Final Report

Pervious Pavements - Installation, Operations and Strength
Part 3: Permeable Paver Systems

Work Performed for the Florida Department of Transportation

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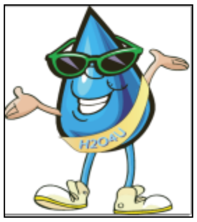

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation. Furthermore, the authors are not responsible for the actual effectiveness of these control options or drainage problems that might occur due to their improper use. This does not promote the specific use of any of these particular systems.

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16. Abstract

Pervious pavement systems are now being recognized as a best management practice by the Environmental Protection Agency and the state of Florida. The pervious pavement systems is designed to have enhanced pore sizes in the surface layer compared to conventional pavement types, encouraging flow of water through the material. This research project investigated the infiltration rates, rejuvenation techniques, sustainable storage of the components and complete systems, water quality, and the strength properties of pervious concrete pavements. The work was conducted at the field labs of the Stormwater Management Academy at UCF.

The study of permeable interlocking concrete pavement systems (pavers) by Oldcastle showed that they perform as intended, even in a worst-case scenario of excessive sediment loading conditions and high ground water table levels. Maintenance by the use of a vacuum sweeper truck improved the infiltration rate and works best when the surface is wet for all sediment types, especially fine-grained cohesive sediments such as the crushed limerock fines. Under normal sediment loading conditions it is expected that the Oldcastle paver systems will perform well above 2 in/hr. The amount of sustainable storage in the entire cross section of the permeable paver systems is about 20%.

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INTRODUCTION

Permeable pavement systems are now being recognized as a best management practice by the Environmental Protection Agency (USEPA, 1999) and the new Draft Statewide Stormwater Rule for the state of Florida. This type of pavement system allows rapid passage of water through its joints and infiltration of the underlying soils. A number of these systems are being evaluated at the Stormwater Management Academy field laboratory on the campus of the University of Central Florida.

The natural processes of the water cycle have been fundamentally altered by human development and construction practices. In the natural state, stormwater falls to the earth and gets absorbed into the soil and vegetation where it is filtered, stored, evaporated, and re-dispersed into the ever flowing cycle. The current state of this cycle has reduced this process due to the vast impervious pavements which have sealed the earth's natural filter (Cahill, et al., 2003). In 2005, it was recorded that 43,000 square miles of land in the United States have been paved (Frazer, 2005). Impervious pavements related to automobiles account for two thirds of these surfaces (Lake Superior, 2010).

Permeable pavements provide an alternative to the traditional impervious pavements and due to their porous nature; these ecological consequences can be minimized or even prevented. The advantages include reducing the volume of surface runoff, reduced need for stormwater infrastructure, less land acquisition for stormwater ponds, improved road safety by reduced surface ponding and glare, and a reduced urban heat island effect. Additionally permeable pavements, by using regional or recycled materials such as local crushed concrete aggregates, can contribute to earning LEED^{TM} points. Permeable pavements allow stormwater to flow into the soil as opposed to flowing over impervious surfaces picking up accumulated contaminants and carrying them offsite. Once an impervious pavement is replaced with a pervious pavement stormwater is allowed to reach the soil surface where natural processes are able to break down the pollutants (Cahill, et al., 2003). According to Brattebo and Booth (2003), infiltrated water from pervious pavement had significantly lower levels of zinc, copper, motor oil, lead, and diesel fuel when compared to runoff from an impervious asphalt pavement.

Notwithstanding the past developments and experiences, there still exists some uncertainty with regard to the infiltration rates with time, the quality of the water that infiltrates, and its strength that has raised some questions about their use as a stormwater management alternative for conventional pavements. An essential aspect of this research involved investigating the infiltration rates, rejuvenation techniques, sustainable storage of the components and complete systems, water quality, and the strength properties of these pavements. Infiltration rate measurements are conducted using an Embedded Ring Infiltrometer Kit (ERIK) device developed at the Academy (Chopra et al, 2010). Storage of water in each material as well as the entire systems is measured in the laboratory and is based on Archimedes's principles of water displacement. Water quality of samples collected through an under drain were analyzed for nutrients using the onsite water quality lab. Strength analysis includes field investigations which include pavement evaluation by means of the FDOT Falling Weight Deflectometer (FWD) equipment.

The Stormwater Management Academy at the University of Central Florida conducted water quantity, water quality, and strength analysis of the Oldcastle AquaFlow permeable paver systems. The primary goals for this research are:

1. Evaluate long term infiltration rates and the reduction in these rates due to sediment clogging and effectiveness of rejuvenation using vacuum sweeping. The rates are determined using the ERIK device.
2. Determine sustainable storage values of the aggregates and surface layer components of the system as well as the entire system storage values.
3. Evaluate the quality of water infiltrating through the system, specifically nutrients.
4. Determine parameters that represent strength performance of Oldcastle permeable pavement systems.

The following sections describe the installation of the three full scale pavement sections, laboratory experiments, and a discussion of the results obtained from the study.

Permeable interlocking concrete pavement systems offer designers and planners an effective tool for managing stormwater. The permeable paver system manages stormwater by increasing the rate and volume of infiltration and the reduction of the volume of runoff. By reducing runoff from pavement surfaces, a reduction in the amount of pollutants carried downstream by runoff water can be achieved to minimized non-point source pollution.

Permeable pavers systems are similar to conventional pavers except they are designed with increased joints or gap sizes between the bricks to allow larger aggregates (ie. #89 stone) to fill the joints instead of conventionally filling with sand, in order to increase the pore sizes and encourage more water movement. The performance of permeable paver systems is dependent on the degree of clogging of the opening and pore spaces by fugitive sediments and debris that get deposited onto the surface by both natural and human erosion. How fast a permeable pavement system will infiltrate stormwater throughout its service life will change through periodic sediment accumulation on the surface and maintenance.

This report presents the results of infiltration rates due to high levels of sediments accumulation throughout the entire cross section and the rejuvenation of the pavement system using a standard vacuum sweeper truck. The infiltration testing in this study is conducted by the use of an Embedded Ring Infiltrometer Kit (ERIK) to measure the vertical in-situ infiltration rates of different cross sections of permeable interlocking concrete pavement systems. The new draft statewide stormwater rule in Florida suggests that the minimum vertical hydraulic conductivity of the pervious pavement system (pavement and sub-base layers) shall not be less than 2.0 inches per hour indicated by an ERIK test, based on the 85% removal pervious pavement design criteria.

The ERIK infiltrometer is embedded into the entire pavement system section that is the pavement layer, bedding or choker course layer, stone open graded base layer, and sub-base layer, to measure the vertical infiltration rate. For the purpose of the study, the pavement surfaces are intentionally loaded with large amounts of soil types (A-3, A-2-4, and limerock fines) to simulate long term worst case scenario of long term clogging. This is done to test the effectiveness of vacuum cleaning as a rejuvenation method for permeable paver systems to restore its original state of permeability or an improvement from its clogged condition. The results of this study will provide designers, regulators, and contractors with an understanding of how well a permeable interlocking concrete pavement system performs, as per infiltration of water, and the effectiveness of the proposed maintenance method of vacuum truck for the restoration of the clogged pavement system in a fully operational system.

Background

Impervious surfaces are responsible for a significant portion of the nation's leading threat to surface water quality, nonpoint source pollution (US EPA 1994), by producing and transporting un-natural quantities, dynamics, and quality of stormwater runoff into receiving waters. Unlike pollution generated from a single, identifiable source like a factory, the pollutants in stormwater runoff may discharge from many points of source with uncontrolled amounts of pollutants. Since the exact quantities of stormwater and pollutants in the stormwater cannot be predicted for all discharge points from every impervious surface, it becomes difficult to treat the runoff effectively and economically.

In the past, the principal concern about runoff from pavements has been drainage and safety, focusing primarily on draining the water off the pavement surface as quickly and efficiently as possible (Chester and James, 1996). Historically many have considered that once the stormwater was off the pavement surface and into the drainage structure that the problem was solved and the "out of sight, out of mind" concept has been exercised all too often. Unfortunately this water once drained from the pavements surface has to end up somewhere downstream and typically causes negative impacts to ecosystems resulting in habitat loss. The pavement is designed with sufficient cross slope and longitudinal slopes to increase the velocity of the runoff water conveying it away from the pavement before ponding can occur. The result of increased velocity, the ability of stormwater to cause erosion, channel widening, sedimentation, flooding, and spreading of pollutants downstream is enhanced. Furthermore, impervious pavements are designed with costly measures taken to prevent water from accumulating directly under the pavements and subsequently damaging the structure. Although many pavement designers hope that wearing courses can be kept virtually watertight with good surface seals and high-tech joint fillers, the inevitable stresses and pressures of traffic, temperature fluctuations, oxidation and weathering, and freeze thaw are constantly working to open cracks that allow water to enter. Once the water is in the pavement system it becomes trapped and unable to be expelled quickly developing pore water pressures that result in piping and pumping effects that erode away subsoils causes serious problems to the structure. The only sure way to keep water from accumulating in the structural section is to drain it using a key feature of including a layer of very high permeability (33 in/hr to 333 in/hr or even greater) material under the full width of traffic lanes is suitable for good internal drainage of the systems to prevent deterioration (Cedergren, 1994). The U.S. pavements or “the world’s largest bath tubs” according to Henry Cedergren incurred economic losses of an estimated $15 billion/yr due to poor drainage practices, which can reduce the service life down to 1/3 of a typical well drained pavement (Cedergren, 1994).

The larger volumes of runoff produced by impervious surfaces and the increased efficiency of water conveyance through pipes, gutters, and other artificially straightened channels, results in increased severity of flooding in areas adjacent and downstream of pavements. It was reported by Chester (1996) this shift away from infiltration reduces groundwater recharge, fluctuates the natural GWT levels that could threaten water supplies and reduces the groundwater contribution to stream flow which can result in intermittent or dry stream beds during low flow periods. When runoff bypasses the natural filtering process provided by soils, access to critical ecosystem service is lost and additionally valuable land is not sacrificed to a single-use.

The permeable pavement systems can also function as parking areas as well as on-site stormwater control (Dreelin, et. al., 2003). Smith (2005) compares permeable interlocking concrete pavements to infiltrations trenches, which have been in use for decades as a means to reduce stormwater runoff volume and pollution, recharge groundwater, and at the same time be used to support pedestrian and vehicular traffic. Research conducted on permeable pavement systems by Scholz (2006) shows that the structure itself can be used as an "effective in-situ aerobic bioreactor," and function as "pollution sinks" because of their inherent particle retention capacity during filtration due to its high porosity. Most all of the pervious pavement systems share similar applications and all have several advantages over traditional impervious pavement systems. To mention a few, pervious/permeable pavement systems reduce overall runoff, level of pollution contained in runoff, ponding/hydroplaning, tire spray, glare at night, tire noise, skidding from loss of traction, velocity and temperature of runoff, erosion, and sedimentation (Tennis, et. al., 2004). The enhanced porosity allows for good infiltration and geothermal properties that help in attenuation of pollutants. Additionally due to the porous nature of the permeable pavement systems offer trees the necessary air and water exchange allowing roots to grow naturally instead of uprooting in search of air and water and causing damage to nearby pavements. More trees in parking lots can benefit owners by providing aesthetics to their property while effectively reducing the heat island effect associated with impervious pavements. Trees and plants serve as our natural solar pumps and cooling systems by using the sun's energy to pump water back to the atmosphere resulting in evaporative cooling. The permeable pavement systems allow water to evaporate naturally from the systems similar to natural soils also providing a cooling effect which can even prevent tire blowouts caused by high temperatures.

The sub-base of the pervious pavement system is designed to store rainwater and percolate into sub-soils restoring the natural ground water table levels for supply water wells for irrigation and drinking. It is important to allow the natural hydrological cycle to remain in balance to efficiently move water from surface water, groundwater, and vegetation to the atmosphere and back to the earth in the form of precipitation. Alteration in this cycle such as a decrease in infiltration can cause unwanted impacts resulting in quantity and quality of water that may not be sufficient to provide for all intended economical uses. We should be able to design structures to control water related events at a risk that is acceptable to the people of an area and within budget expenditures (Wanielista et. al., 1997).

Even though pervious pavement systems have been around for many years there is still a lack of needed experimental data associated with the in-situ performance over time. Barriers to the uptake of pervious pavement systems include technical uncertainty in the long term performance and lack of data, social perception, adoption, and maintenance (Abbot and Comino-Mateos, 2003).

Literature Review

This research is intended to meet the need by practitioners and researchers to quantify the performance of pervious/permeable pavements systems under field conditions. That is the ability of the complete system (surface and sub-base layers) to store and infiltrate stormwater before it becomes available for runoff. The lack of field data has been an impediment to the use of pervious pavements as a stormwater control tool to help prevent the amount of runoff from a pavements surface. Most of what has been researched before on pervious/permeable pavements systems has been surface infiltration monitoring which does not give information on clogging effects that may happen below the surface layer of the pavement. Field and laboratory studies have already been conducted on surface infiltration rates of permeable pavements including 14 PICP (permeable interlocking concrete pavement) sites where Bean (2004) reported median infiltration rates of 31.5 in/hr and 787.4 in/hr when the sites were in close proximity to disturbed soil areas and sites free from loose fines respectively (Bean et. al., 2007). Another study by Illgen et al (2007) reported infiltration rates of a PICP car park site in Lingen, Germany at initial rates of 8.0, 11.0, and 18.3 in/hr initially and final rates ranging between 5.4 and 11.2 in/hr. It was noted by Illgen et al (2007) that clogging effects due to fine material accumulating into the slots or voids are greatly influencing the infiltration capacity and can cause a point-wise decrease of the infiltration rate by a factor of 10 or even 100 compared to newly constructed pavements. An embedded ring device developed to monitor influences of sub-layer clogging does reveal any sub-layer clogging. Pavement system clogging potential can be tested before and after multiple vacuum sweep attempts. This provides insight into the restoration of these systems over time and at a particular site given its parent soil conditions.

The infiltration rates are measured using constant head permeability methodology by adding water to the surface of the pavement inside the extended embedded ring and keeping track of how much water is added over a period of time while maintaining a constant head level. This method is similar to a laboratory constant head permeability test except for the volume of water is measured upstream of the sample instead of downstream because the nature of the field test which allows water to percolate into the ground where it cannot be collected for measurement. By embedding the ring into the pavement system at a certain depth, the ring prevents water from flowing laterally in a highly permeable layer and instead directs the water vertically downward through any layer of interest. This vertical flow path is more similar to how water will behave in a real rain event in which water is prevented from flowing laterally by other rainwater flowing adjacent to any one spot in the pavement system.

Infiltration Rate

The infiltration rate is the velocity of water entering a soil column, usually measured by the depth of water layer that enters the soil over a time period. Infiltration is a function of the soil texture (particle size distribution) and structure (particle arrangement). The infiltration rate is not directly related to the hydraulic conductivity of a media unless the hydraulic boundary conditions are known, such as hydraulic gradient and the extent of lateral flow (Brouwer, et al. 1988). The infiltration rate is influenced by the soil layers, surface conditions, degree of saturation, chemical and physical nature of soil and liquid, and pressure head and temperature of the liquid (ASTM D3385, 2009). It should be noted that filters or porous materials through which a liquid or gas is passed to separate fluid from particulates have both a particle retention and a permeability function (Reddi, 2003). Infiltration rate is relevant to the studies on leaching and drainage efficiencies, irrigation requirements, water seepage and recharge, and several other applications.

Laboratory Infiltration Methods

Laboratory infiltration testing has been done using rainfall simulators for water supply, computerized falling/constant head permeameters (some with high precision pressure transducers and data acquisition systems, and flume or hopper systems with sprinkling units and tipping gauges for measurement of infiltration of pervious/permeable pavements (Anderson, 1999; Illgen, et. al., 2007; Montes, 2006; Valavala, et. al., 2006). Many of the laboratory tests are classified as destructive tests since either slabs or cores were cut and extracted from existing field pavement sites. The process of cutting pavements may introduce fines into the samples and washing samples may do the opposite and remove some of the existing clogging sediments found on the pavements in an in-situ condition. It was reported that even though all the samples coming from a particular placement were taken from the same slab, different porosities and hydraulic conductivities within a slab were important and suggested that one sample will not suffice to identify parameters (Montes, 2006). Two core samples taken from another site apparently had no connecting pore channels through the 4 inch diameter core sample, which resulted in no flow through. Other samples taken from the same slab had measured values of 19.8 – 35.4 in/hr. The highest hydraulic conductivity values obtained from the tests were reported outside the range of common expected values for pervious concrete, but were on the vicinity of the highest laboratory measurements reported by Tennis et al. (2004). The higher values reported for the pervious concrete samples were around 1,866 in/hr (Montes, 2006).

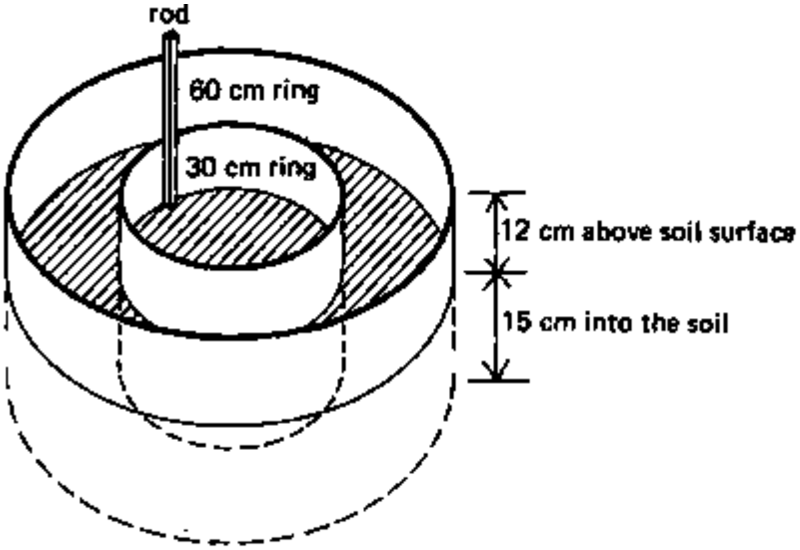
Field Infiltration Methods

Exfiltration field studies have been completed on infiltration monitoring of pervious/permeable systems by measuring the exfiltration from the systems. Previous studies investigated pervious/permeable pavements under natural rainfall conditions and measured exfiltration, runoff, water depths in pavements systems, and/or precipitation in order to determine infiltration rates through the systems (Abbot and Comino-Mateos, 2003; Brattebo, 2003; Dreelin et. al., 2003; Schlüter, 2002; Tyner, et. al., 2009). Methods used to measure these parameters consisted of using perforated pipes located in the sub-base draining water into tipping bucket gauges for monitoring of ex-filtrated water. In one of the studies, infiltration tests were carried out using a falling head method from an initial head of about 33 inches to a final height of about 8 inches above the pavements surface (Abbot and Comino-Mateos, 2003). It was noted in the report that the measured rates (some as high as 15,287 in/hr) do not represent actual rates which were achieved during actual rainfall events with a column of water applied at such a significant head.

Other researchers used several methods for determining infiltration such as the bore-hole percolation test method, a strategy of completely filling plots with water from an irrigation hose and water depths in monitor wells measured, and finally the use of a double ring infiltration test mentioned below (Tyner, et. al., 2009). In this study, different exfiltration methods underneath the pavement systems were investigated to encourage higher exfiltration rates on a compacted clayey soil in eastern Tennessee. They found the performance of trenches filled with stone exfiltrating at 0.43 in/hr to be the highest, followed by ripping with a subsoiler exfiltrating at about 0.14 in/hr, then boreholes filled with sand at about 0.075 in/hr.

Double-Ring Infiltrometer

The double-ring infiltrometer test (DRIT) measures the infiltration rate of soils, in which the outer ring promotes one-dimensional, vertical flow beneath the inner ring. Results from the DRIT are influenced by the diameter and depth of the ring embedment as test at the same site are not likely to give identical results. The results are recommended primarily for comparative use (ASTM D3385, 2009). Testing procedure is as described by the ASTM standard test method for infiltration rate of soils in field using double-ring infiltrometer ASTM D3385. **Error! Reference source not found.** presents a typical double-ring infiltrometer set-up for field testing (Brouwer, et al. 1988).



(Courtesy: Brouwer, et al. 1988)

Figure 1: Double Ring Infiltrometer (used for soils)

The limitation of using the DRIT on pervious systems is that the rings cannot be driven into the pavement surfaces unlike a soil or vegetative surface. In addition, typically soils or vegetative surfaces that would be tested using the DRIT would exhibit a more homogeneous and isotropic strata than a pervious pavement system with layers of significantly different sized aggregates. Therefore, due to lateral migration of water in the more permeable layers, the test cannot measure the true vertical (one dimensional) infiltration rate of the entire pervious system that is made up of several sub-base layers with varying permeability. This is why the second outer ring is needed when conducting a DRIT, to provide an outer ring of water that creates a curtain of water around the inner "measured" ring and preventing the inner ring water from migrating laterally during the test. It is incorporated to mimic an actual rain event in which there would be the same curtain of water surrounding any one spot on the pavement. In some of the past experiments using DRIT, Bean et. al. (2007) reported instances of water back up and upward flow, out of the surface near the outside of the outer ring, due to lower permeability of the underlying layer.

More limitations, encountered when using the surface infiltration rate tests on highly permeable surfaces, is the difficulty in maintaining a constant head or steady state flow through the system during the test, the large amount of water required to run a test, and the need to transport this water to remote locations. According to Bean et. al. (2007) many of the permeable pavement sites had surface infiltration rates that were greater than the filling rate for the DRIT.

Single Ring Infiltration Test

A modified version of the double-ring infiltrometer is the Single Ring Infiltration Test (SRIT) which uses only a single ring to perform surface inundation test. It was mentioned that there was difficulty in not only transporting the required amount of water to remote sites to run the DRIT or SRIT, but difficulty was also encountered when filling the inner ring with water at a faster rate to maintain a constant head above the surface (Bean et. al. 2007).

The Surface Inundation Test procedure involved recording the time that water started pouring into the single ring from a five gallon bucket until the water in the ring was emptied. The force of five gallons of water immediately poured on the surface of a clogged pavement may also cause some un-natural dislodging or unclogging of the sediments that are trapped in the surface pores. Plumbers putty was applied to the bottom of the ring and in any joints between pavers to prevent leakage. It was noticed during tests on Permeable Interlocking Concrete Pavers (PICP) and pervious concrete (PC) that the water actually flowed horizontally under the ring bottom and then percolated vertically upward through the pavement surface outside of the single ring, which in turn over predicted the actual surface rates. However, DRIT or SRIT provides a method for quantifying the surface infiltration rates of pervious pavements and may serve as a surrogate for the pavement's surface hydraulic conductivity (Bean et. al. 2007).

Destructive Test Methods

Other test methods include extracting cores of the pavement layers and analyzing the samples in a laboratory. This is a destructive method that may change the pore structures of the flexible pavements and clog pores generated during the coring process. This test method is limited by the inability to repeat at the exact same location on the pavement and compare to tests conducted at different times of sediment clogging that is encountered in the field.

Laboratory Permeability Methods

Most laboratory methods use constant or falling head permeameters that may be equipped with rigid walls (metal, glass, acrylic, PVC, etc.) for coarse grained soils/aggregates and flexible walls (rubber) to prevent sidewall leakage for fine grained samples. Associated sidewall leakage from rigid walled permeameters is usually negligible for sandy and silty soils with permeability rates above 5×10^{-2} cm/s or 70.9 in/hr (Reddi, 2003). These existing permeameters can be computerized and equipped with high precision pressure transducers and data acquisition systems. Three types of permeability tests include: constant (gradient controlled), variable (gradient controlled), and constant flow rate (flow controlled pump at a constant rate) which uses a programmable pump with differential pressure transducers

Field Permeability Methods

Investigations on field measurement of infiltration rates of pervious/permeable systems include test methods requiring sealing of the sub-base and installing perforated pipes that drain infiltrate to a collection point or other ex-filtration collection methods. Research has been conducted by a setup containing a sealed sub-base with eight 6-inch perforated pipes used to drain the area from 16 flow events recorded with a v-notch weir and Montec flow logger (Schlüter, 2002). Others have monitored field scale infiltration rates by measuring runoff, precipitation, and infiltration using a tipping bucket gauge. Similar methods for determining field permeability rates of in-situ soils include:

1. Pump test (by pumping water out of a well and measuring GWT drawdown after pumping),
2. Borehole test (using GWT measurements and variable head tests using piezometers or observation wells).

For cases where soil types vary in the domain, the permeability value obtained using the Pump test equations only reflect an effective and averaged value. Both natural and engineered soils are known to exhibit spatial variability in permeability. In natural soils, variability comes from the fact that soil strata/layers were subjected to the different compression forces during formation. In engineered soils and pervious/permeable systems layered placement and compaction subject these compression forces resulting in generally horizontal permeability being greater because of larger vertical compression forces (Reddi, 2003).

Embedded Ring Infiltrometer Kit

In order to effectively measure the in-situ performance of the pervious system infiltration capacity over time, an in-place monitoring device named Embedded Ring Infiltrometer Kit (ERIK) was developed at University of Central Florida (UCF), Orlando. It is similar to the existing (ASTM D3385, 2009) test for infiltration measurement of soil/vegetated surfaces using a Double Ring Infiltrometer Test (DRIT). The ERIK device was designed to overcome any difficulties in obtaining infiltration measurements of the pervious system using an efficient, accurate, repeatable, and economical approach. The relatively cheap, simple to install and easy to use device, has no computer, electrical, or moving parts that may malfunction during a test. The kit includes two essential components: one “embedded ring” that is installed into the pavement system during time of construction and the other a monitoring cylinder reservoir for flow rate measurement purposes used during testing.

The embedded ring is entrenched at predetermined depths into the pavement system to enable measurement of infiltration rates of different layers of the system. There are two types of the ERIK device embedded ring namely short-ring and long-ring ERIK. The short-ring ERIK is extended to the bottom of the pavement layer to measure the infiltration rate of the pavement only. On the other hand, the long-ring extends down to the bottom of the sub-base layer or even deeper into the parent earth underneath the system to monitor the entire pervious system given the parent earth soil conditions. The embedded ring is a pipe made of a hard-wearing synthetic resin made by polymerizing vinyl chloride (PVC) which extends through the pavement layer under consideration. This prevents the lateral migration of water which causes false measurements. The true vertical (one dimensional) steady state infiltration rate can be measured using the ERIK. **Error! Reference source not found.** below, presents the plan and section views of the ERIK embedded ring as installed in a permeable pavement system while not conducting a test.

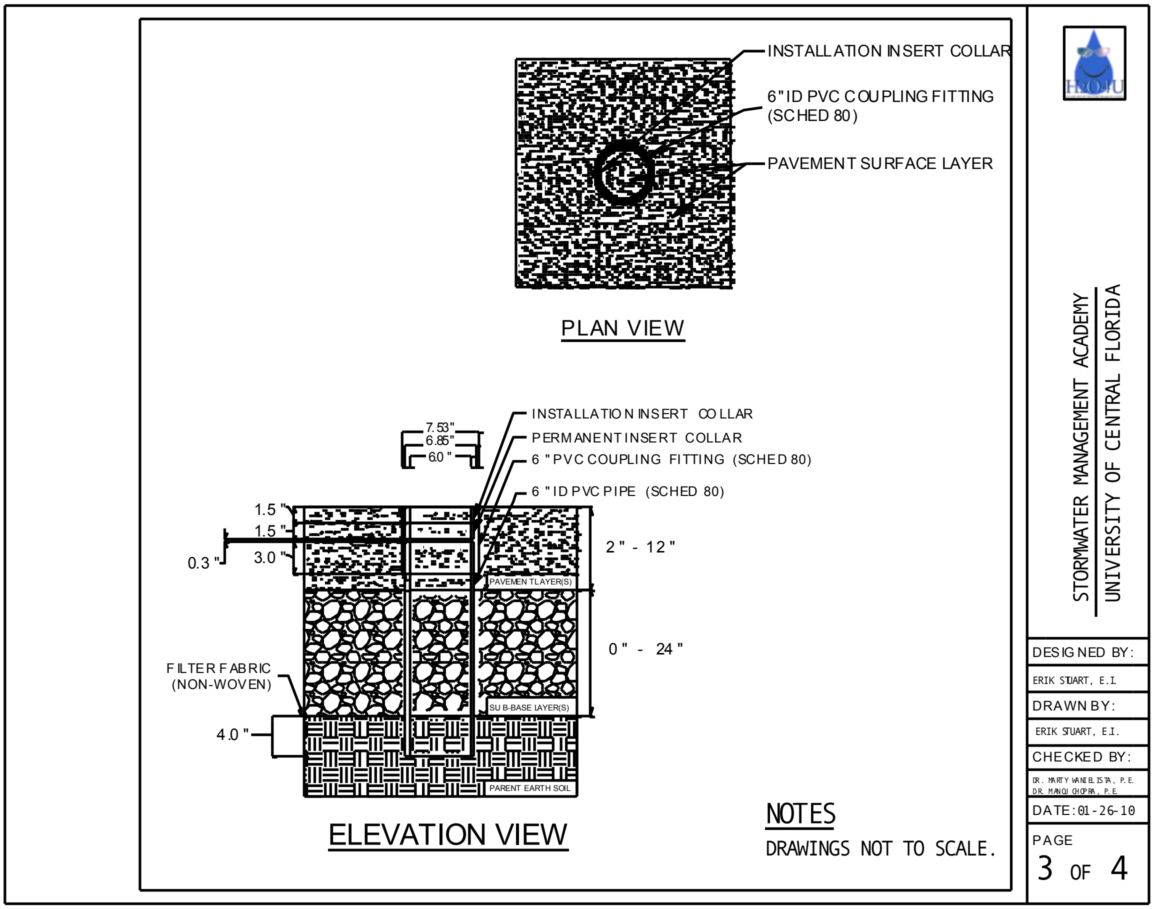


Figure 2: ERIK monitoring tube

The top of the embedded ring is installed flush with the pavement's surface for ease of pavement construction and to prevent any tripping hazard during the use of the pavement shown in. In large surface areas of pavement, the embedded ring may function as a grade stake set at an elevation consistent with the final elevation of the pavement surface. The embedded ring allows for screeds, floats, trowels, or any other placing and finishing tools to perform normally and again may even improve their workability. In addition, the ring does not extend beyond the pavement surface; neither does it interfere with the natural conditions that impact pavement surfaces such as: sediments from wind and water erosions that may accumulate on or penetrate into the system, and sediments from automobile tracks driven into the surface pores of the pavement inside the ring.

However, when conducting an infiltration test with the ERIK, a temporary "constant head test collar" is inserted into the top of the embedded ring, extending above the surface to a desired constant head height and is removed whenever a test is completed, illustrated in Figure 3 below. This height is determined based on the height of curbing around the pavement that is capable to provide a certain head of water above the pavement surface during a flood event or minimal head of one or two inches, for a worst case scenario. This study tested with one or two inches of head to be conservative and since the curbing used was flush with the pavement surface.

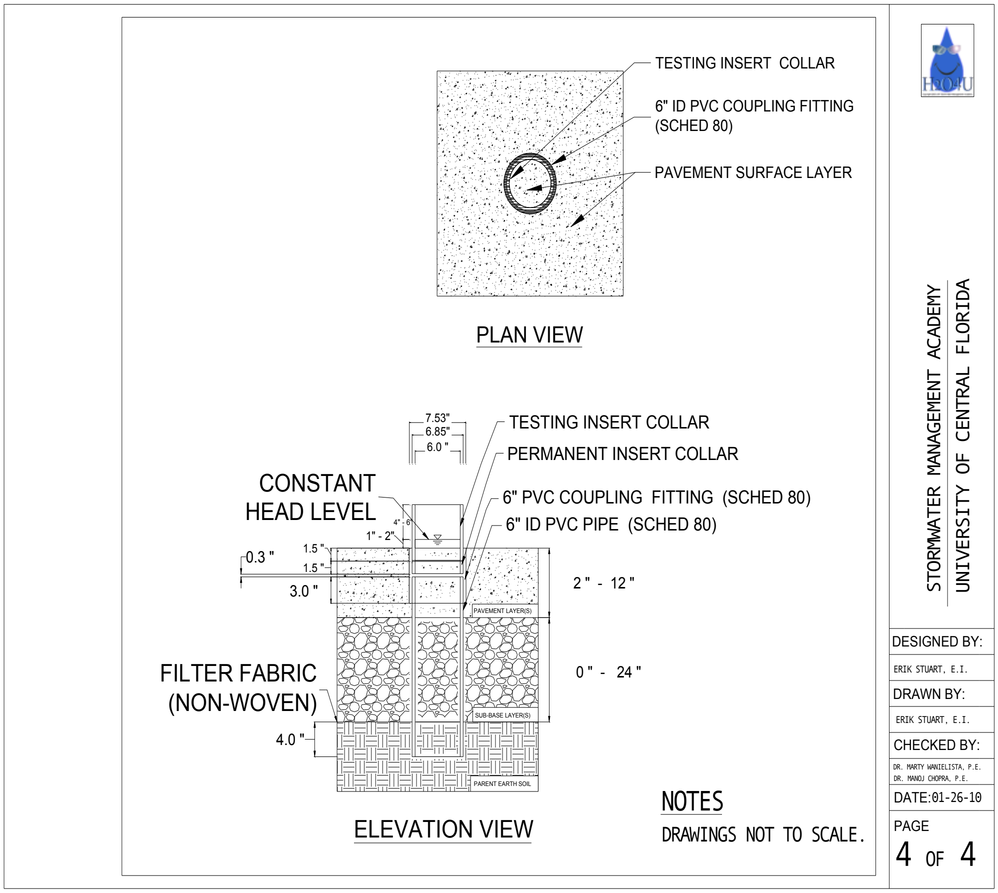


Figure 3: ERIK embedded ring installed

The second component of the ERIK device, that is the monitoring reservoir, is composed of Schedule 40 PVC piping material. The monitoring component of the kit for measuring flow during testing is essentially a graduated cylinder made of clear Schedule 40 PVC with an adjustable valve near the bottom of the cylinder. The cylinder is graduated with marks at predetermined intervals that make it easy to record and then convert measured flow rates to inches per hour (in/hr), which is typically how rainfall rates are measured. The plan and elevation views of the monitoring device are presented in **Error! Reference source not found.** 4.

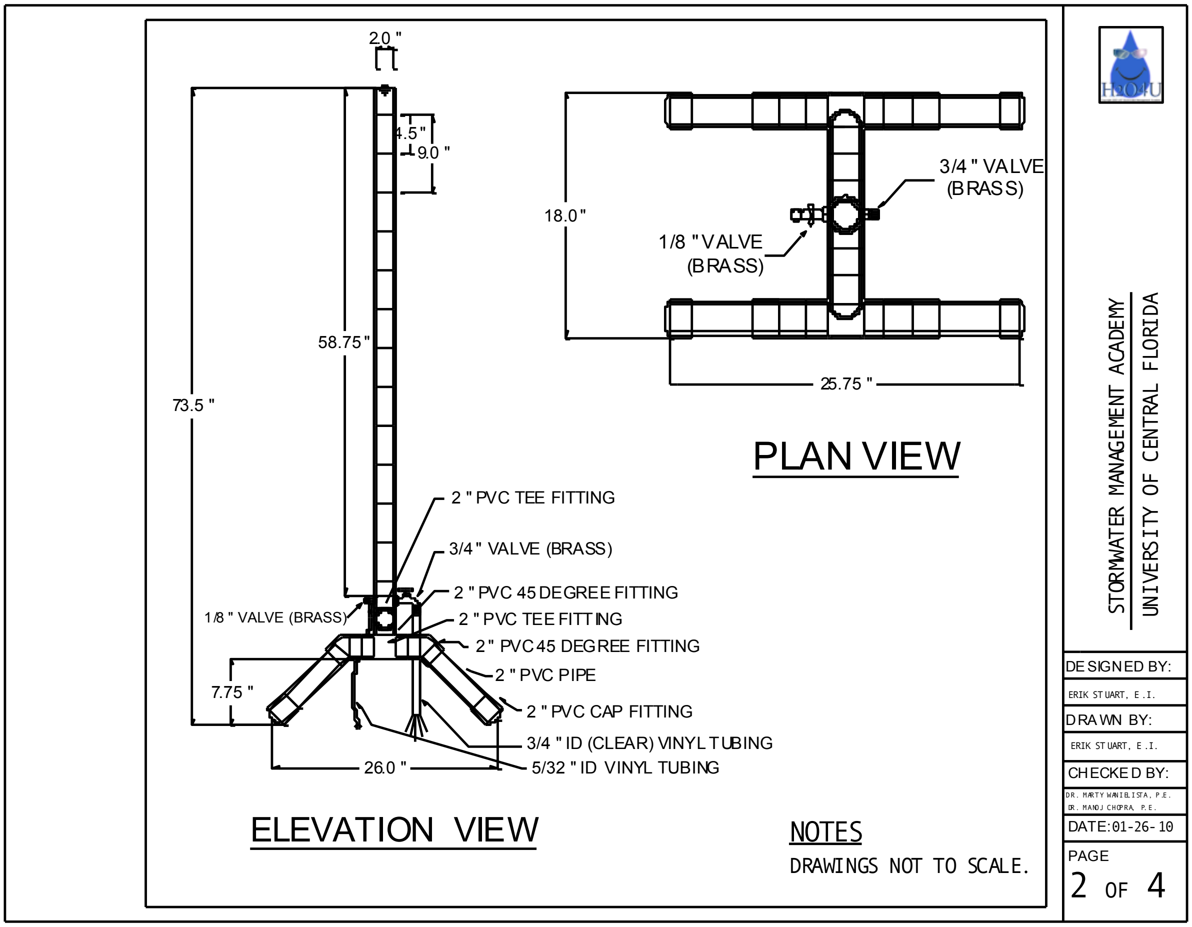


Figure 4: ERIK monitoring cylinder reservoir

PAVEMENT INSTALLATION AND SETUP

Permeable interlocking paver pavement (Oldcastle, 2005) is constructed at the University of Central Florida’s Stormwater Management Academy laboratory including 3 (three) equal sections (11 ft x 20 ft) totaling 660 sq ft for this paver type all with bricks assembled in the same herring bone pattern. Impervious concrete flush perimeter curbing is recommended and used for edge restraint extending 16 inches deep while two rows of 2 ft x 2 ft x 2 in impervious stepping stones were placed vertically in line to partition between the three permeable system sections. Due to the size of the project the parent soils are prepared by excavating the total depth of the system using skid steer loader, grading by back-blade of the loader, then compaction using a “walk behind” vibratory plate compactor. Aggregates are brought in by trucks and dumped directly into place before leveling and compacting shown below in Figures 5and 6. Once soils are prepared the curbing is cured a separation filter fabric is placed on top of the parent earth soil and extends up the curbing. One of the sections called the “rejuvenation” section comprised of the $3^1/_8$ inch thick brick laid on a 2 (two) inch bedding coarse layer of #89 (limerock) followed by 4 (four) inches of #57 stone (granite) and bottom layer is 7 (seven) inches of #4 (granite) all placed on top of the parent earth soil. The “Fill” section has the same cross section with the exception of granite being utilized for the #89 stone bedding course instead of limerock. The “Bold&Gold” section is similar to the rejuvenation section except for the bottom layer which consists of 2 (two) inches of Bold&Gold placed on the bottom of the layer with 5 (five) inches of #4 (granite), then 4 (four) inches of #57 stone, the 2 (two) inch bedding course, and finally the $3^1/_8$ inch permeable paver brick.

All sections were compacted with the vibratory plate compactor in lifts while placing each stone layer then the surface of the bricks are compacted after they are laid and filler stones are swept into the joints. These filler stones are the same that was used as the bedding course layer (#89 limerock).

Embedded ring infiltrometers are placed two per section that are set flush with the surface of the bricks and extend down 14 inches, the bottom ending in the #4 stone. The inside of the embedded rings are constructed with the same layers and thicknesses as the rest of the section.

Figure 5: Site and Formwork Layout

Figure 6: Aggregates placed, leveled, then compacted

These steps were all done according to the manufacturer's specifications. Figure 7 depicts the final pavement system with the three sections delineated by the curbing.

Figure 7: Final Layout of Pervious Pavement Sections with ERIKs

Setup for Infiltration and Rejuvenation

Infiltration and rejuvenation studies began by measuring initial infiltration rates soon after installation and curing was completed. After about a month and a half of measurements, the sections were then intentionally loaded with a layer of A-3 soils, approximately 2 inches thick, spread evenly across the surface with the skid steer loader to simulate long term sediment accumulation conditions (see Figure 8 below). The sediments were then washed into the pores using a garden hose (see Figure 9 below) to simulate accelerated rain events that would eventually wash this sediment into the surface pores by transport processes. The skid steer loader then was driven over the sediments back and forth until the sediments were sufficiently compacted into the pores simulating traffic loading.

Figure 8: Spreading of A-3 sediments evenly over entire Rejuvenation section

Figure 9: Washing in A-2-4 soils with garden hose

The embedded infiltrometers were then used to determine the post loaded infiltration rates to evaluate the loss of the system's infiltration capacity due to the clogging by the sediments. Finally, a standard street sweeping vacuum truck cleaned the pavement surfaces to simulate typical, real life maintenance.

It was noticed that the vacuum force was unsatisfactory at detaching and removing the soils in a dry and hardened state (see Figure 10). At this time, water was added to saturate the pavements surface. This was done by spraying a garden hose onto the pavement surface until water ponded on the pavement surface and the sediment was sufficiently soft. Once water was introduced, the fine grained sediments reached their liquid limit, became plastic and mobile, and the vacuum force was able to remove the sediment from the surface. The vacuum force was enough to remove even the filler stones in the joints of the bricks shown in Figure 11. Once the surfaces were vacuumed, post-rejuvenation ERIK measurements were continued on the paver systems.

Figure 10: Unsuccessful vacuuming of A-3 soils when dry and hardened

Figure 11: Successful vacuuming of A-3 soil when surface was saturated with water

These observations lead to the recommendation of coordinating the maintenance using a vacuum truck either during or immediately after large rain events or if ponding is noticed on the pavement surfaces. The draft statewide stormwater rule recommends nuisance flooding as an additional indicator of a clogged pavement from the ERIK device, and this study verifies that vacuuming during the occurrence of water ponding on the surface will result in optimum rejuvenation using a vacuum truck.

Sustainable Storage Evaluation Setup

Sustainable Void Space

The sustainable void spaces or pore volume that could occupy water during testing were tested for the surface layer materials and sub base layers separately in small containers and then the entire cross sections were built in larger barrels and tested to see what effect, if any, was caused by mixing near the interfaces of the layers. The individual surface materials and the barrels were loaded with sediments and then vacuumed while conducting tests throughout to also see the how sediments would reduce the amount of storage by occupying the empty pore spaces and if these voids could be rejuvenated with a vacuum force.

Due to the nature of the testing, a setup that allowed for repeatability of tests was required to measure the reduction of sustainable storage after clogging, and the rejuvenation of that storage after performing vacuuming on the sample surfaces. To achieve this, small half gallon plastic containers with screw on lids were chosen for the bench scale testing shown in Figures 12 and 13.

Figure 12: Half Gallon Jar picture for component testing

Figure 13: Half Gallon containers being loaded with sediments

A larger (12”x19”x47”) glass aquarium container (see Figure 14 below) was needed to test the storage within the bricks with joints filled.

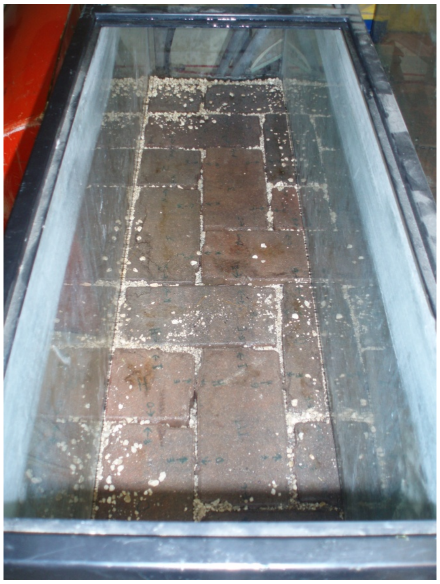


Figure 14: Brick paver (surface layer component) tested in large glass aquarium (12" x 19" x 47")

Since some of the larger aggregates had noticeably larger gaps near the side walls of the ½ gallon containers, the porosities of the #4 sized aggregates were also tested in the large aquarium see Figure 15 below.

Figure 15: Number 4 Aggregates tested in large glass aquarium (12" x 19" x 47")

The bench scale testing was performed to examine the storage values of the individual aggregate components that make up the system layers. The containers were modified by turning them upside down, cutting the bottom out, and then assembling filter fabric around the threaded opening using a rubber band to keep the fabric in place. This allowed for the lid to be screwed on to seal the bottom in order to measure storage of water, then the lid could be removed after testing to drain (by gravity) the pore water. Subsequent tests could be conducting on the sample samples without disturbing or changing the structure of the materials. Also washing and compacting of sediments into the materials and later vacuuming could be done while testing the storage values at the different levels of clogging and rejuvenation. The surface layer (bricks with filler stones in joints) is tested in the laboratory using 55 gallon glass aquariums.

Laboratory Porosity

In accordance with this understanding, a variety of substrates were tested including: the aquaflow pavers assembled in the herring bone pattern with joints filled with #89 pea rock, pea rock (#89 stone), crushed concrete (#57 stone), limerock (#4 stone) and granite (#4) stone.

Again, in order to properly attain replicable results from the testing method, the proper inventory of materials is required. This inventory includes: the aforementioned specified testing media, a 1.89 liter ½ gallon (US) (½ gallon (US)) plastic jar (including the cap), a 18.92 liters (5 gallon (US)) bucket, nonwoven geotextile (Marifi 160N), rubber bands, a scale capable of reading to 0.01g (SWL testing utilized the OHAUS Explorer Pro), an evaporation pan, 1 cubic foot (Ft^3) of sand, a paint brush, box cutters, 12.7mm (½ inch) polyurethane tubing, plastic Tupperware, a proctor hammer, an oven and a digital camera and data sheet for the purpose of documentation.

The set up procedure included wrapping end with the existing lid opening with the non-woven geotextile. Next, rubber bands were used to fasten the geotextile in place. The cap was then fitted over the newly installed geotextile and the specified testing media was placed in the modified ½ gallon jar to the specified “Fill Line”, as illustrated in Figure 16.

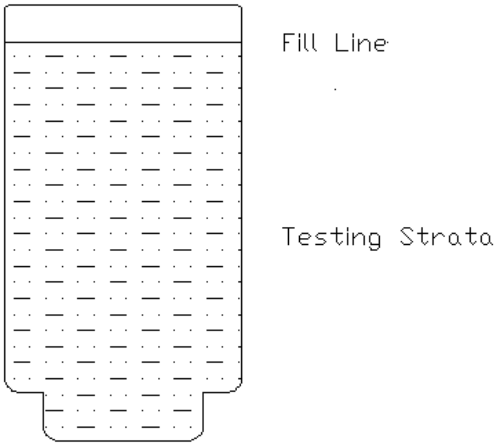


Figure 16: Half Gallon plastic jar cross section for component testing

Upon the completion of the set up procedure, the experimental process is as follows:

- Place one Tupperware unit (739 mL/25 fl. Oz. unit) on the scale; this unit is utilized to prevent direct spillage onto the scale.
- Tare the scale to zero.
- Place the sample on the Tupperware.
- Take and record the dry weight of the sample.
- Place the sample into a 5 gallon (US) bucket.
- Fill the bucket with water allowing water to seep up through the bottom of the filter fabric wrapped container until it reaches the fill line on the exterior of the modified plastic jar.
- Utilizing a sink/polyurethane tubing setup.
- Continue to slowly saturate the sample.
- Allow the sample to rest in the water for approximately 30 (thirty) minutes; during this time, occasionally tap the exterior of the jar to eliminate air voids (Haselbach, et. al., 2005).

- Quickly remove the sample from the 5 gallon (US) bucket and place it on the Tupperware (note the Tupperware should still be tared on the scale).
- Record the saturated weight of the sample.
- Remove the bottom cap from the sample allow gravity to drain samples (see Figure 17).
- Allow the sample to dry for 24 (twenty-four) hours.
- Replace the cap over the non-woven geotextile.
- Weigh the sample recording the weight of the semi-dry sample.

Figure 17: Half Gallon Jars draining by gravity

Component porosity utilizes weight based calculations to attain total, effective and sustained porosity measurements. The following equations were used:

The porosity of a material is given by:

$$n(\%) = \frac{V_{Voids}}{V} \qquad \text{Equation 1}$$

The total volume (V) can be determined by filling the testing apparatus with water to the designated fill line:

$$V = \frac{W_{water\ to\ Fill\ Line}}{\gamma_{water}} \qquad \text{Equation 2}$$

After adding the desired media into the testing apparatus, the volume of voids (V_{Voids}) can determined via the following equation:

$$V_{Voids} = W_{Water\ Added}/\gamma_{Water} \qquad \text{Equation 1}$$

After a 24 hour draining period, the sample is reweighted to determine the amount of residual water remaining. Hence, a new volume of voids (V_{Voids}) value is determined yielding a sustained porosity measurement:

$$V_{Voids}' = W_{Water\ Added\ (Drained)}/\gamma_{Water} \qquad \text{Equation 2}$$

Both the system and component porosity methods focus on a simple method to adequately measure the total and effective porosity based volumetric and weight centric calculations. System (Barrel) porosity testing methodology was explored as a possible means of achieving reproducible results for a porous paving system. The hypothesis was that replicating field conditions exactly on a smaller scale will yield porosity results comparable to actual environmental results.

A specific inventory of materials is required to properly perform the testing procedure discussed above. These materials include: the specified testing media, tap water, a 208.2 liter (55 gallon (US)) plastic barrel, a 2000 milliliter (0.53 gallon (US)) graduated cylinder, a 18.9 liter (5 gallon (US)), a 1-½ inch PVC pipe, nonwoven geotextile (Marifi 160N), rubber bands, epoxy glue, funnel, measuring tape, level, digital camera and finally, a data sheet with a clip board.

The set up procedure for the barrel construction is as follows: prepare a well pipe by cutting a 1-½ inch PVC Pipe to approximately 40 inches in length. Cut slits in the 1-½ inch PVC pipe, these slits should be lined up in 2 (two) rows, which should be on opposite sides of the cylinder (slits should be evenly spaced at ¼ inch intervals up to 16 inches). Subsequently, the bottom 16 inches of the 1-½ inch PVC pipe are to be wrapped in a nonwoven geotextile, utilizing rubber bands to fasten the geotextile in place. At this point, the wrapped 1-½ inch PVC well pipe is approximately centered in the plastic drum, where epoxy glue applied to the bottom surface of the geotextile wrapping and is utilized to hold the material upright and in place. A measuring tape (1.09 meters (1 yard)) or longer is fastened upright against the drum using epoxy glue. It is at this point that each of the specified testing media components are oven dried then installed. The use of a straight edge is employed to ensure that the uppermost surface of the testing media is completely flat.

Upon the completion of the set up procedure, the experimental process is as follows: portion 2000 milliliter (0.53 gallon (US)) of water using the aforementioned graduated cylinder. Pour the measured volume of water into the top of the previously installed 1-½ inch PVC pipe; to minimize water loss due to transfer spillage; a large funnel was placed in the top opening of the 1-½ inch PVC pipe. This amount is recorded and the former steps are repeated until water has saturated the system entirely. Saturation visibly occurs when the top layer of testing material has been entirely submerged. The cumulative water added in addition to the final water level is recorded.

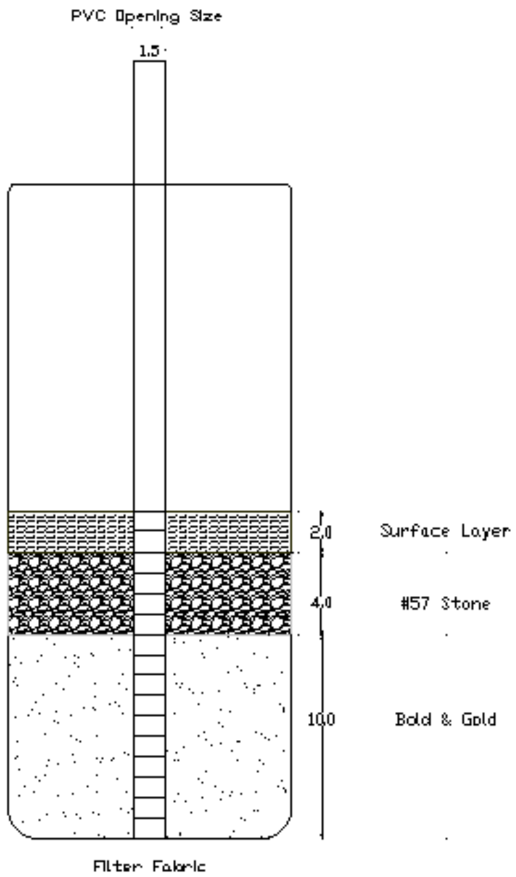


Figure 18: 55 Gallon Barrel for System testing

Figure 19: System testing in 55 gallon barrel

The procedure for the complete systems has been determined by extrapolating the total volume of the specimen based on its height within the 55 gallon drum previously calibrated by adding known volumes of water and recording the height and recording the amount of water added to effectively saturate the sample, the porosity can be calculated by utilizing the following method.

While similar, the primary difference between the component (lab) porosity testing method and system (barrel) method, is, as the name would suggest, the measurement of porosity values of components of a system versus the system as a whole.

The method of calculation also differs between the two processes. System porosity is determined via volumetric calculations.

The porosity equation is:

$$n(\%) = \frac{V_{Voids}}{V} \qquad \text{Equation 5}$$

The volume of voids (V_{Voids}) is determined by the following equation:

$$V_{Voids} = V_{Water\ Added} - V_{Pipe\ I.Diameter} \qquad \text{Equation 6}$$

This, subsequently, can be calculated as:

$$V_{Voids} = V_{Added} - (H_{Water\ Added} * \frac{\pi d_{Inner}^2}{4}) \qquad \text{Equation 7}$$

The total volume (V) can be determined via the following equations:

$$V = V_{Barrel} - V_{Pipe\ O.Diameter} \qquad \text{Equation 8}$$

Based on a prior analysis correlating barrel height to volume of fluid present, the following equation has been prepared:

$$y = 1.745x$$

Where *x* represents the height of the fluid specimen in feet, and *y* represents the subsequent volume acquired in cubic feet. This can then be used to calculate V_{Barrel}:

$$V_{Barrel} = H_{Water\ Added} * 1.745 \qquad \text{Equation 9}$$

Therefore:

$$V = (H_{Water\ Added} * 1.745) - (H_{Water\ Added} * \frac{\pi d_{outer}^2}{4}) \qquad \text{Equation 10}$$

Water Quality Setup

Restoring the natural hydrologic cycle using permeable brick paver systems to reduce the volume and rate of stormwater runoff can also result in water quality improvement. This is achieved through natural soil filtration and reducing the length of the flow path to the point of drainage. Pollutants accumulate during inter-event dry periods via atmospheric deposition resulting in transport when stormwater runoff flows over impervious surfaces. Allowing stormwater to infiltrate as opposed to flow over impervious surfaces as runoff reduces the transport of said pollutants. This, however, raises the question of the fate of these accumulated pollutants. This study examines the water quality, specifically nutrients, of infiltrated stormwater through Aqua Bric permeable paver systems. The specific water quality parameters examined in this study are pH, alkalinity, turbidity, total solids, ammonia, nitrate, total nitrogen, ortho-phosphate, and total phosphate.

The University of Central Florida's Stormwater Management Academy conducted a water quality analysis on Aqua Bric, presented by Belgard. Due to complications in the field barrels were constructed to isolate variables and examine the quality of water that infiltrates through the Aqua Bric system. The potential water quality benefit of adding a Bold&Gold^{TM}

pollution control layer was also examined. Between August 20th and September 10th, five series of tests were run on the constructed barrel systems. By simulating a rainstorm using a watering can and stormwater collected from a nearby stormwater pond, conclusive results were found and are presented in this report. Aqua Bric, a LEED credited permeable paver, is designed to reduce stormwater runoff and the pollution associated with it. Compared to similar products on the market, it outperforms in harsh climates or freeze thaw cycles (OldCastle). These bricks also meet American with Disability architectural guidelines (Belgard).

A total of eight test barrels were constructed to isolate the variables of interest, the effect of Aqua Bric permeable pavers and the effect of the use of a Bold&Gold™ (B&G) pollution control media layer. There were a total of four barrels constructed with the Bold&Gold™ pollution control media layer and four constructed without, labeled B&G and Fill respectively. All eight barrels had the rock sub-base layers installed in the same manner. The permeable brick pavers were then installed in all but two barrels in the same way they were installed in the field. The two barrels without permeable brick pavers were constructed as controls, one for the B&G system and one for the Fill system. The other six barrels represent replicates of the B&G permeable paver system and the Fill permeable paver system, three replicates for each system.

The following materials were used in the construction of the barrel systems:

1. AASHTO A-3 type soil
2. Bold & Gold™ pollution control media
3. #57 stone
4. #4 stone
5. #89 limestone
6. Aqua Bric permeable brick pavers

7. Non-woven filter fabric
8. Eight 55 gallon drums
9. Eight valves
10. 17 one liter sample jars
11. Nine 5 gallon buckets
12. Watering can

At the beginning of the test series, the barrels were be prepped and the driveway systems constructed inside. First, 2 inches holes were cut above the base of the barrels large enough to fit a nozzle. Nozzles were then installed and sealed. Next, the barrels were cleaned with HCl and DI water. In order to prevent sediment from clogging the nozzles, a 4x4 inch non-woven filter fabric was installed behind each nozzle. The barrels were labeled as follows:

- a. Fill Control
- b. Fill #1
- c. Fill #2
- d. Fill #3
- e. B&G Control
- f. B&G #1
- g. B&G #2
- h. B&G #3

Once all of the barrels were labeled, AASHTO type A-3 soil was poured into each barrel and compacted to a height of 4 inches (Figure 20). Next, a non-woven filter fabric was laid over the soil in all of the barrels (Figure 21).

Figure 20: 4 Inches of Compacted AASHTO Type A-3 Soil Installed

Figure 21: Non-woven Geotextile Separation Fabric Installed

Bold&Gold^{TM} pollution control media was then poured into the four B&G system barrels and compacted to a depth of 4 inches (Figure 22). Next, #4 Stone was placed into all 8 barrels at a depth of 5 inches, then leveled and compacted (Figure 23). #57 Stone was then placed into all 8 barrels at a depth of 4 inches, then leveled and compacted (Figure 24).

Figure 22: 4 Inches of Bold&Gold^{TM} Pollution Control Media Installed

Figure 23: 5 Inches of #4 Stone Compacted

Figure 24: 4 Inches of #57 Stone Compacted

The next layer was a bedding layer consisting of #89 limestone compacted to a depth of 2 inches (Figure 25). Lastly, the brick pavers were placed into all the B&G and Fill system barrels except the two control barrels (Figure 26).

Figure 25: 2 inches of #89 Limerock

Figure 26: Oldcastle Brick Pavers Installed

Once the barrels were completed, the eight 5 gallon buckets were cut in half horizontally and then cleaned with HCl and DI water. Once the buckets were cleaned they were placed under each valve to catch the infiltrated water. Lastly, the sample jars were labeled to match each barrel, two jars per barrel one labeled A and the other B.

The following procedure was followed for each test performed. Tests were run on each barrel twice a week from August 20th to September 10th 2010. Two samples were collected from each barrel, labeled A and B, per test run. First, 5 gallon buckets were placed directly under each valve to catch the water that infiltrates through the system and the valves on the barrels were opened. Next, stormwater was collected from a nearby pond and poured into each of the barrels using a watering can, simulating a rain event. The water was allowed to infiltrate through the system for fifteen minutes prior to sample collection. Two samples were collected for analysis of water quality parameters per test run, making sure the samples were completely mixed. The first sample was collected 15 minutes after filtrate started being collected and the second sample taken after the next 15 minutes and labeled A and B respectively.

Strength Testing Setup

Falling Weight Deflectometer

The Falling weight deflectometer (FWD) is a non-destructive field testing apparatus used for the evaluation of the structural condition and modulus of pavements. It is made up of a trailer mounted falling weight system, which is capable of loading a pavement in such a way that wheel/traffic loads are simulated, in both magnitude and duration.

An impulse load is generated by dropping a mass (ranging from 6.7 – 156 KN or 1506.2 – 35,068.8 lbs) from three different heights. The mass is raised hydraulically and is then released by an electrical signal and dropped with a buffer system on a 12-inch (300-mm) diameter rigid steel plate. When this load is dropped a series of sensors resting on the pavements surface at different distances from the point of impact picks up the vertical deflections caused by dropping the mass. The deflection responses are recorded by the data acquisition system located in the tow vehicle. Deflection is measured in “mils”, which are thousandths of an inch. FWD deflection basins are then used to determine rehabilitation strategies for pavements and pavement system capability under estimated traffic loads.

Back-Calculation Program

The traditional method for interpreting the FWD data is to back-calculate structural pavement properties (Turkiyyah, 2004) which entails extracting the peak deflection from each displacement trace of the sensors (deflection basin) and matching it, through an iterative optimization method, to the calculated deflections of an equivalent pavement response model with synthetic moduli (Goktepe, et al., 2006). Iterations are continually performed until a close match between the measured and calculated/predicted deflection values are attained.

Back-calculation of layer moduli of pavement layers is an application of non-destructive testing (NDT). It involves measuring the deflection basin and varying moduli values until the best fit between the calculated and measured deflection is reached. This is a standard method presently used for pavement evaluation. According to Huang (2004), there is presently no backcalcualtion method that will give reasonable moduli values for every measured deflection basin.

The Modulus 6.0 microcomputer program (Liu, et al., 2001) is one of the available programs that back-calculates layer moduli. This software is used by most DOTs here in the U.S. The Texas Transportation Institute (TTI) developed this computer program and it can be used to analyze 2, 3 or 4 layered structures. A linear-elastic program called WESLEA can then be utilized to produce a deflection basin database by assuming various modulus ratios. Huang (2004) describes a search routine that fits calculated deflection basins and measured deflection basins. Finally, after mathematical manipulations, the modulus can be expressed as:

$$E_n = \frac{q a f_i \sum_{i=1}^{s} \left(\frac{f_i}{f_i \omega_i^m} \right)^2}{\sum_{i=1}^{s} \left(\frac{f_i}{f_i \omega_i^m} \right)} \qquad \text{Equation 11}$$

Where:

f_i are functions generated from the database

q is contact pressure

ω_i^m is measured deflection at sensor i

a is the contact radius

Determination of Layer Coefficients and Structural Number

The layer coefficient (a_i) and structural number (SN) can be estimated from the deflection data obtained from FWD testing. According to (AASHTO, 1993), the effective structural number SN_{eff} is evaluated by using a linear elastic model which depends on a two layer structure. SN_{eff} is determined first before the layer coefficients of the different pavement layers. The effective total structural number can be expressed as:

$$SN_{eff} = 0.0045 h_p \sqrt[3]{E_p}$$ Equation 12

Where:

h_p = total thickness of all pavement layers above the subgrade, inches

E_p = effective modulus of pavement layers above the subgrade, psi

It must be noted that E_p is the average elastic modulus for all the material above the subgrade. SN_{eff} is calculated at each layer interface. The difference in the value of the SN_{eff} of adjacent layers gives the SN. Therefore the layer coefficient can be determined by dividing the SN of the material layer by the thickness of the layer instead of assuming values.

RESULTS AND DISCUSSION

Infiltration and Rejuvenation Results

A total of 83 ERIK measurements were taken for the Oldcastle Aquaflow permeable paver pavement systems. Three rounds of sediment loading and vacuum sweeping have also been completed. This section describes the results of the ERIK measurements on the three pavement types. Figure 27 below shows the cross sectional view of the embedded ring infiltrometers (north and south) and the resulting measured infiltration rates are displayed graphically in Figures 28 and 29 below. The results shown below are for the Rejuvenation section.

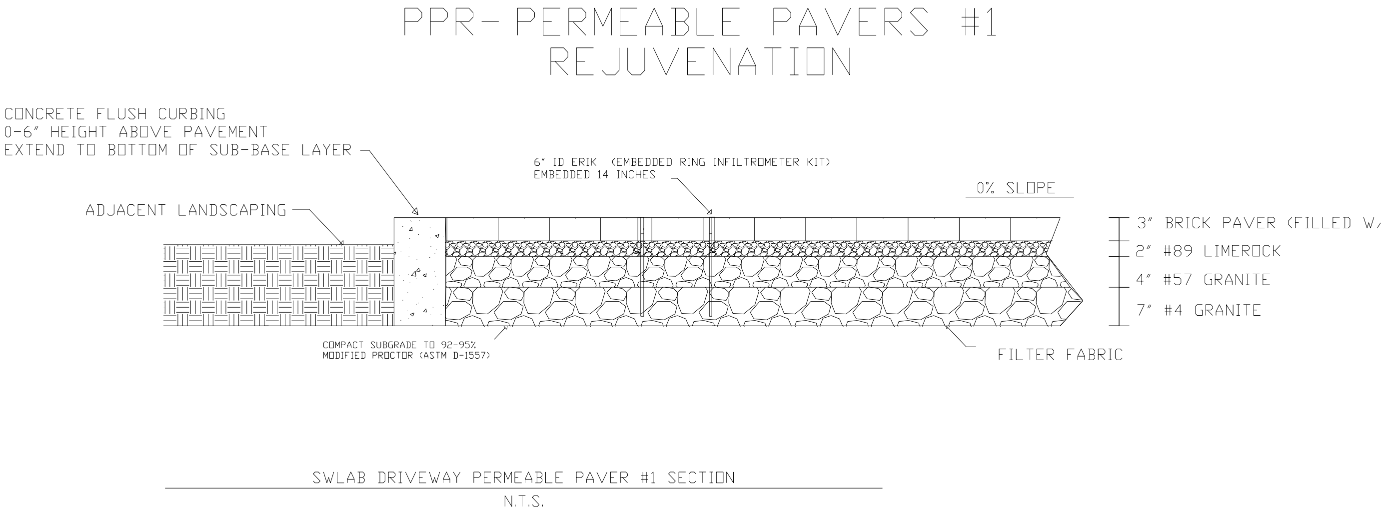


Figure 27: Permeable Pavers Rejuvenation Cross Section

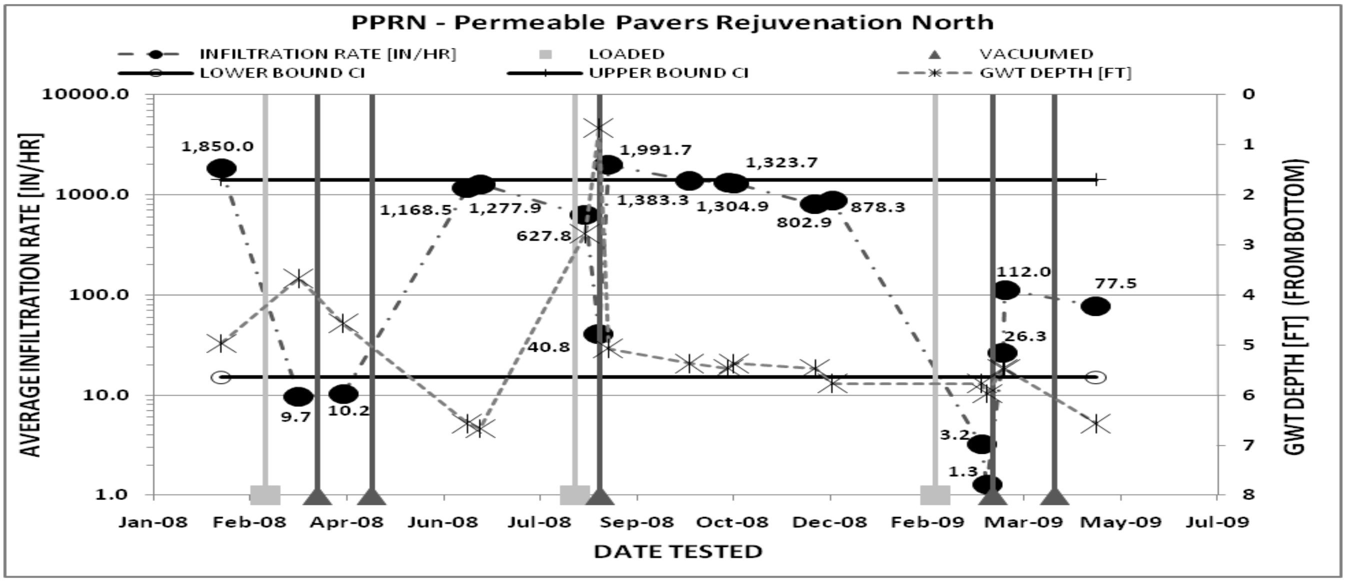


Figure 28: Infiltration Rate (ERIK) Results for the Permeable Pavers Rejuvenation North Section Infiltrometer

The north infiltrometer measured an initial rate of 1850 in/hr at the beginning of the study period. After sand was used to clog the system the rate was reduced to 9.7 in/hr. The first vacuum attempt only restored the rate to 10.2 in/hr but when re-vacuumed, the rate was rejuvenated back up to 1169 and 1278 in/hr. The crushed limerock fines were washed in and compacted into the surface pores next, which caused the rate to fall to 627.8 and 40.8 in/hr during the second set of post-loaded ERIK tests. The vacuum truck performed maintenance, and increased the infiltration of the pavers to 1992 in/hr followed by three tests measuring 1383, 1305, and 1324 in/hr. After about a month the rate had dropped to measured rates of 802.9 and 878.3 in/hr. Towards the end of the study period, the pavement was loaded again with the sandy soils and resulted in decreased infiltration rates measured at 3.2 and 1.3 in/hr. The restoration of the infiltrating capacity of the system was effective by increasing the measured rates to 26.3 and 112.0 in/hr during the next two tests. The pad was vacuumed once more and the post-cleaning rate measured in at 77.5 in/hr.

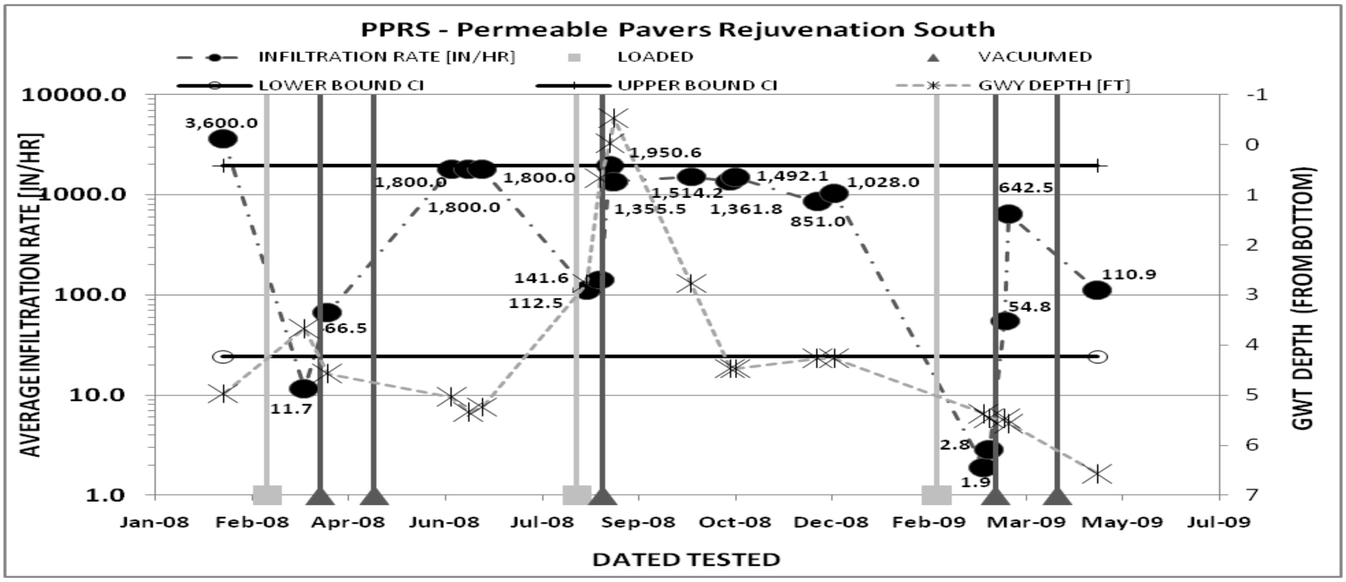


Figure 29: Infiltration Rate (ERIK) Results for the Permeable Pavers Rejuvenation South Section Infiltrometer

The south infiltrometer had consistent results with the north during testing, with measured rates ranging from over 1000 in/hr to less than 2.0 in/hr. The initial rate was measured at 3600 in/hr before sediment loading took place. The sand managed to clog the system reducing the rate to 11.7 in/hr, but was rejuvenated by vacuuming back up to 66.5 in/hr. The pavers were vacuumed a second time which significantly un-clogged the system to rates above 1800 in/hr even during a time when the GWT was above the bottom of the system. The infiltrometer used to measure high rates of infiltration was damaged, so on these three tests an infiltrometer that maxed out at 1800 in/hr, was used until a new measuring device was constructed. The limerock fines were used next to clog the pavement reducing the measured rates to 112.5, and 141.6 in/hr during the post loading tests. After vacuuming the rates were increased back to measured rates ranging from (1,951 - 851) in/hr during the next four months of testing. The pavement was finally loaded again with sandy soils which depreciated the measured rates down to 2.8 and 1.9 in/hr for the post loading tests. Two post vacuum tests were conducted and the measured rates were 54.8 and 642.5 in/hr, then after another vacuuming event the measured rate recorded was 110.9 in/hr.

It should be noted that the pollution control system designated as PPBG had two 14 inch long infiltrometers installed which did not extend into the Bold&Gold media shown in Figure 30. The bottom of the infiltrometer was above the Bold&Gold layer and hence did not measure infiltrated water through this layer. The initial results seen in Figure 31 measured by the north infiltrometer was 1775, 150.4, and 141.4 in/hr before a vacuum was performed

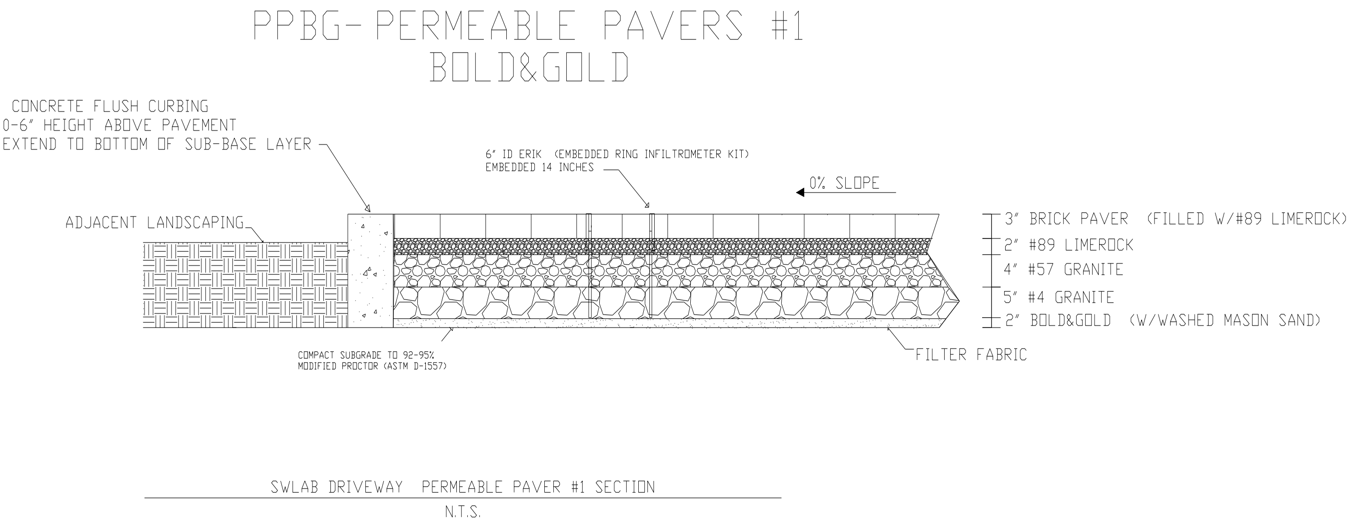


Figure 30: Permeable Pavers Bold&Gold Infiltrometer Cross Section

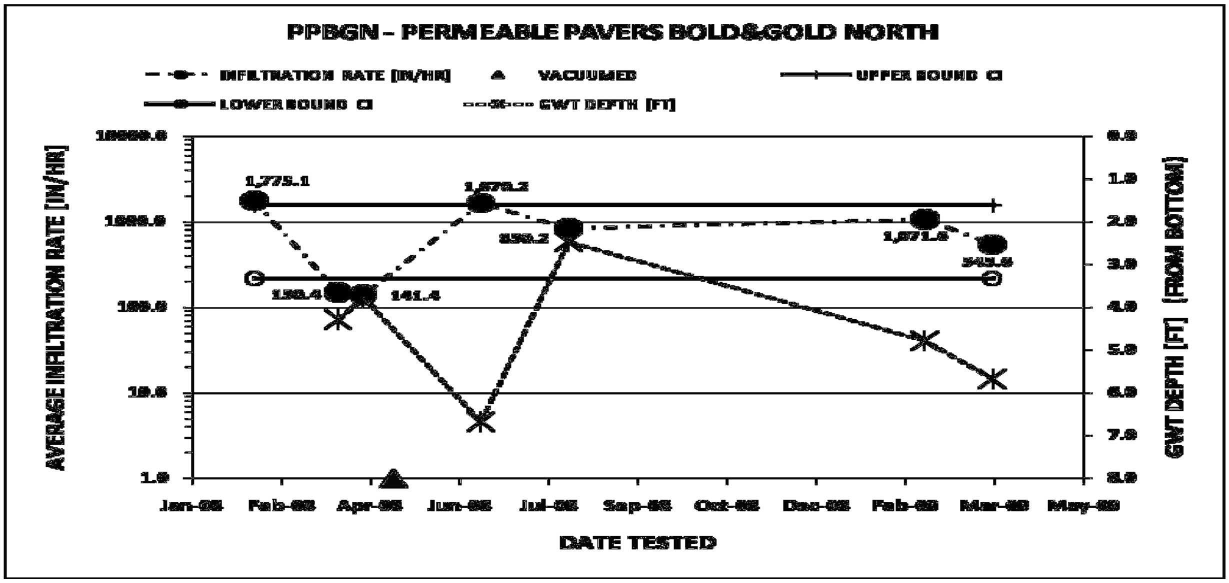


Figure 31: Infiltration Rate (ERIK) Results for the Permeable Pavers Bold&Gold North Section Infiltrometer

The measured rate after maintenance was 1670 in/hr and the later tests resulted in measured rates of 850.2, 1072, and 545.6 in/hr throughout the period of study. All tests were conducted when GWT levels remained lower than 3 feet from the bottom of the system except for the test that measured 850.2 in/hr while the GWT was about 2.5 feet below the bottom of the system.

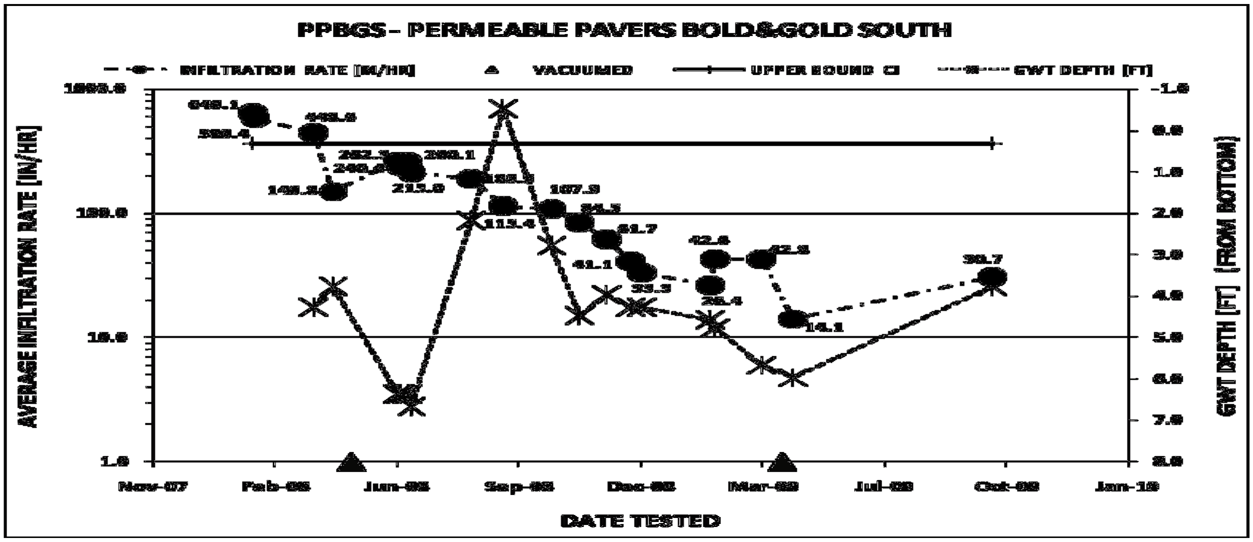


Figure 32: Infiltration Rate (ERIK) Results for the Permeable Pavers Bold&Gold South Section Infiltrometer

Referring to Figure 32 above, the southern infiltrometer measured rates slightly less than the north with initially measured rates of 649.1, 589.4, 448.6, and 149.8 in/hr prior to any maintenance. After maintenance occurred the rate was measured at 262.3 in/hr and steadily declined down to 14.1 in/hr during nine months of naturally eroded sediments clogging the system. The second vacuuming attempt rejuvenated the infiltration rate to a measured 30.7 in/hr.

The other pad consisted of a cross section similar to the rejuvenation pad, with the typical rock reservoir as the sub-base illustrated in Figure 33. The system was equipped with two 14 inch long infiltrometers that extended down to 2 inches short of the bottom of the system (parent earth soil).

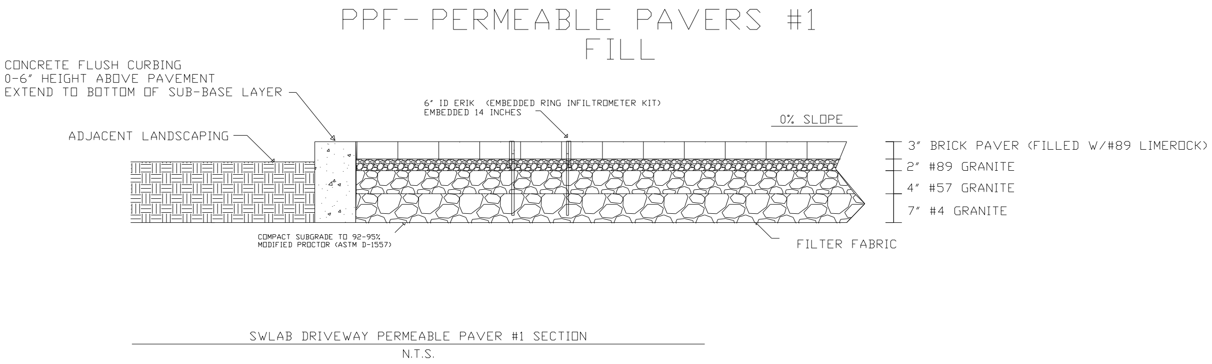


Figure 33: Permeable Pavers Fill Infiltrometer Cross Section

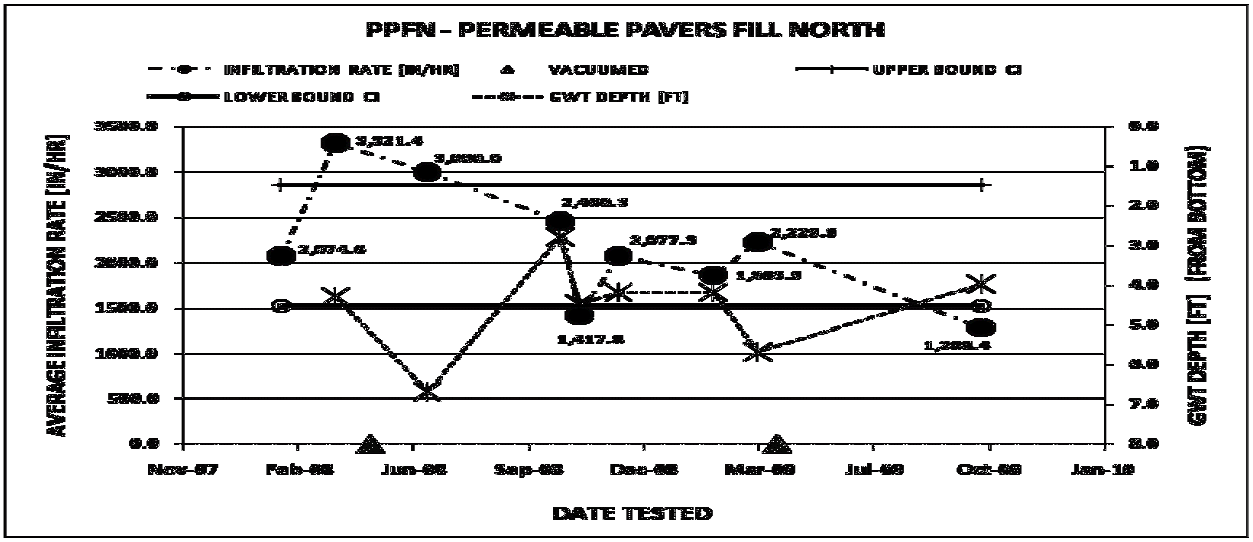


Figure 34: Infiltration Rate (ERIK) Results for the Permeable Pavers Fill North Section Infiltrometer

The north infiltrometer shown above in Figure 34, resulted initially in measured rates of 2075 and 3321 in/hr prior to maintenance via vacuum truck. Once vacuuming occurred the system's measured rates were 3000, 2460, 1418, 2077, 1864, and 2230 in/hr with the GWT fluctuating within a range of about 2.5 to 6.5 feet below the bottom of the system. The system was vacuumed once more and the measured rate after about 6 months of natural loaded sediment accumulation and the final measured rate was 1288 in/hr.

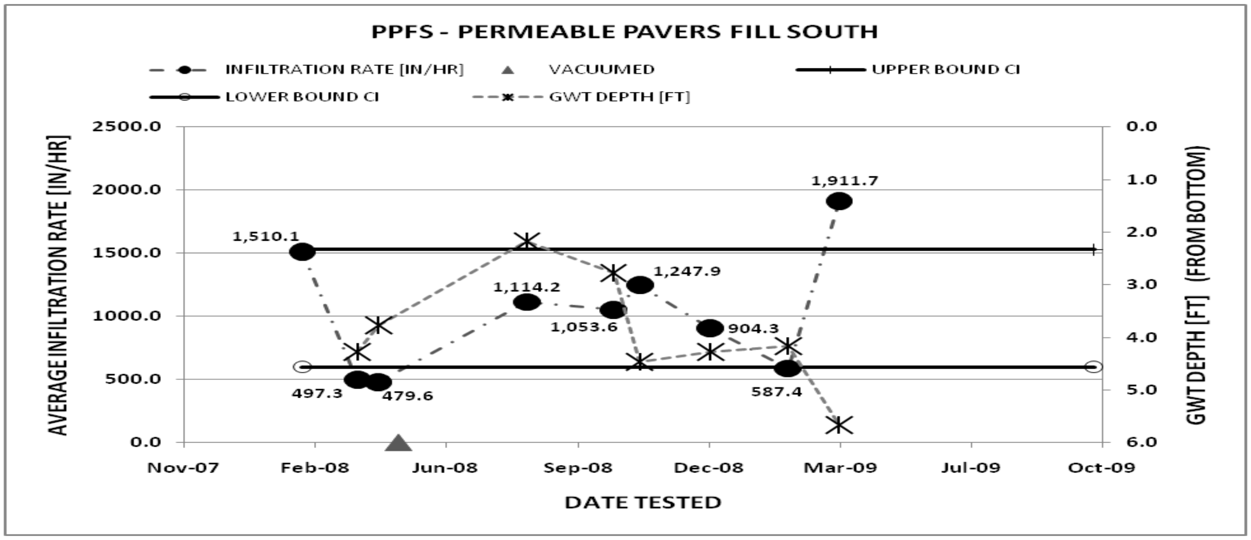


Figure 35: Infiltration Rate (ERIK) Results for the Permeable Pavers Fill South Section Infiltrometer

The southern infiltrometer started out infiltrating at 1510 in/hr during initial testing and was reduced down to 497.3 and 479.6 in/hr by naturally occurring clogging (see Figure 35 above). The pad was then vacuumed and the measured rates were restored to values of 1114, 1054, 1248, 587.4, and finally 1912 in/hr throughout the remaining 10 months of testing. The reason for the highest measured infiltration rate at the end of the test period may have been caused by it being the time where the GWT was at its greatest depth of more than feet below the system.

Sustainable Storage Evaluation Results

Sustainable Storage Evaluation

The results of testing the porosities of the individual component materials are tabulated in Table 1 below. The total porosity of the surface layer including the bricks with #89 limerock filled in the joints measured in the aquarium is 13.7%. This number represents the porosity of the surface layer after the materials were oven dried, while the rest of the tests were conducted without oven drying the materials thus can be considered effective porosity. There is a significant difference in the total and effective porosities measured (almost a 50% reduction) as reported in the table the average effective porosity value is only 7.7%. Next, the pavers were loaded with sandy sediments to induce clogging of the surface pores which resulted in an average effective loaded porosity of 4.0%. This reduction is due partially due to the fact that some of the volume of sediment particles is now occupying the once empty pore spaces but also due to a larger number of smaller pore sizes that retain a larger volume of moisture in the once air filled pores at the time the pores were larger enough so gravity alone could more easily drain the water from the pore. It was observed during the testing that much of the sediments seemed to be trapped near the surface and only penetrated about half the distance downward. This observation agrees with the data that shows that only about half of the empty pore spaces were filled with sediments. After vacuuming the surfaces much of the sediment clogged filler stones were extracted by the suction force and were needed to be replaced with clean filler stone by sweeping back into the joints between the bricks. Porosity measurements were taken after replacing the filler stones and an average effective porosity of 7.8% has been recorded. This result confirms that the clogging sediments did in fact stay near the top half of the total pore spaces and were able to be effectively removed by vacuuming the surfaces of the bricks, restoring the storage within the surface layer back to the original condition. This proves the surface layer to be effective at filtering sandy sediments and preventing them from entering the sub-layers, protecting them from any reduction in storage capacity.

The sub-base layer materials were testing using the small scale ½ gallon containers were tested for total (over dried) and effective (gravitational drainage) porosities. The #89 stone (pea rock) provided an average total porosity of 41.5% and an effective porosity of 36.5%. The larger #57 stone gave values of 47.1% total and 41.4% effective porosity averages in the small containers. The #4 limerock was measured at 50.4% total porosity and an effective porosity value of 45.2% as measured in the small containers. The #4 granite stones provided average measured total porosity of 45.2% while effective porosity was 43.6%, which one would expect the total and effective to be more similar in the granite, a much less porous stone that the limerock. It should be noted that the more porous stones will retain moisture and have a greater effect between the total and effective porosity values. Since it was observed that there were large voids near the aggregates and the sidewalls of the containers the #4 stones were retested in the larger glass aquarium to check the double values where this possible error could be reduced. When tested in the aquarium the total porosity of the #4 aggregates were measured to be slightly lower values (44.0% instead of 50.4%) for the limerock and (43.0% instead of 45.2%) for the granite materials, proving that the smaller containers with larger than normal gaps between the aggregates and sidewalls had a non-conservative effect on the porosity measurements.

Table 1: Individual Component Material Porosity

Oldcastle Pavers PP	AVERAGE MEASURED POROSITY [%]			
MATERIAL TYPE	Total	Effective	LOADED	VACUUMED
Oldcastle Pavers PP	13.7	7.7	4	7.8
(#89) Pea rock	41.5	36.5		
(#57) Crushed concrete	47.1	41.4		
(#4) Limerock	50.4	45.2		
#4 Limerock *tested in Aquarium	44.0			
(#4) Granite	45.2	43.6		
#4 Granite *tested in Aquarium	43.0			
Bold&Gold	38.9	15.2		

Presented below in Figure 36 is the results for testing the amount of water storage within the complete cross section (using the 55 gallon barrels) of the Oldcastle AquaFlow permeable pavers including the surface layer, bedding layer, and stone reservoir sub-base layers. The first five initial tests were conducted without introducing any sediments to the systems to investigate the total or maximum storage available.

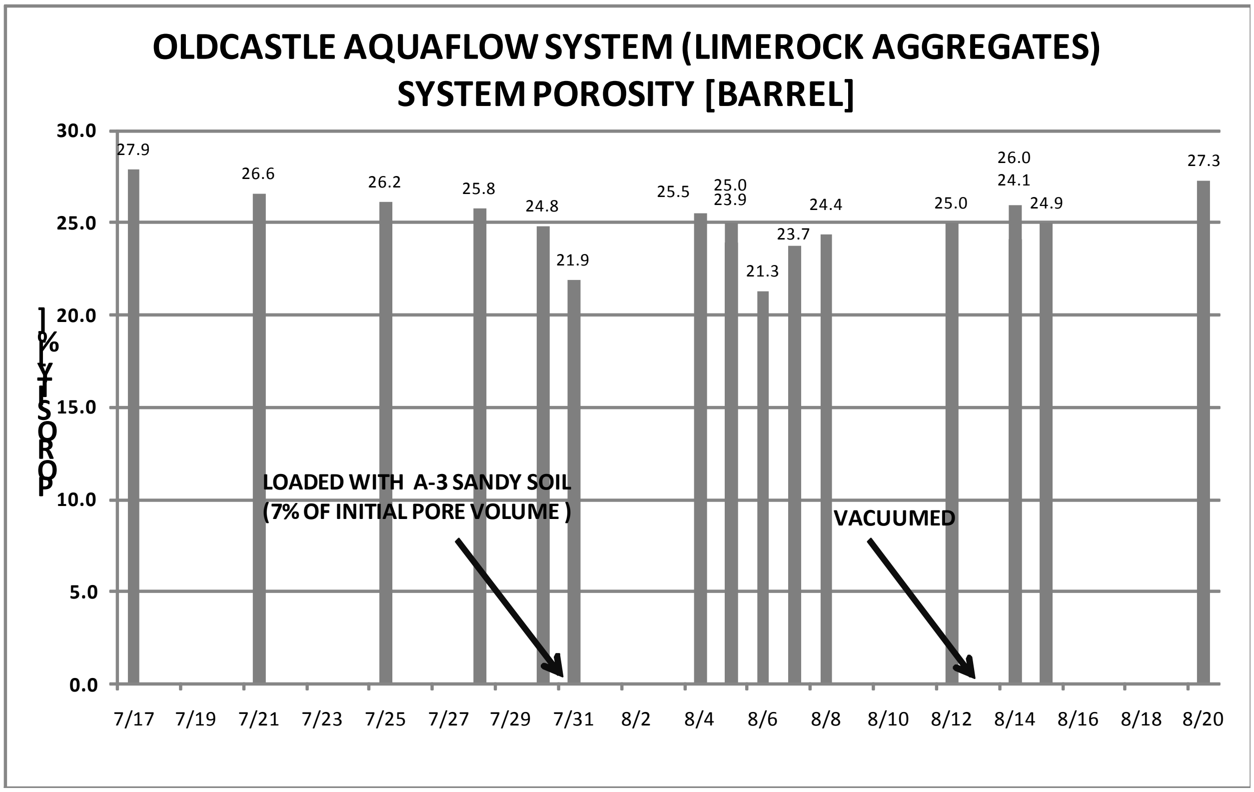


Figure 36: System porosity results using 55 gallon barrels (#4 granite)

The first value 27.9% storage represents the total porosity of the system since the materials were oven dried before placement into the barrels. Due to the large pore sizes of the aggregates, the next four values representing the storage within the system after only a few days of drainage did not decrease much as the storage volume was able to be recovered. Only the micropores in the aggregates and near the contact points, and dead-end pores small enough to prevent gravity from transmitting this water downward due to capillary pressure exceeding the force of gravity in such a small pore size are able to retain some of the water. These next four tests represent the effective porosity (26.6% - 28.8%) of the system in which can be expected of the in-situ pavement that is not oven dried to remove the residual water in the micropores. The sixth test is conducted after loading with 7% of the initial pore volume measured by the initial test using A-3 soil on the surface of the paver bricks and washing into the pores while simultaneously pumping the infiltrated water out of the well pipe from the bottom of the stone reservoir (see Figure 37 below).

Figure 37: Washing loaded sediments into pores while pumping infiltrated water out through well pipe

After the loading takes place the porosity reduced down to 21.9% as the effective porosity when the system was tested after only one day of drainage, while the next five tests indicate only a slight decrease in the measured porosity when there were more days allowed for draining. This indicates that the most of the sediments remained near the surface and only occupied a small portion of the total voids of the system. After the sediments were vacuumed from the surface and testing the last three tests measured values slightly greater than the loaded and almost back to the initial five tests indicating that the sediments did in fact remain near the surface pores where vacuuming is effective in removing and restoring the capacity of the system's storage.

Figure 38 below presents the results of the same cross section but using granite #4 aggregates instead of limerock.

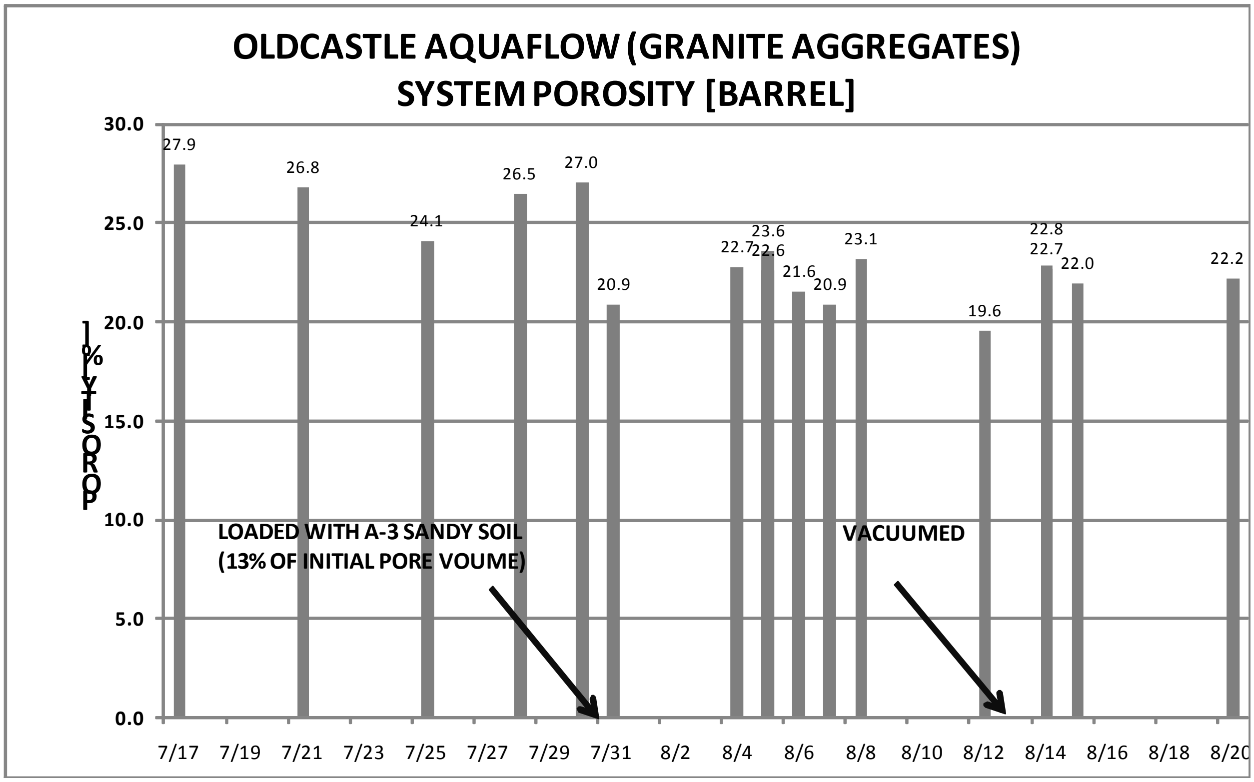


Figure 38: System porosity results using 55 gallon barrels (#4 limerock)

The initial testing results are similar with the first value measured at 27.9% with the next four tests ranging from 24.1% - 27.0% before any sediments were introduced to the surface. By loading with 13% of the initial total porosity measured using A-3 soils, the available percentage of voids able to store water was reduced to 20.9% after only a day of draining and reached a maximum of about 23% after several days of draining. By vacuuming the surface the measured porosity remained at about 23%, indicating that vacuuming was not able to recover the very small amount of sediments that got into some of the initially open pores. This may have been due to the smoother surface of the granite aggregates that allow some of the sediments to fall deeper into the systems' layers where the vacuum was ineffective at removing.

The theoretical porosity of the entire system was calculated given the total and effective porosity values of the individual components and then compared to the actual systems constructed in the 55 gallon barrels. The theoretical storage using a weighted porosity of the entire systems were calculated by adding the porosity values by the depths of each layer and then totaled to represent storage within the entire system. The theoretical calculation of the system's (total) storage with the #4 limerock was calculated at 6.4 inches of the entire 16 inch cross section using the total porosity values. When comparing to the actual barrel storage using measured total porosity values the entire 16 inch deep cross section's storage is only 4.5 inches. The same calculation using the limerock aggregates effective porosity values produced a theoretical storage of 5.2 inches within the 16 inch cross section, whereas the actual barrel tests measured storage of 4.1 inches, which proves that there is some mixing of the layers which causes a slight decrease in the storage voids of the complete system.

In conducting the same analysis of the systems with the #4 granite aggregate instead of the #4 limerock the theoretical total storage in the system is calculated to be 6.2 inches with the actual barrel measurement of 4.5 inches. The effective theoretical storage in this system is calculated at 5.1 inches while the actual barrel storage is measured at 4.2 inches. It can be concluded that the actual total porosity of a complete system is about, on the average 28.5% less than if calculated theoretically and the actual effective porosity is about, on the average 19.3% less than calculated theoretically.

Water Quality Results

Typical stormwater and surface water nutrient concentrations in several locations around the greater Orlando area are shown in Table 2 below. It can be seen that nutrient concentrations are low for all parameters listed. The reason for being concerned with nutrients in stormwater is not due to the concentrations measured but the significant volumes of water generated. As expected, the pH values are near neutral and there is buffering capacity available to help keep the pH in the neutral range. Nutrient concentrations of water collected from both the B&G systems and the Fill systems did not vary significantly from these values except total nitrogen for the B&G systems.

All the intended water quality parameters were analyzed and an Analysis of Variance (ANOVA) test was performed (α=0.05) to compare the nutrient levels in the different systems. Several parameters lacked consistency and are not shown here, namely: alkalinity, turbidity, and total solids. It should be noted that these parameters were well within typical stormwater ranges shown in Table 2. Examination of the replicate samples for both the Bold&Gold^{TM} and fill systems showed no significant difference (α=0.05) for any of the water quality parameters and therefore were averaged to produce more readable graphs.

Table 2: Typical Nutrient Concentrations for Surface Water and Stormwater for the Orlando Area

Parameter	Local lake median value(1)	Local Stormwater average(2)	Local Stormwater Standard Deviation(2)	South Eastern Stormwater median value(3)
Ortho Phosphorus (OP) [mg/L as PO_4^{3-}]	0.012	-	-	0.34
Total Phosphorus (TP) [mg/L as PO_4^{3-}]	0.117	0.15	0.07	0.68
Total Nitrogen (TN) [mg/L]	0.87	0.79	0.18	-
Nitrate (NO3) [mg/L]	0.026	-	-	0.6±
Ammonia (NH4) [mg/L]	0.02	-	-	0.5
TSS [mg/L]	4.9	-	-	42
TDS [mg/L]	122	76	40	74
PH	7.8	6.9	0.2	7.3
Alkalinity [mg/L as CaCO3]	45.9	54₣	20	38.9

www.cityoforlando.net/public_works/stormwater/
Wanielista & Yousef (1993)
Pitt et. al., (2004)
¤ Monthly average

± Nitrite and Nitrate
₣ Alkalinity given as HCO_3^-
¥ Based on 2004 data

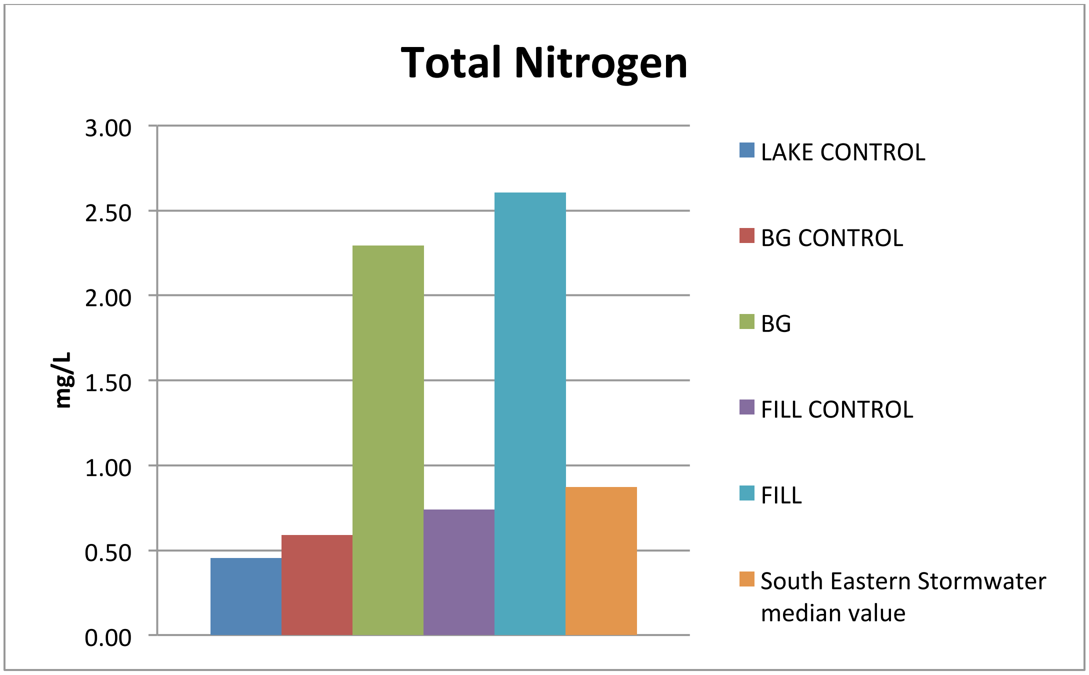


Figure 39: Total Nitrogen Results

Figure 39 shows the total nitrogen results for all the systems tested, the stormwater pond water used to simulate the rain events, and the south eastern stormwater median value. After analysis of the results it was shown that the Bold&Gold^{TM} system was not significantly different (α=0.05) from the fill system. This shows that the addition of the sub-base pollution control layer has no significant effect on total nitrogen concentration. It was observed that all the systems tested had higher concentrations than the stormwater used to simulate the rain event. This was likely due to the fact that local soil was used to simulate the sub-base and likely leached nutrients, however it should be noted that both the fill control and B&G control systems were all below the south eastern stormwater median value for total nitrogen. The systems that had the Aqua Bric permeable brick pavers were observed to have a significantly higher concentration of total nitrogen which might be due to the composition of the bricks or the conditions where the bricks were stored just to name a few.

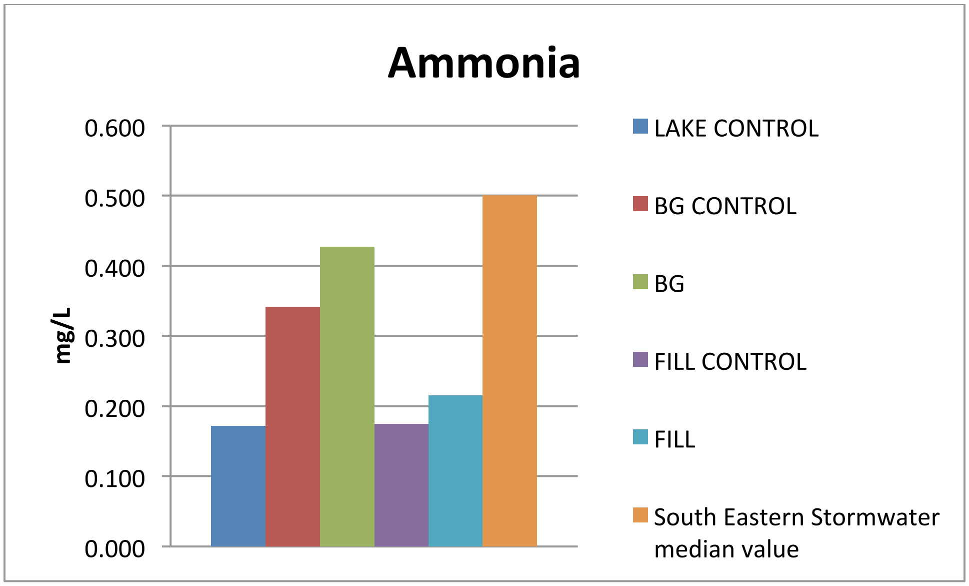


Figure 40: Ammonia Results

Figure 40 shows the ammonia nitrogen concentration results for all the systems tested, the stormwater pond water used to simulate the rain events, and the south eastern stormwater median value. After analysis of the results it was shown that the Bold&Gold^{TM} system was significantly different (α=0.05) from the fill system. This shows that the addition of the sub-base pollution control layer increased the ammonia concentration compared to the fill system. It should be noted however, that both systems had very low ammonia concentrations that were lower than 0.5 mg/L which is the south eastern stormwater median value. This increase is not viewed as significant and was likely a result of chemical conversions that took place in the soil matrix or the precision of the testing methods used.

It was observed that all the systems tested had higher ammonia concentrations than the stormwater used to simulate the rain event. This was likely due to the fact that local soil was used to simulate the sub-base and likely leached nutrients. Similar to the total nitrogen results, the systems that had the Aqua Bric permeable brick pavers were observed to have a higher concentration of ammonia. While this was not statistically significant (α=0.05), the trend was somewhat consistent. The higher ammonia concentration may be a result of the composition of the bricks, the conditions where the bricks were stored, or the level of precision of the test methods to name a few.

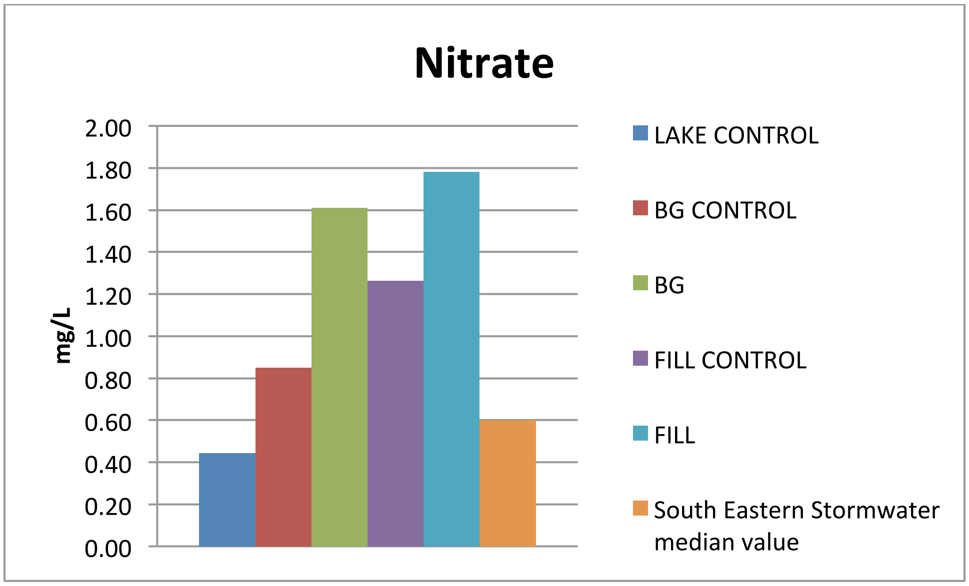


Figure 41: Nitrate Results

Figure 41 shows the nitrate nitrogen concentration results for all the systems tested, the stormwater pond water used to simulate the rain events, and the south eastern stormwater median value. After analysis of the results it was shown that none of the system were significantly different (α=0.05) from each other. This shows that the addition of the sub-base pollution control layer had no significant effect on the nitrate concentration. It should be noted however, that the B&G control system and the B&G system were lower than the fill control system and the fill system respectively. This is not viewed as significant and was likely a result of chemical conversions that took place in the soil matrix or the precision of the test method used.

It was observed that all the systems tested had higher nitrate concentrations than the stormwater used to simulate the rain event and the south eastern stormwater median value. This was likely due to the fact that local soil was used to simulate the sub-base and likely leached nutrients. Similar to the total nitrogen results, the systems that had the Aqua Bric permeable brick pavers were observed to have a higher concentration of ammonia. While this was not statistically significant (α=0.05), the trend was somewhat consistent. The higher nitrate concentration may be a result of the composition of the bricks, the conditions where the bricks were stored, or the level of precision of the testing methods to name a few.

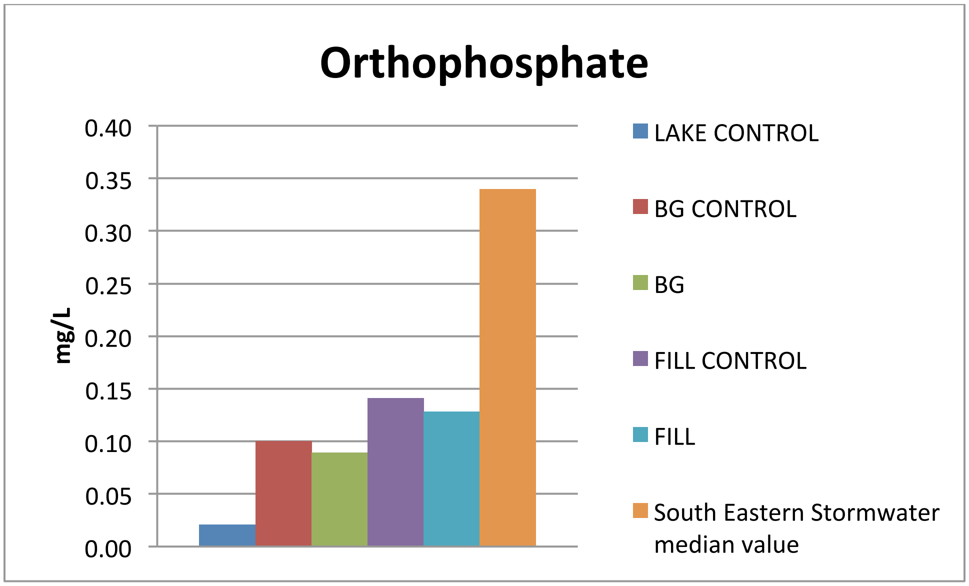


Figure 42: Ortho-Phosphate Results

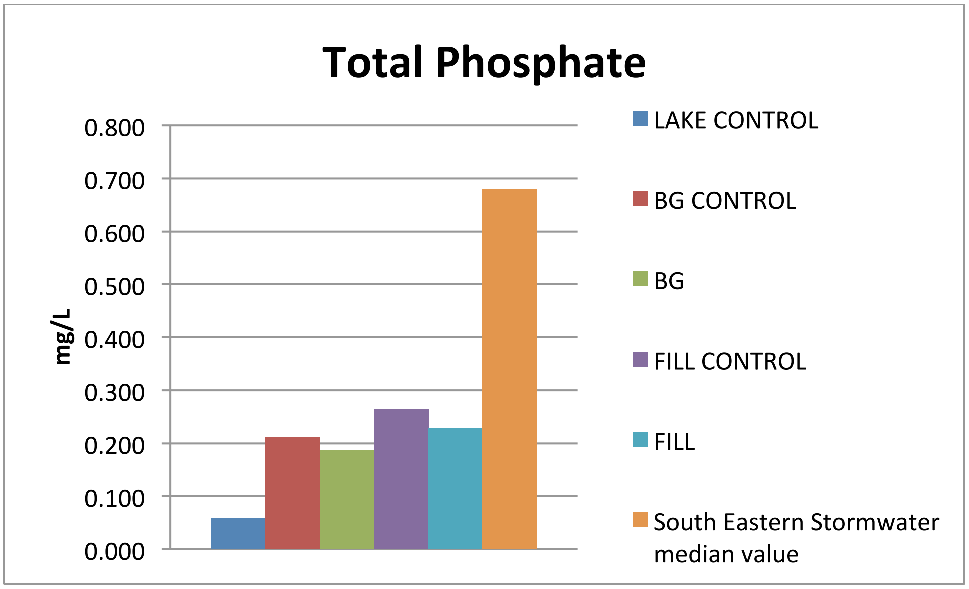


Figure 43: Total Phosphate Results

Figures 42 and 43 show the ortho- and total phosphate concentration results, respectively, for all the systems tested, the stormwater pond water used to simulate the rain event, and the south eastern stormwater median value. After analysis of the results it was shown that none of the systems were significantly different (α=0.05) from each other. This shows that the addition of the sub-base pollution control layer had no significant effect on the ortho- and total phosphate concentrations compared to the fill system. It should be noted however, that both systems had very low ortho- and total phosphate concentrations that were lower than 0.34 mg/L for ortho-phosphate and 0.68 mg/L for total phosphate which are the south eastern stormwater median values. None of the tested systems ortho- and total phosphate concentrations are significant and do not pose any substantial risk to receiving water bodies.

It was observed that all the systems tested had higher ortho- and total phosphate concentrations than the stormwater used to simulate the rain event. Again, this was likely due to the fact that local soil was used to simulate the sub-base and likely leached nutrients. It should be noted that the B&G control system and the B&G system had lower ortho- and total phosphate concentrations than the Fill control and Fill systems respectively. This was not significant however and due to the low concentrations no significant reduction should be expected.

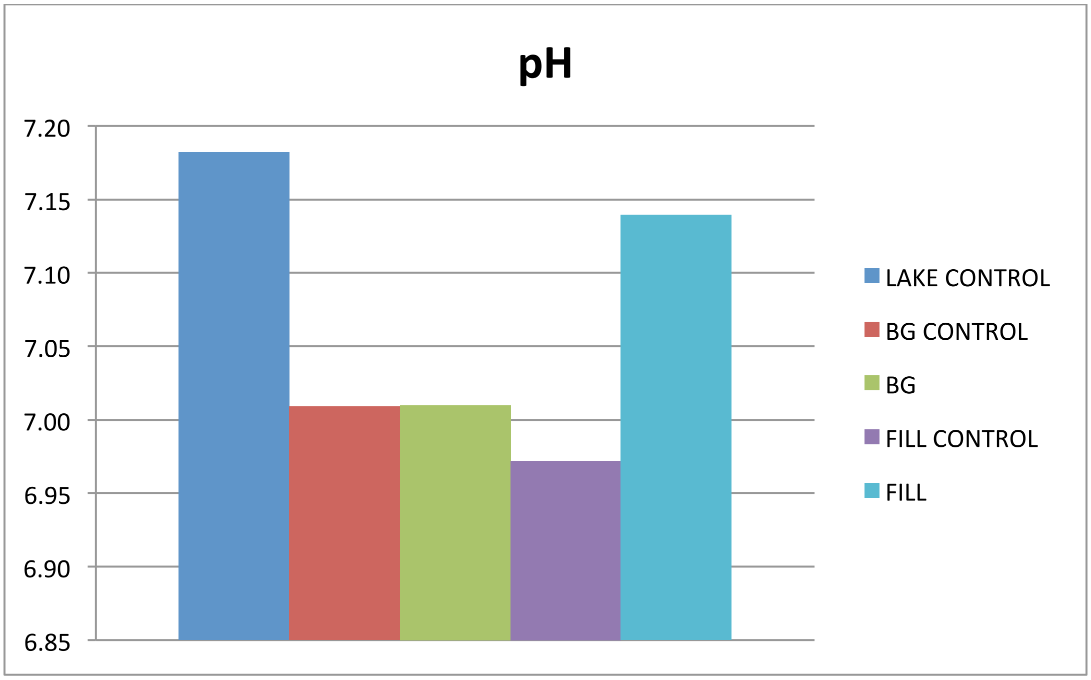


Figure 44: pH Results

Figure 44 shows the pH of the water that infiltrated through the systems tested as well as the stormwater used to simulate the rain events. It was observed that all systems had a neutral pH. Data collected but not presented here on alkalinity shows that the filtrated water has sufficient buffering capacity.

Strength Results

FWD test results are not realistic for these types of pavements and are not presented. This is due to the fact that these are not monolithic systems and thus wave propagation through the system is not able to reliably predict the strength properties.

CONCLUSIONS AND OBSERVATIONS

General Observations

Observations made during the installation of the pavement sections include some issues with the acquisition of the three different sized aggregates (#89 stone, #57 stone, and #4 stone) required for construction of the sub base layers. Although the #89 stone is needed for the bedding layer to provide a flat surface to lay the bricks, and a larger aggregate is used to provide more strength to the system, it may not be necessary to need both the #57 stone and #4 stone in the lower layers. It may be beneficial to only use one layer (ie. #57 stone) for the bottom layer in terms of the constructability of the systems and ease of acquiring the materials separately. The materials had to be brought in separately to prevent mixing and due to availability both granite and limerock was required to make up the layers. However the materials were brought in by dumpster trucks which allowed for easy placement of the aggregates into place without any need to store the materials on site. Also by using truck to dump materials directly into place, limited machinery was needed to place the aggregates into their finally placement where the pads were located.

There was a moderate amount of small localized settling noticed throughout the sections that was caused by heavy vehicles (semi-trucks, dump trucks, heavy construction equipment, etc.) soon after installation, but was easily fixed by pulling up the bricks and adding aggregates underneath with compaction before returning bricks back into place. Once these small repairs were made the system remained flat with no further settlement occurring even after being subjected to the heavy vehicular traffic. The strength of the bricks were sufficient to resist any raveling or breaking apart of the surface layer that was noticed in some of the aggregate-binder pavement surfaces that were also tested under the same conditions.

Infiltration Rates

The determination of infiltration rate was conducted for normal operations, intentional sediment loading, and rejuvenation of the system. During the study period, the ERIK device was used 83 times and 97.6% of the runs provided values above the minimum of 2.0 in/hr for all three sections measured by the north and south infiltrometers. For the Rejuvenation section, 94.7% of the results, for Bold&Gold 100%, and for the Fill section, 100% of results showed values greater than or equal to 2.0 in/hr for the north and south infiltrometers. Regardless of the excessive amount limerock fines and sandy A-3 soils spread about, washed in, and compacted into the surface pores, the lowest infiltration rates measured by the north and south infiltrometers was 1.3 and 1.9 in/hr respectively for the Rejuvenation section. These values can be expected to be representative of a field application that has undergone excessive sediment buildup on the surface of these pervious pavements either from an accidental spill or erosion and sediment deposition onto the surfaces over a long period of time.

The results from this study indicate that permeable interlocking concrete pavement systems will perform as intended, even in a worst case scenario excessive sediment loading conditions and high ground water table levels. Maintenance by the use of a vacuum sweeper truck will improve the infiltration rate when used in during a dry or saturated wet surface condition for sandy sediments and will work best when the surface is wet and saturated for all sediment types, especially fine-grained cohesive sediments such as the crushed limerock fines.

Under normal sediment loading conditions it is expected that the Oldcastle Aquaflow systems will perform well above 2 in/hr. Under intense, heavy sediment loading of fine grained sediments the rates may fall below 1.5 in/hr (1.3 in/hr the lowest measured), but can be rejuvenated by the use of a standard vacuum sweeper truck back up to above 1.5 in/hr (5.1 in/hr the lowest). The amount of sediment loading depends on the site location and its exposure to sediments being brought onto the pavement's surface by natural (wind and water laid sediments) or un-natural causes (ie. Tire tracking of sediments, spills, etc.)

It should be noted that the vacuum suction strength is sufficient to not only remove the clogging sediments in the surface pores, but actually lift the filler aggregate up and out of the joints between the bricks. This observation helped to qualitatively ensure the effectiveness of the vacuuming process, but indicated that loosely placed filler stone must be replaced after each vacuuming regime is completed. This may involve quite a bit of labor for instances where frequent vacuuming maintenance is required.

This permeable pavement system is recommended as an effective infiltration BMP that will perform well throughout its service life. If the infiltration performance is degraded due to sediment accumulation mainly in the surface pores enabling standard vacuum trucks to successfully improve its capability to infiltrate stormwater above 2.0 in/hr stated as the minimum rate recommended rate for this type of system in the statewide draft stormwater rule.

Sustainable Storage

After multiple porosity tests were conducted on all the individual components that make up the entire pavement cross sections and the actual constructed systems during conditions including oven dried samples, gravity drained samples, loaded with sediments, and after the sediments have been vacuumed from the top surfaces conclusions can be made on the sustainable storage within each system. It was found that the actual storage within a constructed system can be less than the calculated theoretical storage found by measuring each individual component.

To be conservative, the actual measured values of the complete systems should be used to identify what the storage is in a desired section, as the amount of mixing at the interfaces of each layer will depend on what materials are used. With this, the amount of storage in the entire cross section of the permeable paver systems is about 20%.

Water Quality

This study examined the quality of water that infiltrates through two permeable paver systems, a system containing a Bold&Gold^{TM} pollution control layer and a system without. In the results section above, it was observed that the quality of water that infiltrates through these systems is typical of concentrations measured in stormwater in the Orlando Florida area. It was shown that for the conditions examined, the use of a Bold&Gold^{TM} pollution control media layer is not justified. While stormwater is typically treated prior to discharge to a surface water body these systems allow the stormwater to infiltrate onsite and therefore do not discharge to a surface water body. This implies that when assessing the water quality benefit of these systems, reduction in water volume needs to be taken into account.

Based on the results of this study the nutrient mass reduction could be determined by calculating the volume retained by these systems and event mean concentrations. This would give the pollutant mass retained within the pervious system and not discharged into a receiving water body or stormwater pond. An example problem is presented below to show this calculation.

Sample Calculations for Quantifying Water Quality Improvement

For this example consider a 1-acre pervious parking lot using the Aqua Bric permeable paver system as the specified product. The cross section for this system consists of a 5 inch deep layer of # 4 granite stone, a 4 inch deep layer of # 57 limerock, a 2 inch deep layer of # 89 stone with 3 1/8 inches of Aqua Bric permeable pavers on top. There is a non-woven filter fabric separating the parent earth soil from the rock layer. The parking lot is located in Orlando Florida and a 25 year design storm is to be used. The TN and TP mass reduction expected from this site for a 25 year storm event will be determined. The TN and TP concentrations used are those presented in Table 2 above for average Orlando stormwater concentration and median southeastern United States stormwater concentration, respectively. The TN concentration is shown as 0.79 mg/L as N and the TP concentration is shown as 0.68 mg/L as PO_4^{3-}.

Using the pervious pavement water management analysis model located on the Stormwater Management Academy website (www.stormwater.ucf.edu), a runoff coefficient for this system is determined as 0.65. Using the rational method which states that $Q = CiA$, a rainfall excess value can be determined. First the rainfall intensity and duration that has a 25 year return period needs to be determined from the Orlando Florida intensity, duration, and frequency (IDF) curve. Based on this IDF curve the design intensity is 8.4 in/hr for a duration of 10 minutes. Using the rational method, it is determined that the rainfall excess flow rate is 5.46 cfs and multiplying that by the 10 minute duration gives a runoff volume of 3,276 cubic feet, or 92,766 liters. Therefore, the TN mass leaving the system is 73.3 grams and the TP mass leaving the system is 63.1 grams.

Now the mass leaving a typical impervious parking lot needs to be determined for comparison. Assuming a runoff coefficient of 0.95 for regular impervious asphalt the rainfall excess flow rate is 8.04 cfs and multiplying that by the 10 minute duration gives a runoff volume of 4,826 cubic feet, or 136,673 liters. Therefore, the TN mass leaving a typical impervious asphalt parking lot is 108 grams and the TP mass leaving the system is 92.9 grams. This shows that the Aqua Bric permeable paver system specified would have a TN mass reduction of 34.7 grams (32%) and a TP mass reduction of 29.8 grams (32%) for a one acre parking lot.

The above analysis and example problem shows that there is a water quality benefit to using the Aqua Bric permeable paver system. This benefit is only realized, however, through taking into account the volume reduction. The yearly TP and TN mass reduction has the potential to be much higher considering that more than 90% of the rainfall events in Orlando Florida are less than one inch, which would not generate any runoff.

Strength Evaluation

Strength of permeable pavers could not be determined in the field using the FWD test as this type of system is not monolithic.

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