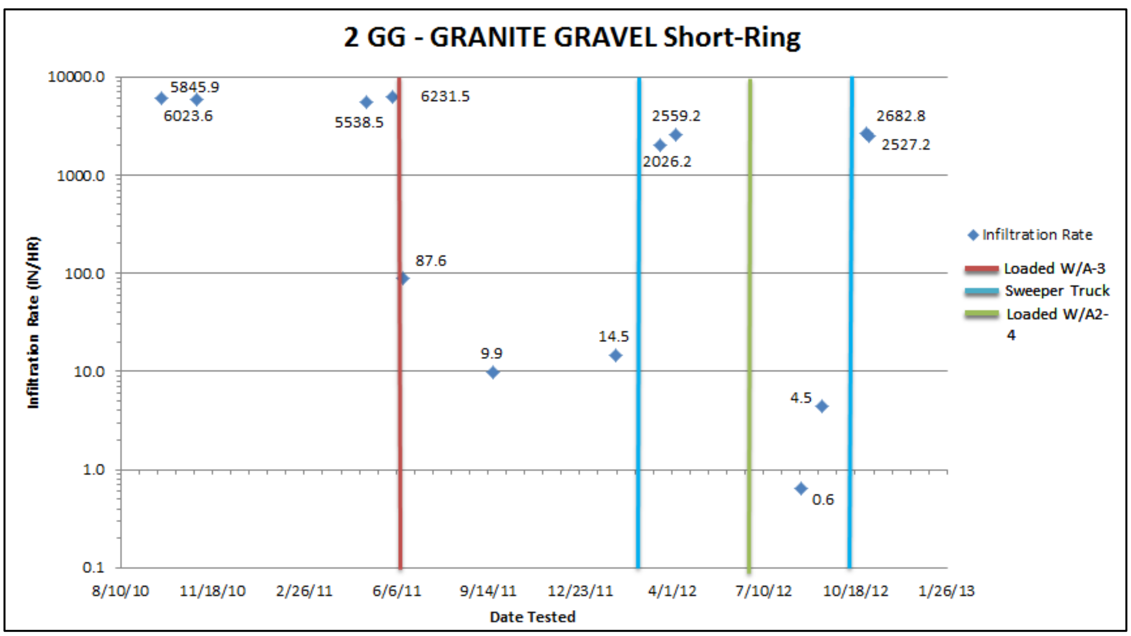

Figure 33: 2 GG Short-Ring

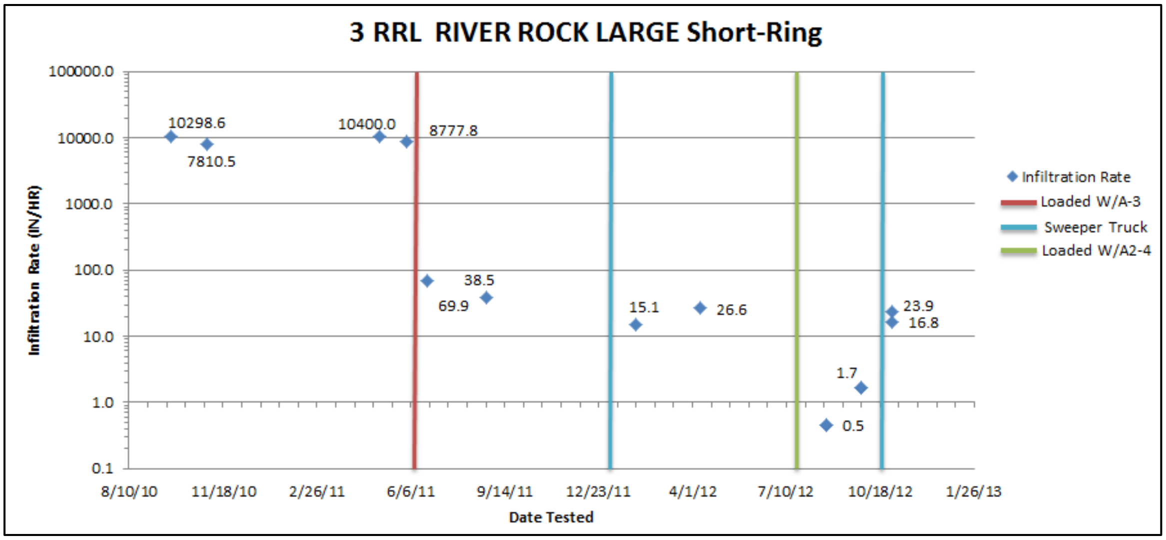

Figure 34: 3 RRL Short-Ring

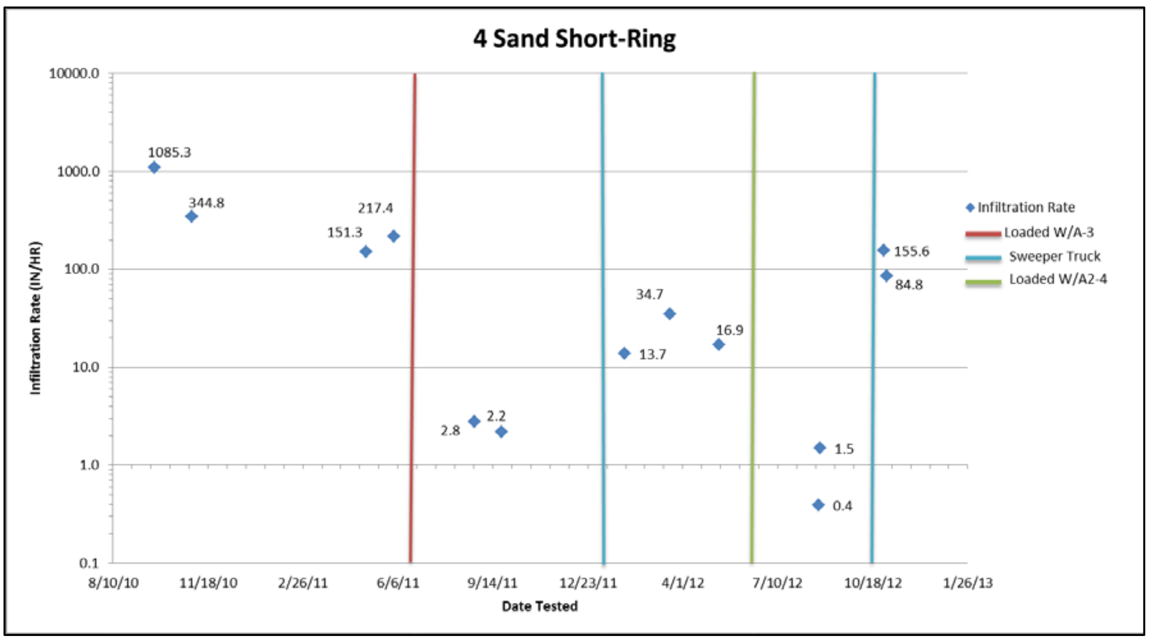

Figure 35: 4 Sand Short-Ring

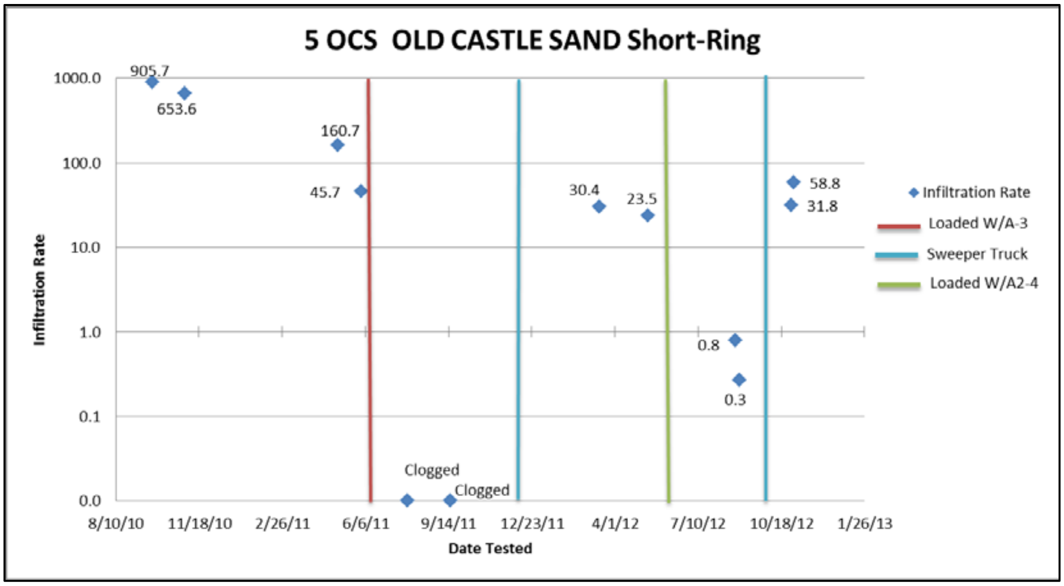

Figure 36: 5 OCS Short-Ring

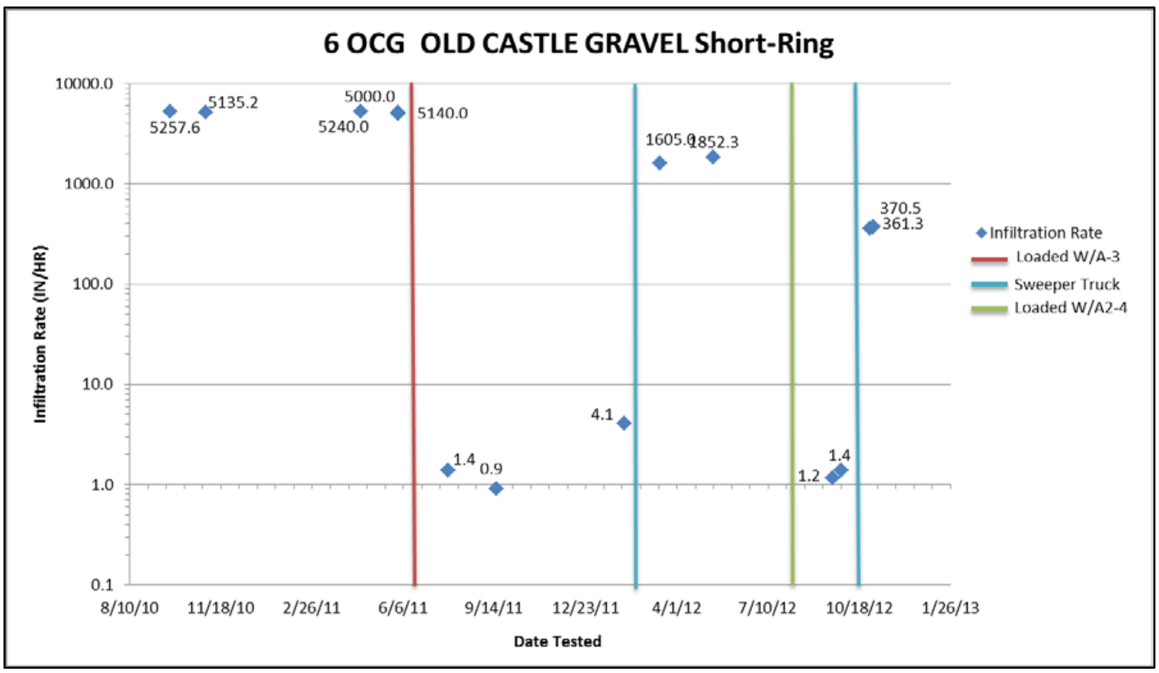

Figure 37: 6 OCG Short-Ring

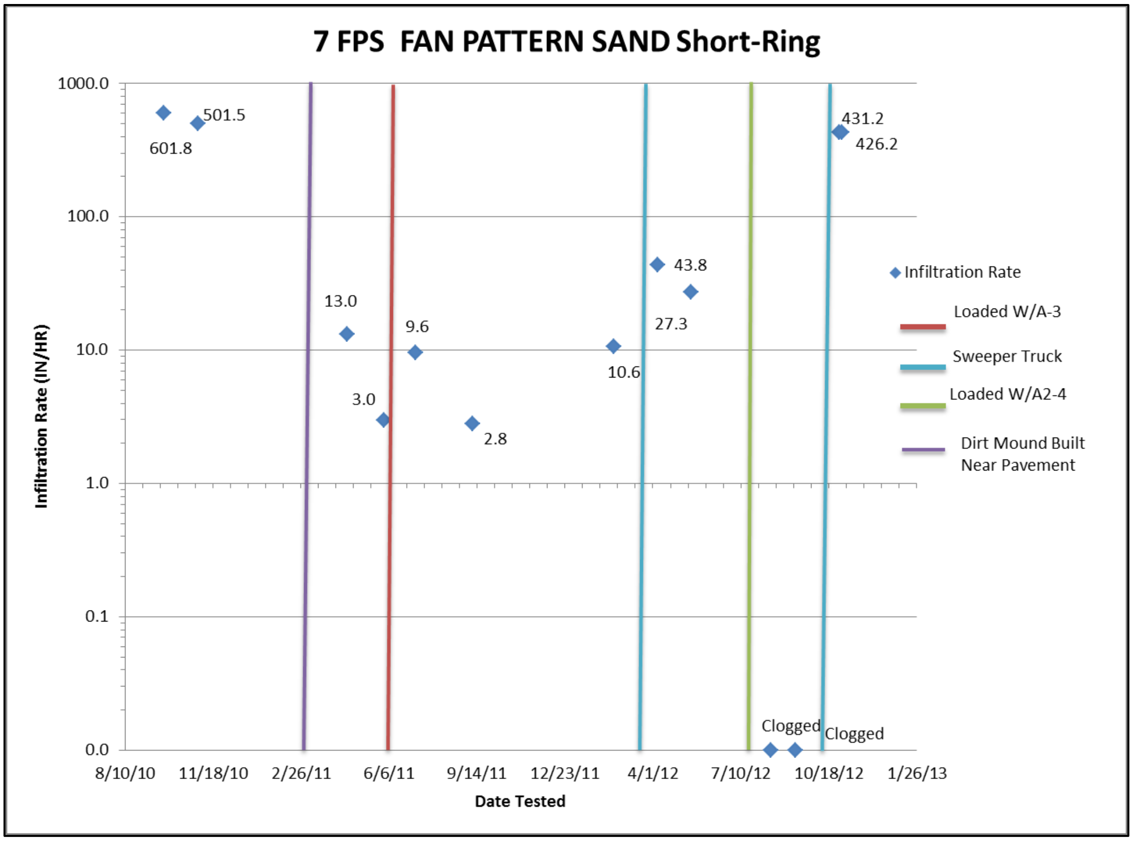

Figure 38: 7 FPS Short-Ring

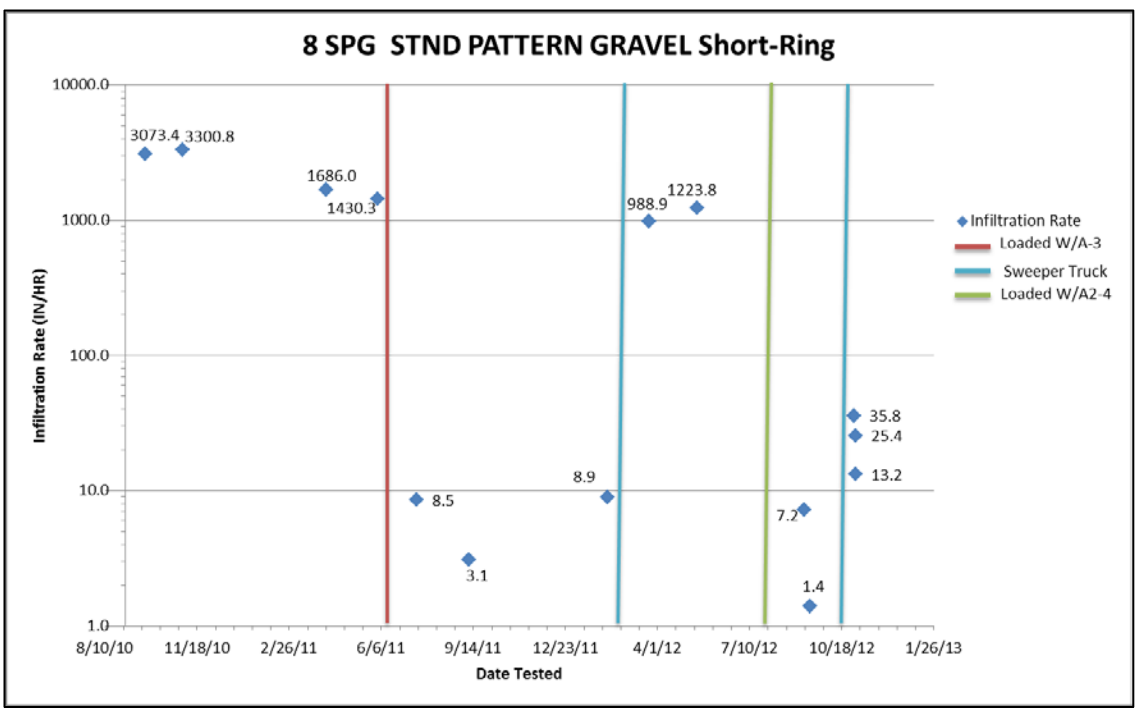

Figure 39: 8 SPG Short-Ring

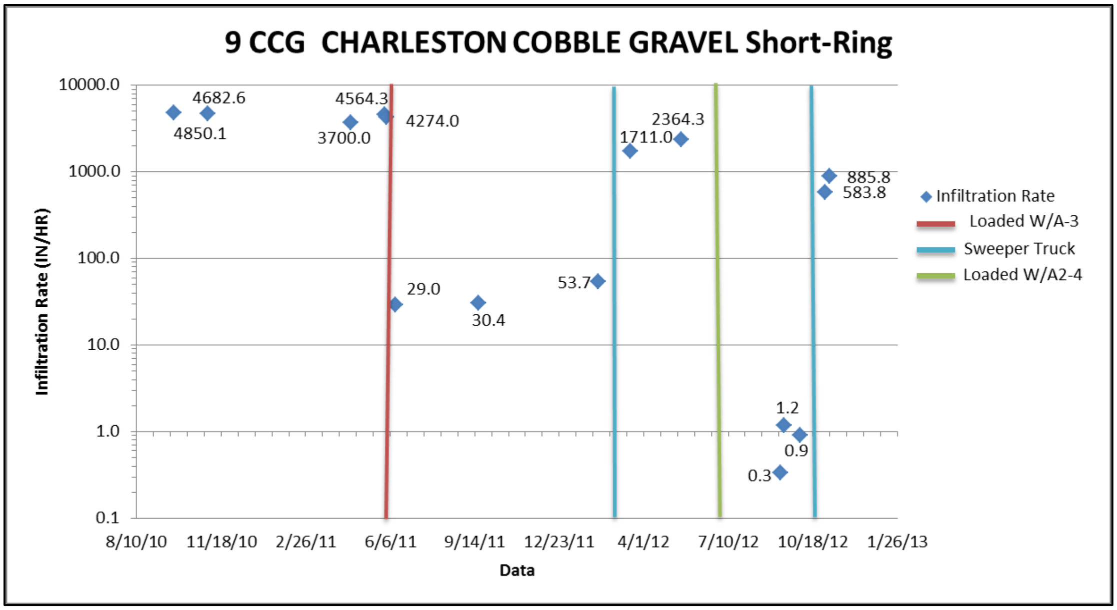

Figure 40: 9 CCG Short-Ring

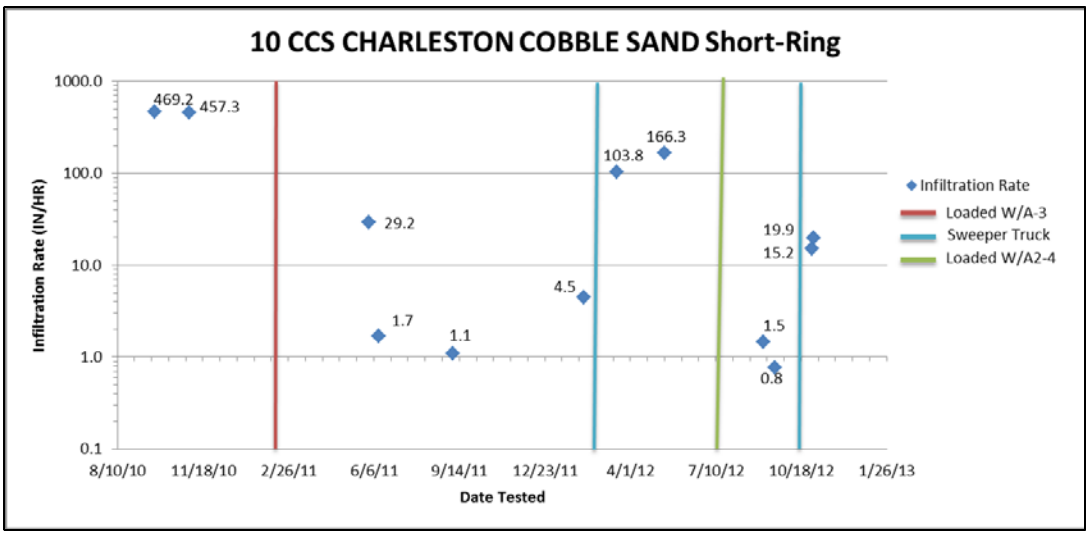

Figure 41: 10 CCS Short-Ring

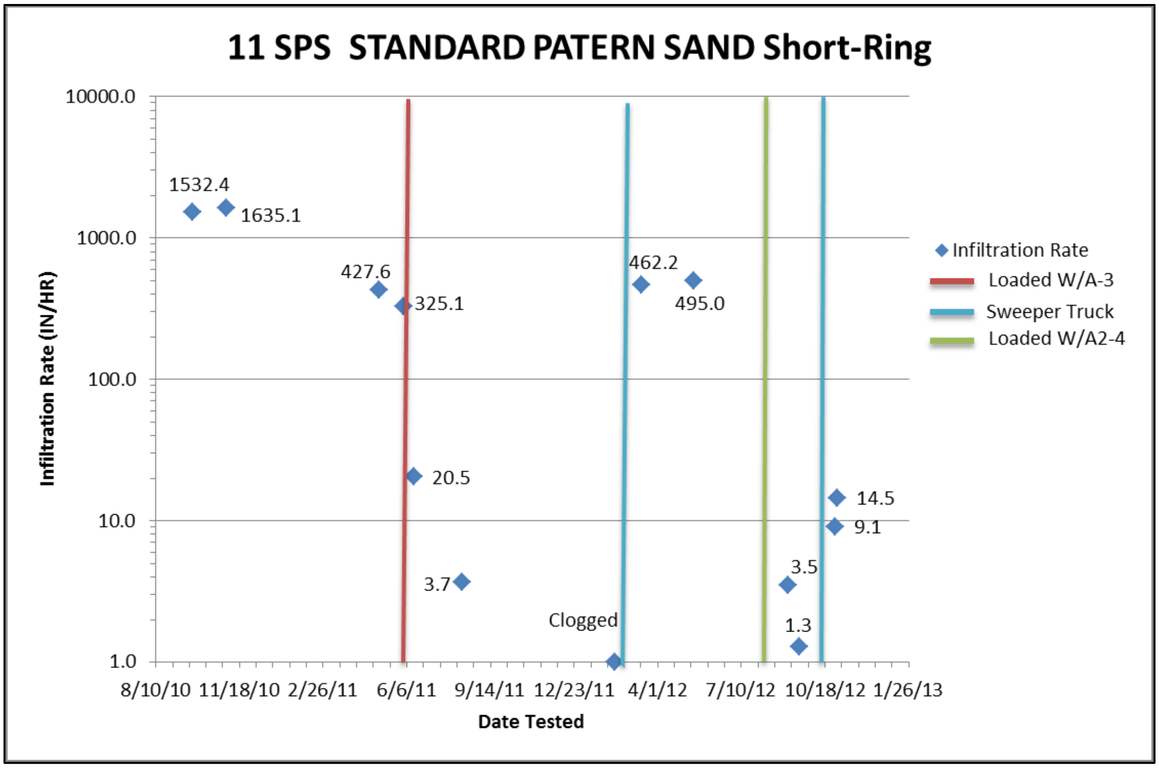

Figure 42: 11 SPS Short-Ring

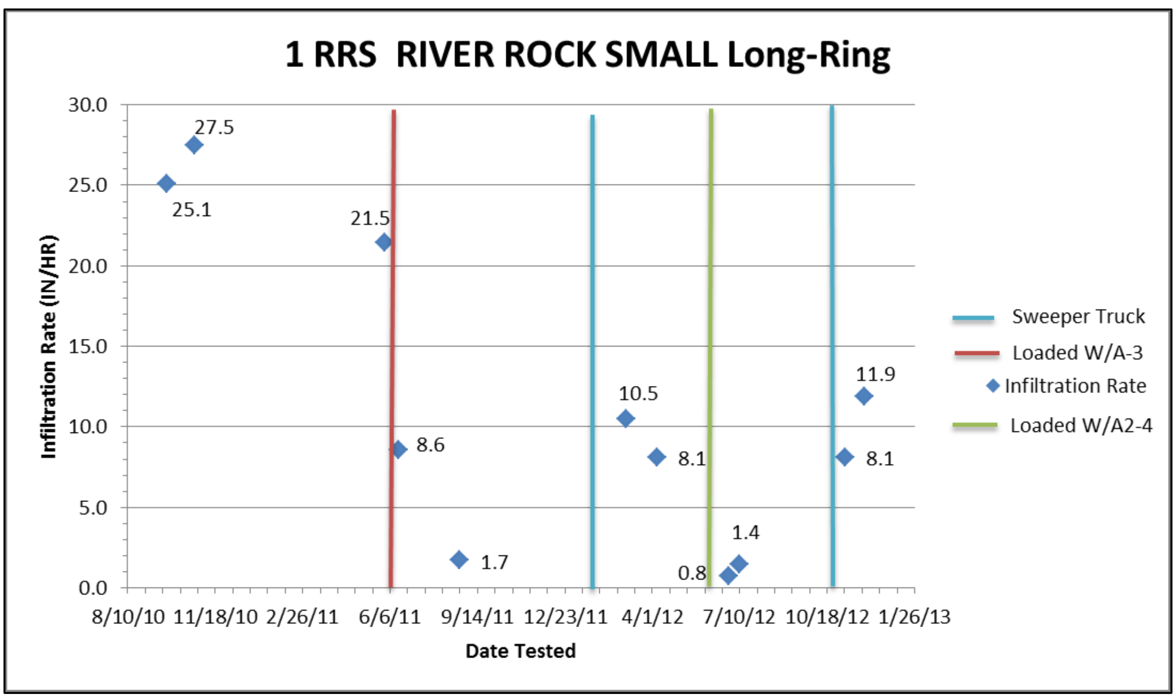

Figure 43: 1 RRS Long-Ring

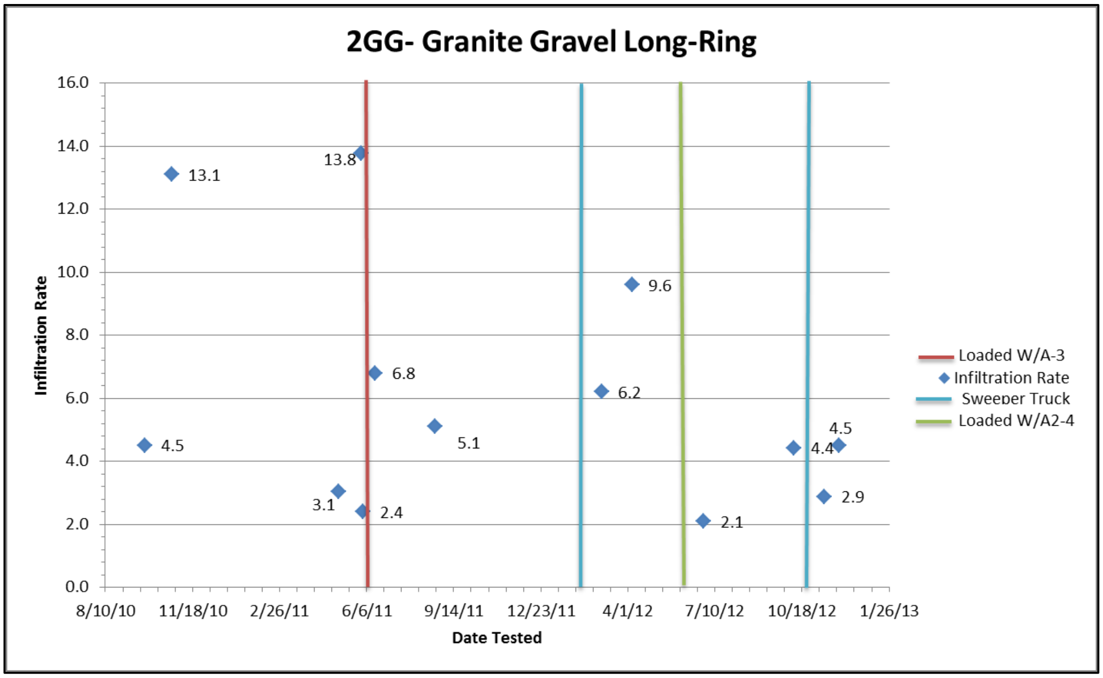

Figure 44: 2 GG Long-Ring

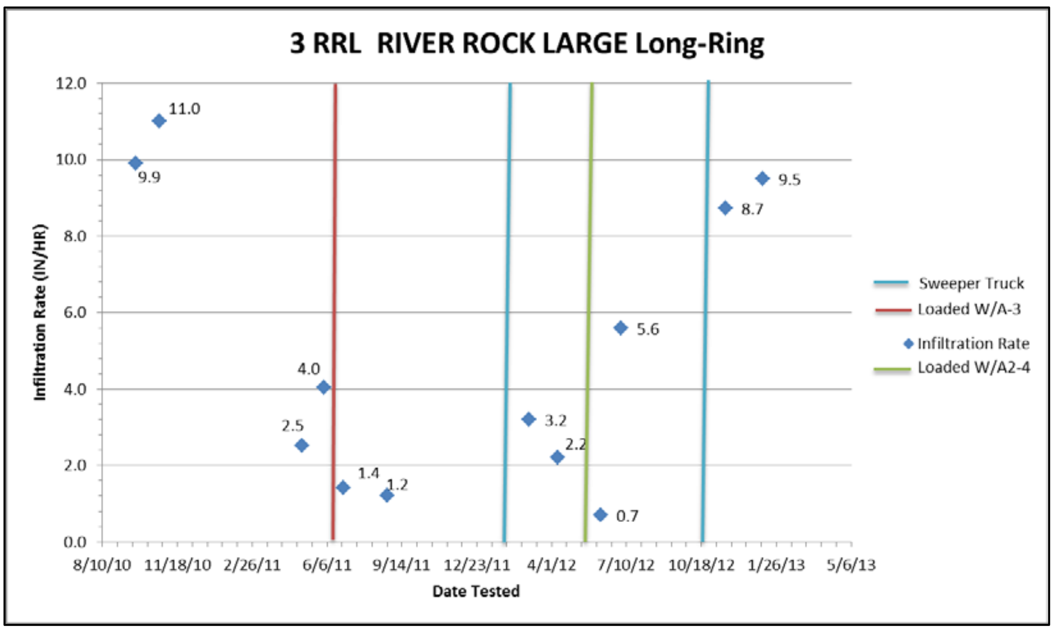

Figure 45: 3 RRL Long-Ring

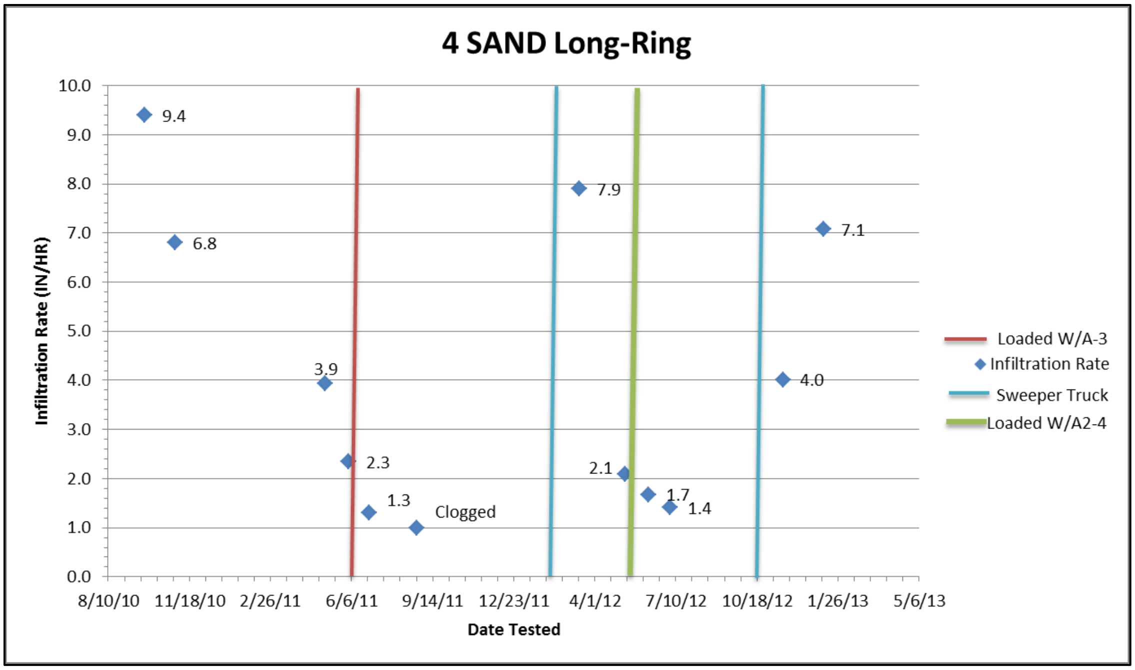

Figure 46: 4 Sand Long-Ring

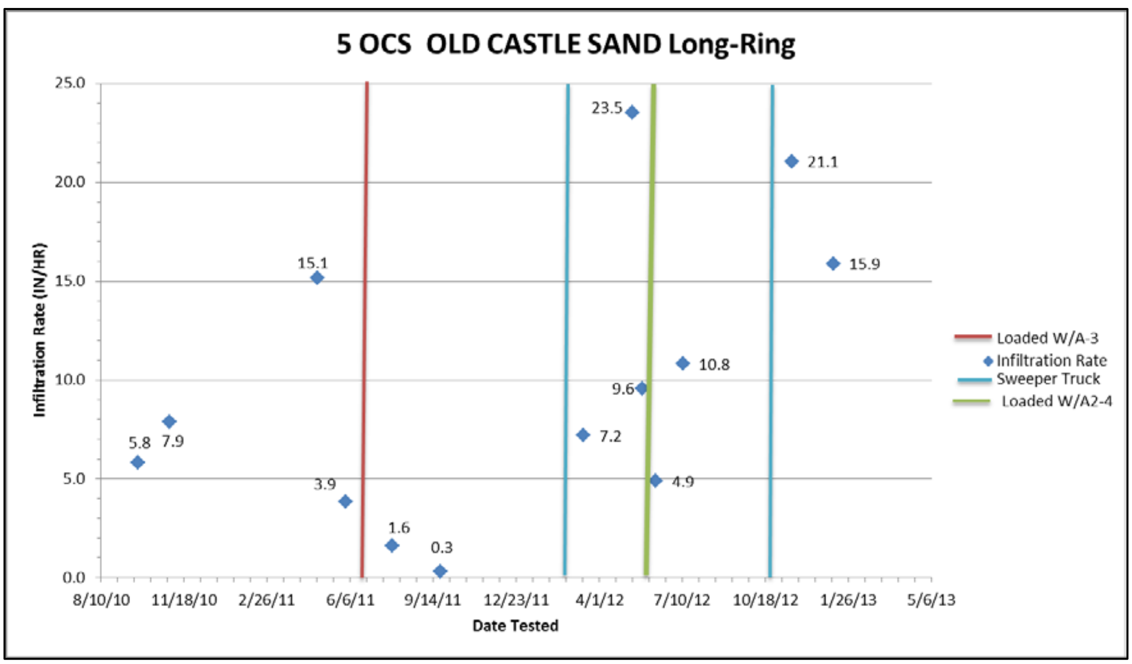

Figure 47: 5 OCS Long-Ring

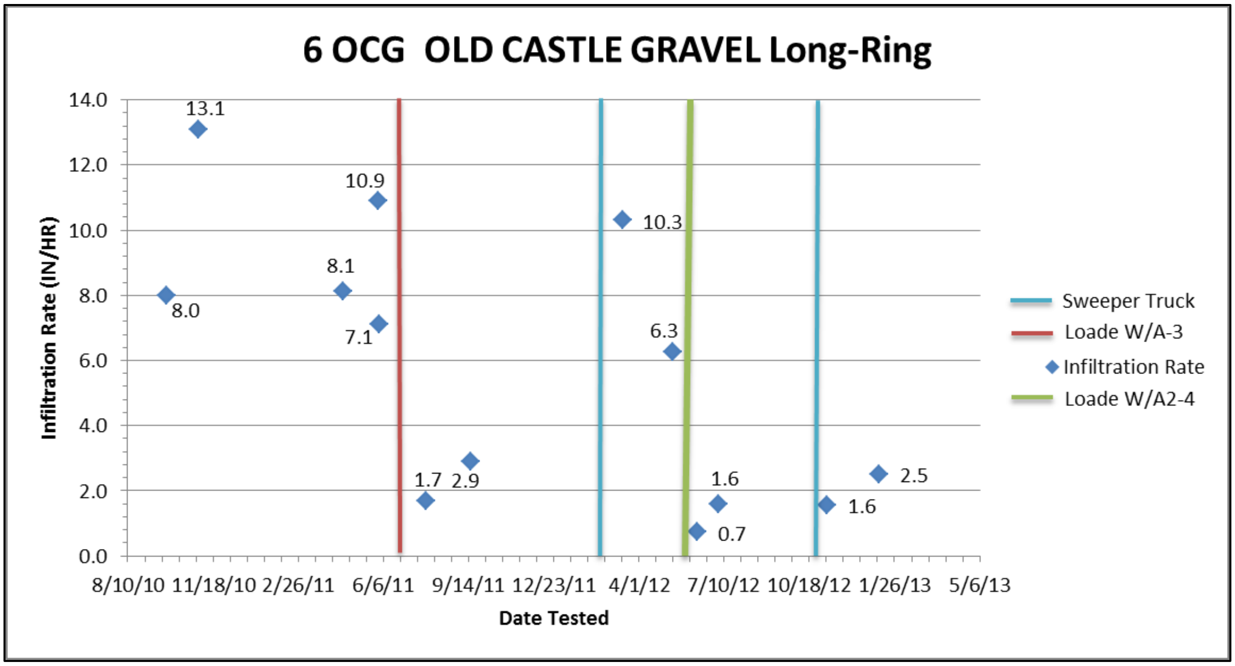

Figure 48: 6 OCG Long-Ring

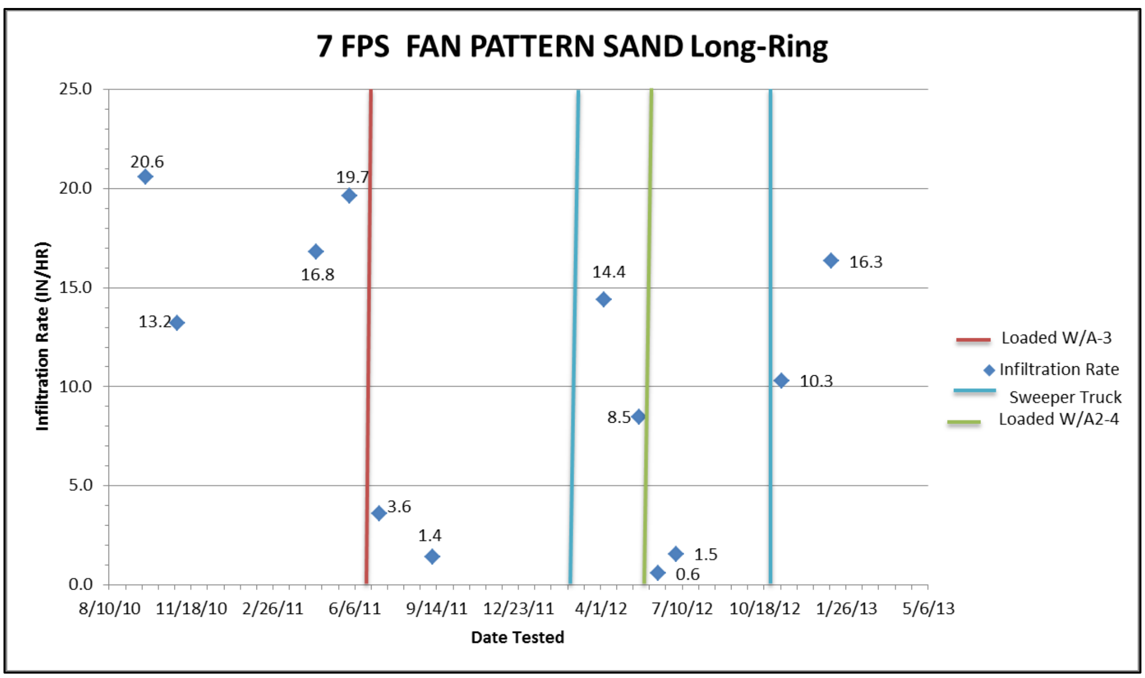

Figure 49: 7 FPS Long-Ring

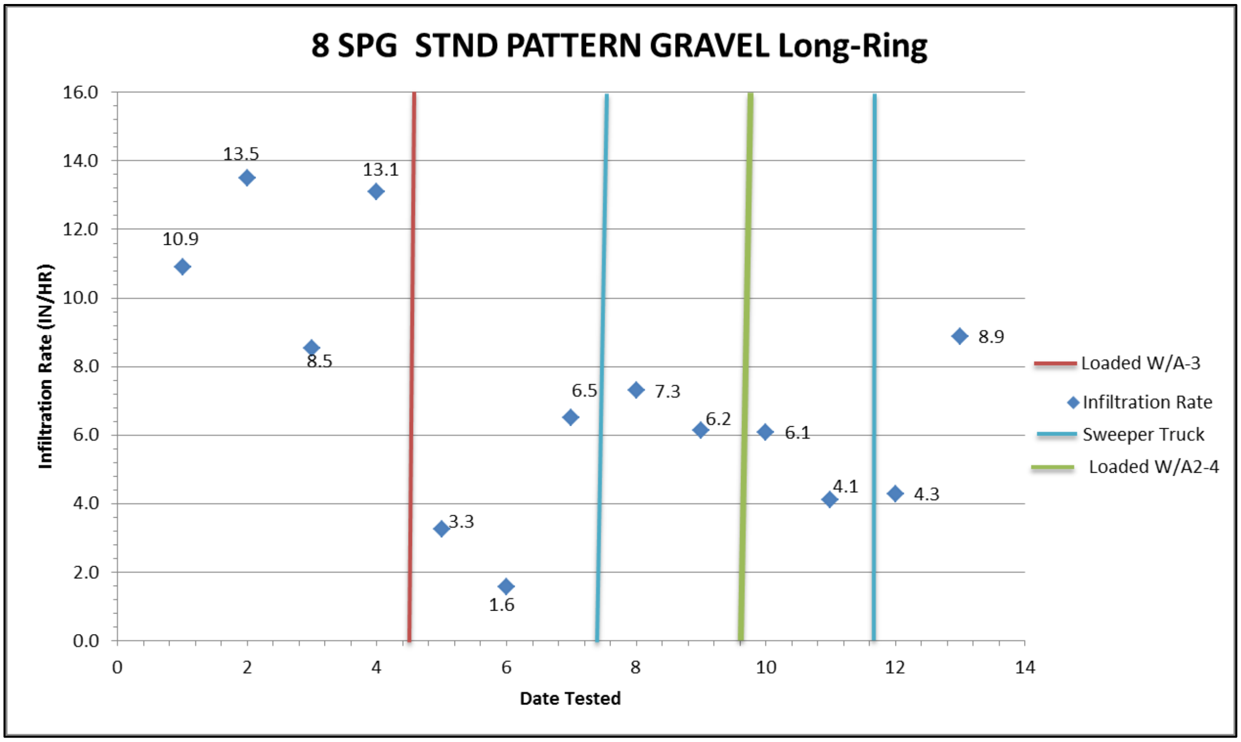

Figure 50: 8 SPG Long-Ring

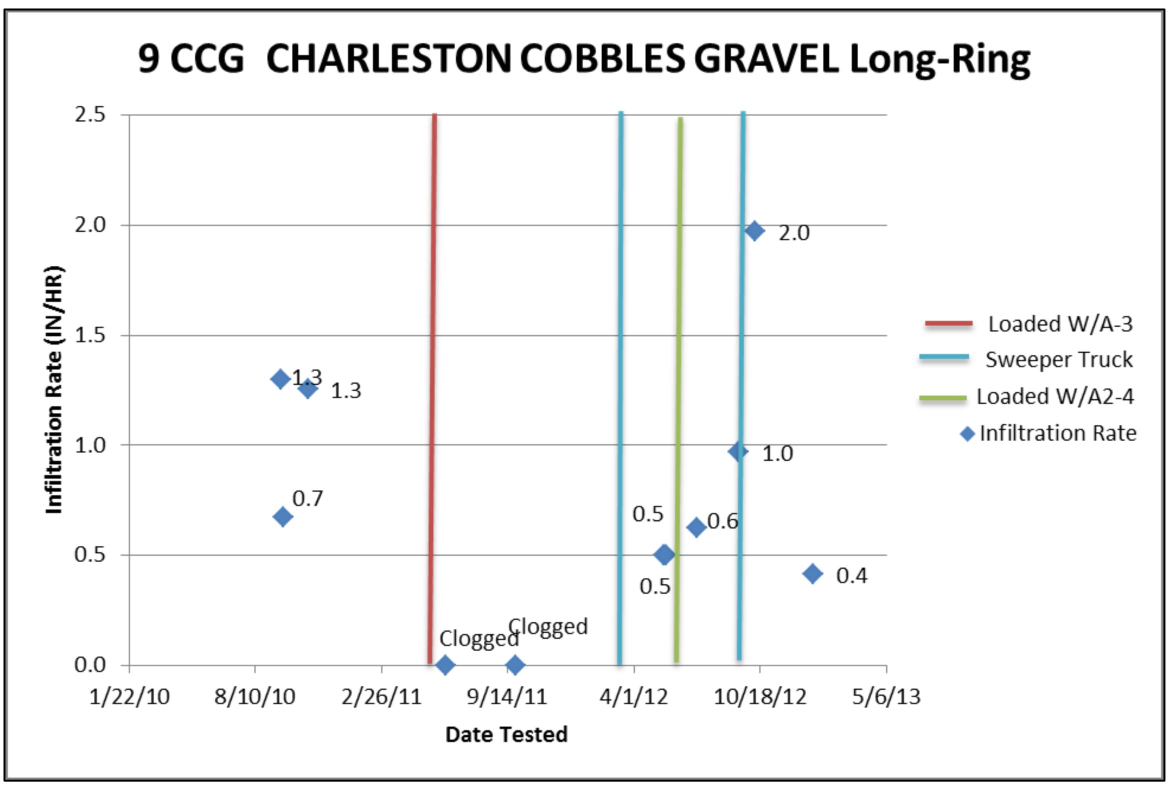

Figure 51: 9 CCG Long-Ring

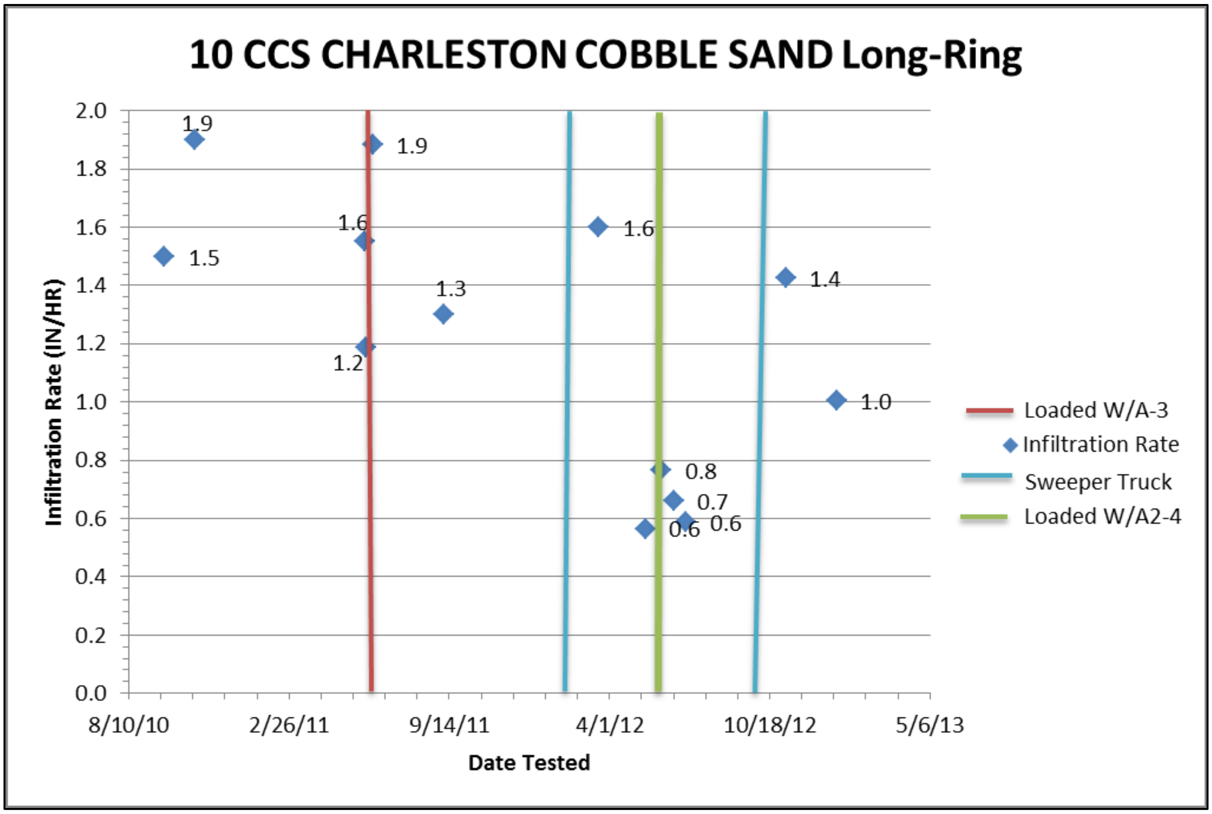

Figure 52: 10 CCS Long-Ring

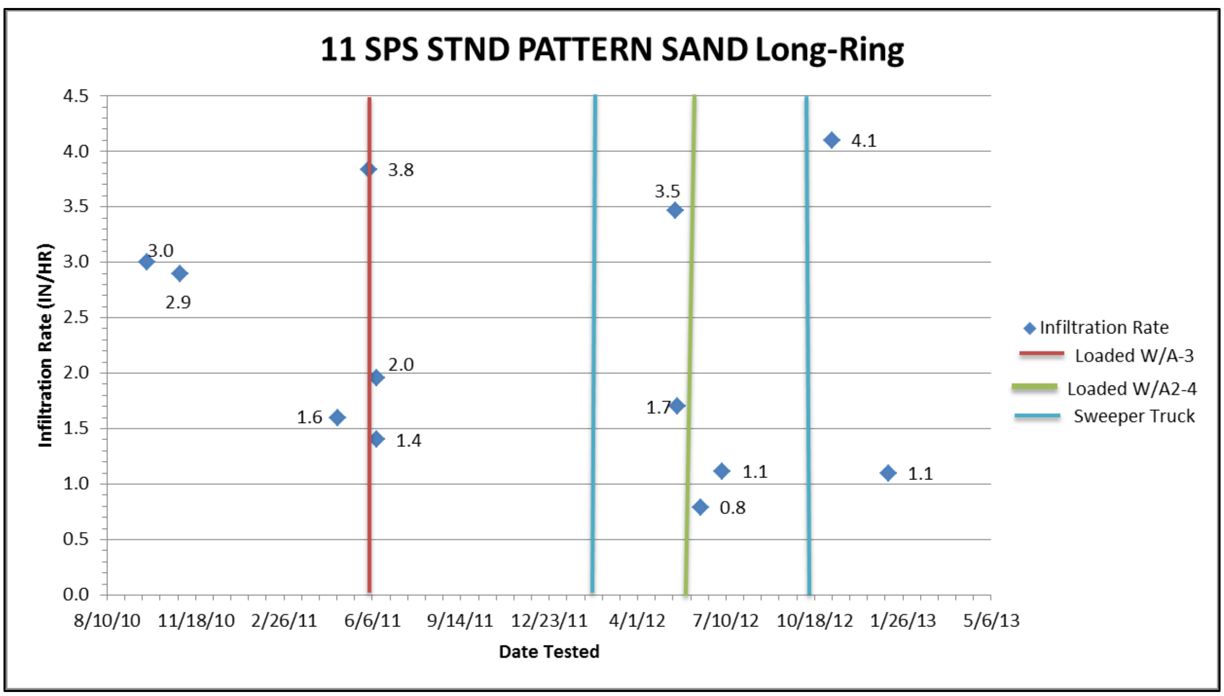

Figure 53: 11 SPS Long-Ring

ECOSYSTEMS
PERMEABLE BONDING AGENT

ADVANTAGES	EcoSystems	Polymeric Sand	Sand
Maintains positioning of stones	YES	YES, when dry	NO
High compressive strength, flexible	YES	NO	NO
Suitable for vehicular loads	YES	Some	NO
Permanent alternative to polymeric sand	YES	N/A	NO
Quick and easy mixing process	YES	YES	N/A
Can be used on joint widths 3/16” to 6”	YES	Some	NO
No final cleaning or acid washing required	YES	NO	N/A
Non Hazing	YES	NO	NO
Self-leveling and self-compressing	YES	NO	NO
Resistant to chemicals, ideal for pool decks, UV resistant	YES	NO	NO
Freeze/thaw properties and resistant to de-icing salt	YES	Some	N/A
Permeable grout, LEED credit	YES	NO	N/A
Resistant to weeds and digging insects	YES	NO	NO
Easy to clean, can be pressure washed	YES	NO	NO

ECOSYSTEMS
PERMEABLE BONDING AGENT

UCF STORMWATER ACADEMY INFILTRATION DATA 2-1-14

TEST AREA	PRODUCT / JOINT FILLER NOTE: All sand and gravel were mixed with EcoSystems Grout	LONG PIPE INFILTRATION INCHES PER HOUR	SHORT PIPE * INFILTRATION INCHES PER HOUR
1	RIVER ROCK (SMALL 1/4" to 3/8")	25.1	4,510.7 *
2	#89 GRANITE (1/4' to 3/8")	4.5	6,023.6 *
3	RIVER ROCK (LARGE 3/4" to 1")	9.9	10,298.6 *
4	20/30 SAND	9.4	1,085.3 *
5	OLDCASTLE AQUA-BRIC with 20/30 SAND	5.8	905.7 *
6	OLDCASTLE AQUA-BRIC with #89 GRANITE	8	5,257.6 *
7	FAN PATTERN COBBLE with 6/20 SAND	20.6	601.8 *
8	STRAIGHT PATTERN COBBLE with #89 GRANI	10.9	3,073.4 *
9	CHARLESTON COBBLE with #89 GRANITE	0.7	4,850.4 *
10	CHARLESTON COBBLE with 20/30 SAND	1.5	469.2 *
11	STRAIGHT PATTERN COBBLE with 20/30 SANI	3	1,532.4 *

*** Short Pipe data is higher because the infiltration pipe is installed so water will flow into the pipe and exit into the sub base gravel above the filter fabric. The Long Pipe rates are slower because the pipe is installed through the filter fabric and into the natural soil. Designed stormwater systems would use the East Pipe data.**

Please refer to the full UCF study from the Stormwater Management Academy for full details and test data.