Final Report

Pervious Pavements - Installation, Operations and Strength
Part 1: Pervious Concrete Systems

Work Performed for the Florida Department of Transportation

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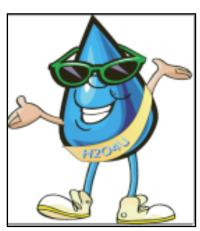

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16. Abstract

Pervious pavement systems are now being recognized as a best management practice by the Environmental Protection Agency and the state of Florida. The pervious concrete system 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. Pervious concrete pavement systems are able to perform well considering the high level of imposed sediment accumulation throughout the 22-month study period. Out of 119 tests conducted on these sections, only thirteen tests recorded rates below 2.0 in/hr. The pervious concrete pavement systems can be expected to perform above 2.0 in/hr under normal "light to medium" sediment accumulation conditions without any maintenance and the infiltration rate can fall below 2.0 in/hr if under intense "heavy" sediment loading. A standard vacuum sweeper truck to rates above 2.0 in/hr, however, can rejuvenate these systems. The compressive strength values for pervious concrete samples cored from the installation at the field laboratory ranged from 988 – 2429 psi while the compressive strength range of the 8 x 4 cast in place samples was in the range 364 – 1100 psi. The total porosity measured was around 32% while the effective sustainable porosity was found to be around 27%. Water quality results indicate increase in nitrogen, ammonia, total and ortho-phosphate but this could be attributed to the use of local soils for the sub-base, which likely leached nutrients.

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INTRODUCTION

Pervious 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 for the rapid passage of water through either its joints or porous structure and infiltration into the underlying soils. A number of these systems were 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 recycled automobile tire chips (used in construction of the surface layer), tire crumbs (used in blending of the pollution control media), and crushed concrete aggregates, can contribute to earning LEED^{TM} points. Pervious 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 asphaltic 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), a device developed at the Stormwater Management 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 analysis was completed using laboratory scale systems built in 55-gallon drums that simulated the full scale systems in the field. Strength analysis includes field investigations, which include pavement evaluation by means of the FDOT Falling Weight Deflectometer (FWD) equipment.

The primary goals for this research are as follows:

1. Evaluate long term infiltration rates and the reduction in these rates due to sediment clogging and effectiveness of rejuvenation using vacuum sweeping.
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 the rigid 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.

Pervious pavement systems offer designers and planners an effective tool for managing stormwater. These systems manage stormwater by increasing the rate and volume of stormwater infiltration and thus reduce the volume of runoff. By reducing runoff from pavement surfaces, a reduction in the mass of pollutants carried downstream by runoff water can be achieved thus minimizing non-point source pollution.

The pervious concrete system is designed to have enhanced pore sizes in the surface layer compared to conventional pavement types, encouraging flow of water through the material. Porous materials exhibit a filter function that is inversely related to the permeability function regarding sediment capture and water flow rate through the material. Once sediments are present on the surface they will tend to either become trapped near the surface or flow freely through the entire system. The advantage to sediments being trapped near the surface is the ease of removing these sediments with a vacuum force and also the protection of the sub-base layers suffering from a reduction of storage when the pores become filled with sediments. The disadvantage is that clogging (or reduced infiltration rate) right at the surface may prevent stormwater from entering the system before it becomes runoff and the storage below is un-used. The performance of pervious pavement 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. These sediments then get compacted into the pore throats near the surface by vehicles further reducing the rate of infiltration. The rate at which a pervious pavement system will infiltrate stormwater throughout its service life will change based on periodic sediment accumulation on the surface and maintenance performed.

This report investigates the changes in infiltration rates due to high levels of sediment 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 pervious concrete pavement systems. The new draft statewide stormwater rule in Florida suggests that the minimum vertical infiltration rate 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, pollution control sub-base layer, and finally the parent earth below the system 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 a worst case scenario of long term clogging. This is done to test the effectiveness of vacuum cleaning as a rejuvenation method for pervious pavement 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 these pervious pavement systems perform, 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 water bodies. Unlike pollution generated from a single, identifiable source like a factory, the pollutants in stormwater runoff may discharge from many points 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 & James, 1996). Historically, many have considered that once the stormwater was off the pavement surface and into the drainage structure the problem was solved and the "out of sight, out of mind" mentality was implored. 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. Traditional impervious 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 this increased velocity is the capacity of the stormwater to cause erosion, channel widening, sedimentation, flooding, and spreading of pollutants downstream. 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 cycles 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 sub-soils causing serious problems to the structure. The only sure way to keep water from accumulating in the structural section of the pavement is to drain it using a key feature, a layer of very high permeability (33 in/hr to 333 in/hr or even greater) material under the full width of traffic lanes which is suitable for good internal drainage of the systems to prevent this deterioration (Cedergren, 1994). U.S. pavements or “the world’s largest bath tubs” 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) that this shift away from infiltration reduces groundwater recharge, causes fluctuations in 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.

Pervious pavement systems can also function as parking areas in addition to on-site stormwater control (Dreelin, Fowler, & Roland, 2003). Smith (2005) compares permeable interlocking concrete pavements to infiltration 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 and Grobowiecki (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 interconnected porosity allows for good infiltration and geothermal properties that help in attenuation of pollutants. Additionally due to the porous nature of the pervious pavement systems trees are allowed the necessary air and water exchange allowing roots to grow naturally instead of uprooting in search of air and water, 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 pervious 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 stone reservoir/sub-base of the pervious pavement system is designed to store rainwater and allow it to percolate into sub-soils restoring the natural ground water table levels. 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 of 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. Structures should be able to be designed 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).

The strength of a pervious pavement system depends on compressive and flexural properties of the material along with the strength of the supporting underlying subgrade. As a result of its porous nature (no fines) to achieve high permeability, the compressive strength and flexural strength are both lower when compared to conventional concrete and asphalt pavements and these pavements are designed to carry lighter vehicular loads. This report also studies the strength parameters for pervious concrete as a pavement material and establishes the allowable traffic load and volume to provide some degree of confidence related to the strength and durability of pervious pavements.

Literature Review

This research is intended to meet the need by practitioners and researchers to quantify the performance of pervious/permeable pavement 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 reduce the amount of runoff from a pavements surface. Most of the research that has been previously completed on pervious/permeable pavement 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 in 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 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 in the slots or voids greatly influence 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 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 the 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). The 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 in 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).

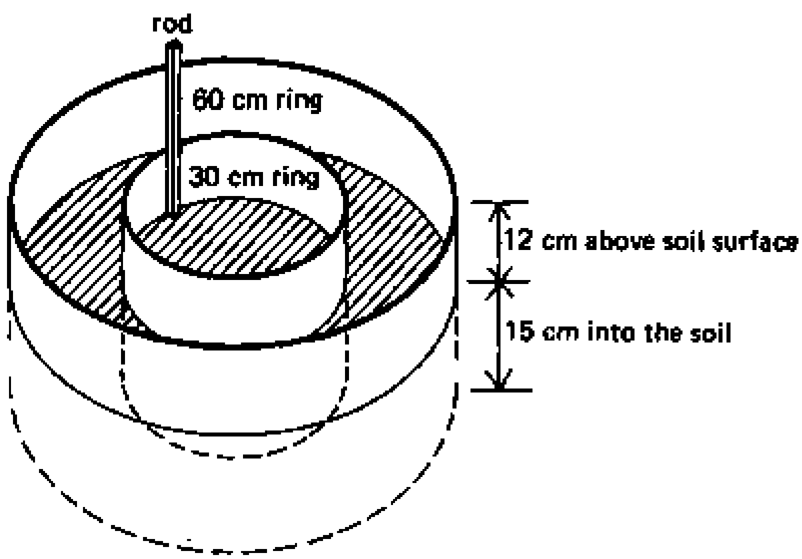
Field Infiltration Methods

Exfiltration field studies have been completed on infiltration monitoring of pervious/permeable pavement systems by measuring the exfiltration of 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 measuring the water depths in monitor wells, 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 subsoil 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 and the pavement properties as tests at the same site are not likely to give identical results. The results are recommended primarily for comparative use (ASTM D3385, 2009). The testing procedure is as described by the ASTM standard test method for infiltration rate of soils in the field using a double-ring infiltrometer. A typical double-ring infiltrometer set-up for field testing is shown in Figure 1 (Brouwer et. al. 1988).



(Courtesy: Brouwer, et al. 1988)

Figure 1: Double Ring Infiltrometer used for measuring infiltration into 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 pavement 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 a 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 that 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 with dust 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. The 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 measurements of infiltration rates of pervious/permeable pavement 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 using 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 pavement systems layered placement and compaction are subjected to 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, nondestructive, 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 giving 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. Figure 2 below, presents the plan and section views of the ERIK embedded ring as installed in a permeable pavement system while not conducting a test.

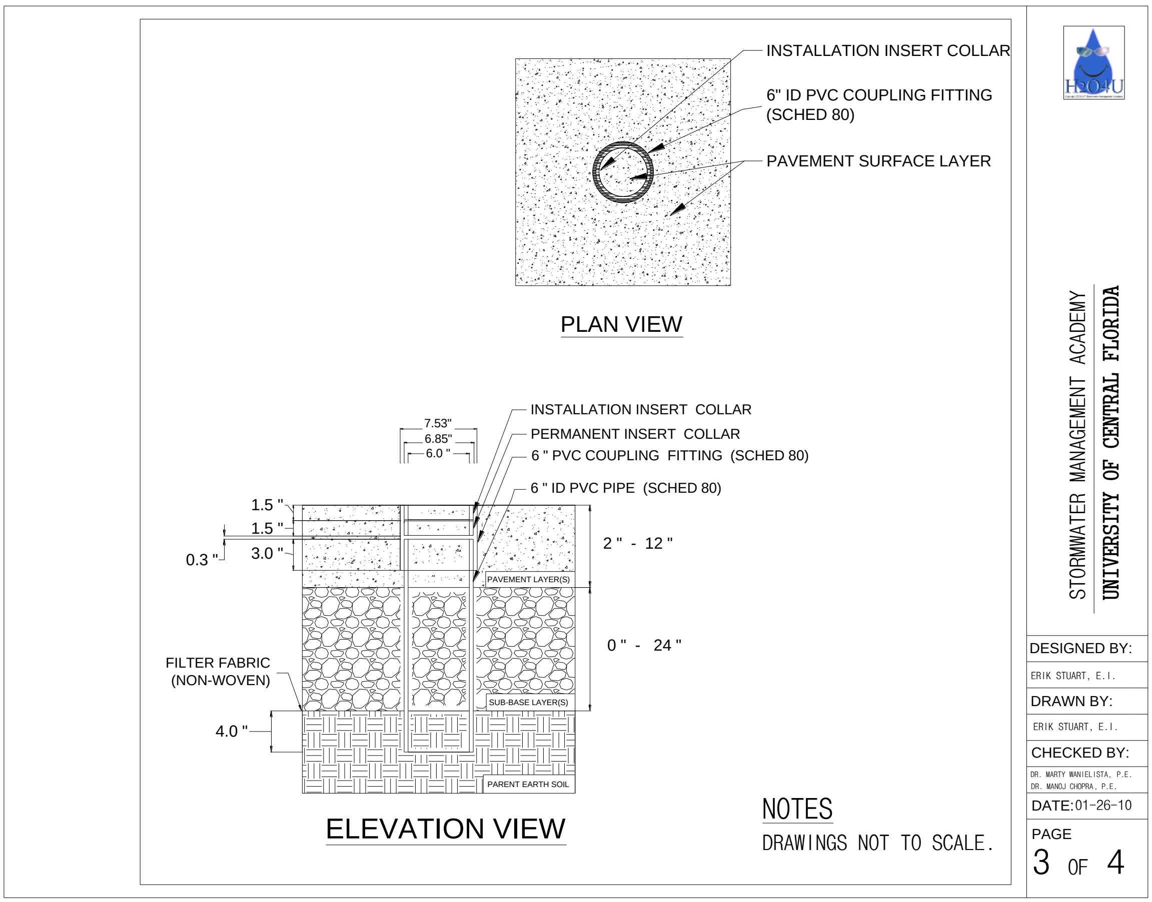


Figure 2: ERIK monitoring tube

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. 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 above 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.

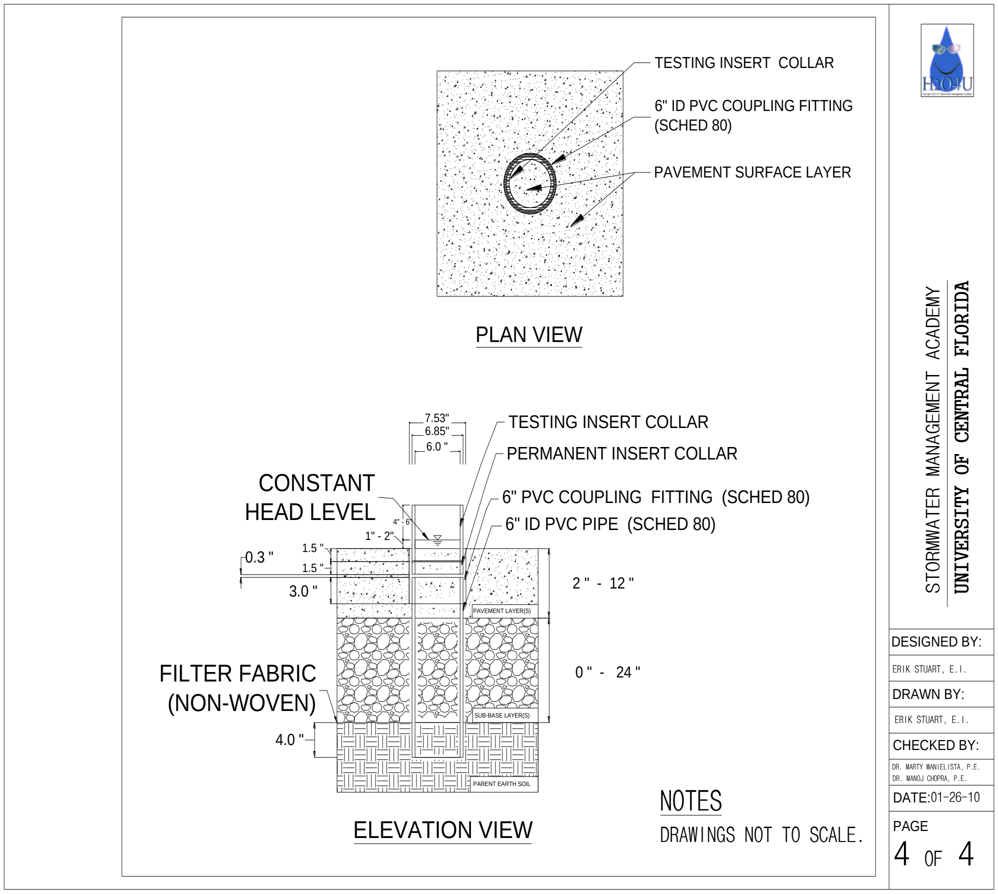


Figure 3: ERIK embedded ring installed

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 Figure 4 4.

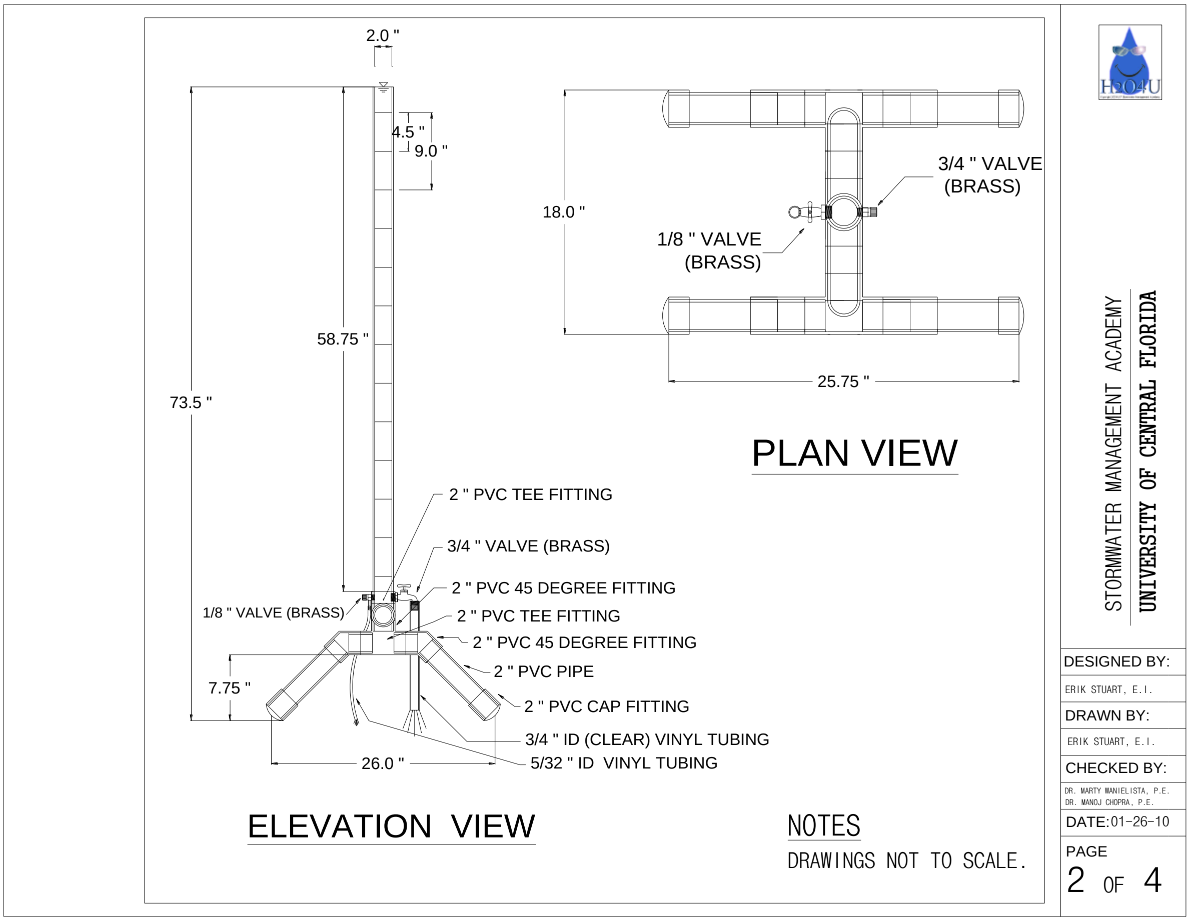


Figure 4: ERIK monitoring cylinder reservoir

Strength of Pervious Concrete Pavements

Ghafoori, et al. (1995b) performed laboratory study of compacted pervious concrete in which it is used as a pavement material. This research investigated the effects of compaction energy, consolidation techniques, mix ratios, curing types and testing conditions on the physical and engineering properties of pervious concrete. The study noted that with proper proportioning and compaction, the compressive strength of 28-day pervious concrete could reach 20.7 MPa (3,000 psi) or greater. Ghafoori, et al. (1995c) suggested the use of the two popular methods (AASHTO and PCA) for pavement thickness design for pervious concrete. This study presented the thickness requirements of pervious concrete pavements based on the engineering properties produced in the laboratory and also different traffic conditions and subgrade characteristics. Huang et al (2006) researched the effects of aggregate gradations on the permeability and mechanical properties of pervious concrete. This study concluded that aggregate gradation significantly affects the strength and permeability of pervious concrete mixtures. Rohne & Izevbekhai (2009) performed field testing on a pervious concrete test cell at Minnesota road testing facility. The results from this study showed that the deflection values for pervious concrete was higher than that of conventional concrete.

Chopra, et al. (2007a) presented results of compressive strength testing of pervious concrete cylinders. Different Aggregate – Cement (A/C) ratio and Water – Cement (W/C) ratios were studied. Pervious concrete with different mix proportions was tested and the average strength was found to be 1700 psi (11.7 MPa). It was noted that higher A/C ratios decreased strength while high W/C ratios decrease porosity. Lastly, Chopra et al. (2007b) presented the field performance assessment of a pervious concrete pavement used as a shoulder for an Interstate rest area parking lot that was monitored over a one year period for wear and water quality. It showed was no significant wear even when 500 axles per week loads were experienced. In addition, the water quality through the PC system was found to be equivalent to rainwater.

Pervious concrete pavements have some significant advantages. However, these systems also have some limitations. The compressive strength of pervious concrete is lower as compared to conventional concrete because of the lack of fines, pore spaces and weaker bond strength between the aggregates. (Yang, et al., 2003). The mode of failure of these pavements is by cracking or excessive raveling, thereby creating surface rutting and loose particles.

PAVEMENT INSTALLATION AND SETUP

Pervious concrete is installed covering a total area of 1500 square foot (ft^2) divided into three different sections: Rejuvenation (PCR), Bold & Gold™ (PCBG), and Fill (PCF). One section (PCR), is designated to receive intentional sediment loading, and the other two for sub-base material comparison under a more natural sediment loading condition. It should be noted that PCR has the same cross section as PCBG with Bold & Gold™ pollution control media utilized as the sub-base layer. PCBG and PCF differ by sub-base material choice intended for comparison of the Bold & Gold™ versus using the local site A-3 soils as the sub-base material. It is important to test the local sandy soils for use of the sub-base material to see if the cost savings could be justified by its performance.

All three sections are designed with six inches of pervious concrete as the surface layer, and ten inches of sub-base layer creating a sixteen inch total depth of sections. Installation of the sections is completed by first excavating the sixteen inches, form and pour concrete perimeter and partitioning curbing, place filter fabric to separate parent earth from bottom of sub-base, placing and compacting sub-base materials ten inches thick, and finally placing the pervious concrete layer over the sub-base. The pervious concrete is cured by covering the surface with plastic sheeting for one week after placement. Pervious pavements are designed to have a level surface, which is intended to eliminate cross slope on a typical impervious pavement or slab.

Layout

Installation of the PC sections starts with a site survey and layout of the proposed section dimensions and elevations. Grade stakes are driven into the ground around the perimeter of the sections to indicate the pavement top surface. The site was prepared by the excavation of a 16-

inch deep section (total depth of the cross sections) and compacted using a walk behind vibratory plate compactor to a level surface.

Curb Installation

Once the parent earth soils are prepared, a more detailed layout of the impervious concrete curbing is completed using stakes and string lines to delineate form board placement and eventually the edge of the curbs (see Figure 5 below).

Figure 5: Curbing formwork and concrete pour

Since it was expected to receive heavy vehicular loading from concrete trucks, semi-trucks, and heavy construction vehicles, reinforcing bars were placed near the middle of the six inch wide curbing, with one bar near the top and one near the bottom shown in Figure 6 below.

Figure 6: Rebar placement to reinforce curbing

The curbing dimensions are 6 inches wide by 16 inches deep, which extends down to the bottom the sub-base depth of the system onto the parent earth soil. Figure 7 below shows the importance of reinforcing the curbing.

Figure 7: Importance of reinforced curbing

Additionally, two impervious concrete pad sections are cast (monolithically) in conjunction with the perimeter curbing. One section is functioning as an apron onto the pervious pavement sections and the other as a turning pad at a location where frequent heavy vehicle turning movements are expected. Once the concrete cures the forms are removed and controlled expansion joints are cut into the surface using diamond tipped concrete cutting saw blades at predetermined locations. Curbing is completed before installing the pervious pavement systems to help restrain lateral migration of aggregates and materials placed during constructing of the systems. For pervious concrete installation the impervious concrete curbing served as a sturdy form for the placement of the material which relies on the form to provide a flat, level, and rigid structure for the ends of the screed and roller compactor to bear on in order to level the pervious concrete. If the forms are not sufficient to hold the weight of the screed or roller they may sag down and cause the finished slab to also sag and become unlevel (see Figure 8 below).

Figure 8: Screed and Roller compactor riding along curbing

Sub-base installation

A nonwoven filter fabric is now placed over the excavated and compacted surface area to separate the parent earth from a 10-inch thick sub-base material shown in Figure 9 below. The sub-base materials are then deposited on the filter fabric using skid steer loaders and compacted using the vibratory plate compactor to a level surface shown in Figures 10 and 11 below.

Figure 9: Filter Fabric Installation

Figure 10: Sub-base installation

Figure 11: Compacting Bold&Gold™ sub-base with vibratory plate compactor

PC Delivery/Discharge

The pervious concrete is installed by NRMCA (National Ready Mixed Concrete Association) certified contractors utilizing standard ready mixed concrete trucks to deliver the pervious concrete to the site. The trucks can deliver up to 7 cubic yards of pervious concrete per load and is discharged out of the truck through a metal chute located on the back of the concrete truck. It should be noted that pervious concrete cannot be pumped using standard concrete pumps, so the truck must be able to get close to the placement if discharged straight from the truck. Pervious concrete is non-plastic or non-flowable (have low workability) when compared to impervious concrete which makes it harder to slide down the chute unless there is steep slope on the chute, meaning the chute cannot be extended far from the truck. It was noticed that the concrete needed to be manually scrapped down and out of the chute once it got stuck and would not flow from the chute (see Figure 12 below).

Figure 12: Pervious concrete must be manually scraped out of chute

Concrete companies should consider placing small vibrators on the chutes to help encourage the concrete to slide down the chute without effort, and may enable extension chutes to be added on to increase the discharge distance from the back of the concrete truck. This may help to reduce or eliminate the need to re-grade tire ruts from the concrete truck before the placement of the pervious concrete (see Figure 13).

Figure 13: Tire rutting

PC Surface Layer

Immediately after placement of the pervious concrete on site, the concrete was spread out using hand tools such as shovels and rakes, to grade and level the surface for screeding. The screeding process involves the use of a straight edge placed on both ends of the perimeter curbing and dragged across the pervious concrete surface to strike off any excess pervious concrete above the form, refer to Figure 14 below.

Figure 14: Screeding of pervious concrete

A spacer (typically rebar or fern strip) is placed on top of the curbing for the screed to slide along so the post-screeded concrete is about ½ inch above the final surface elevation to allow for sufficient compaction. After screeding, spreading additional fresh pervious concrete using shovels filled any observed low spots. Then the spacers are removed and a roller compactor (typically a 8-12 inch diameter steel pipe) is applied by rolling back and forth over the surface until the intended surface elevation is attained, which levels with the top of the forms/curbs, see Figure 15.

Figure 15: Rolling compactor over surface for finishing

Controlled Expansion Joints

Controlled expansion joints are made during placement with a joint roller or “pizza cutter” type rolling tool that forms the joint in the fresh plastic pervious concrete shown in Figure 16 below. This is done instead of saw cutting expansion joints, which would introduce dust to the pervious concrete and potentially cause clogging issues.

Figure 16: "Pizza cutter" tool to place expansion joints

Curing

The pervious concrete was covered with an impermeable covering or moisture barrier, typically plastic sheeting to allow for proper curing for 7 days after placement shown in Figure 17 below. This is necessary due to the accelerated curing time since the open structure allows more cement paste to be exposed to evaporation. In this case, drainage path for expelling water from the center of even the larger paste bodies in pervious concrete is usually much smaller when compared to an impervious concrete slab where the drainage distance is half of the pavements thickness. By covering the pervious concrete with plastic the concrete cures by evaporating water at a slower and more balanced rate which produces a more evenly cured slab.

Figure 17: Plastic curing sheet installation

These steps were all done according to the manufacturer's specifications. Figure 18 depicts the final pavement system with the sections delineated by the curbing.

Figure 18: Final layout of pervious concrete sections

Setup for Infiltration and Rejuvenation

To simulate clogging that is expected on the pavement systems over a long period of time or during a sudden spill event, large amounts of sediments are intentionally spread over the surface of the pervious concrete system rejuvenation pad with a skid steer loader. The sediments are dumped on and then spread evenly about the surface of the pavements from the loader's bucket and spread evenly about the surface as shown in Figure 19 below.

Figure 19: Sediment loading

To simulate field clogging conditions where precipitation would have washed the sediments into the pore structure and then vehicles would have helped by compacting the sediments into the pore throats of the surface and cause vibrations that would agitate the sediments forcing them deeper into the pore structure of the system, a similar approach was taken and shown in Figure 20.

Figure 20: Compacting sediments into surface pores

The sediments were repeatedly washed into the surface pores using a hose and natural precipitation seen in Figure 21, and then driven on back and forth with the loader to create agitation and compaction of the lubricated soil particles into the pavement system.

Figure 21: Washing in sediments with garden hose

The above process is repeated for the limerock fines that were created by placing a layer of #57 limerock over the entire surface and driving on top of the rocks which crushes them until a fine dust is formed (see Figures 22 – 24).

Figure 22: Limerocks loaded over entire surface

Figure 23: Limerock fines left behind from crushing the #57 stones

Figure 24: Limerock fines ready to be vacuumed

The above steps were repeated until the surface pores were clogged to the point in which they would not accept the passage of any more sediment. ERIK testing continued on the clogged pavement systems shown in Figure 25.

Figure 25: Post sediment loading ERIK testing

The surfaces were then vacuum swept using a standard street sweeper vacuum truck that is available and already used to clean conventional impervious pavement surfaces. Vacuuming was conducted on the surfaces during three different conditions namely a dry condition, moist, and then a saturated condition. The vacuum appeared to work well on sandy sediments in a dry or saturated condition but only satisfactory in a moist condition. The small water supply nozzles located on the vacuum truck near the circular sweeper proved to only moisten the surfaces, which made the sediments, stick to the pavement, so a garden hose was used to deliver sufficient amount of water to saturate the surface. The finer grained soils seemed to only be capable of being removed if the surfaces were saturated with water, but not in either a dry or moist condition. Figures 26 – 33 shows the vacuuming operation of the A-3 soil and limerock dust in both dry and saturated conditions.

Figure 26: Dry vacuuming

Figure 27: Dry vacuuming over the ERIK device

Figure 28: Saturating the surface for wet vacuuming

Figure 29: Wet vacuuming over ERIK device

Figure 30: Pavement surface after wet vacuuming

Figure 31: Wet vacuuming of limerock fines

Figure 32: Surface after wet Vacuuming of limerock fines

Figure 33: Limerock fines removed from surface

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 in addition to 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.

After the surfaces are vacuumed ERIK testing indicates how well the clogging sediments are removed based on the increase in infiltration rates measured. Figures 34 and 35 show ERIK testing in progress after the surfaces have been vacuumed. Results of the infiltration tests before and after rejuvenation are presented in an upcoming chapter.

Figure 34: Post vacuum ERIK testing

Figure 35: Post vacuum ERIK testing close up

Sustainable Storage Evaluation Setup

Sustainable Void Space

The sustainable void spaces or pore volume that could hold 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 ½ gallon plastic containers with screw on lids were chosen for the bench scale testing shown in Figure 36.

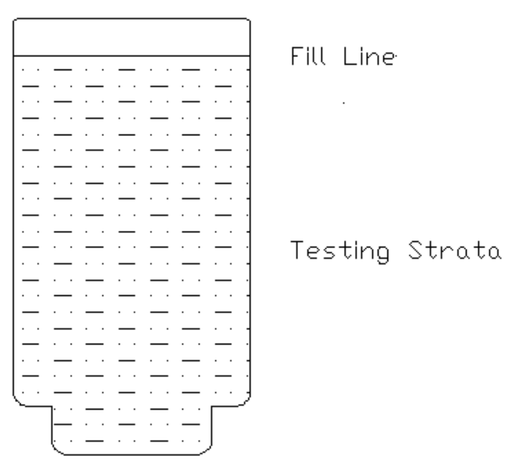


Figure 36: Half gallon container

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.

In accordance with this understanding, a variety of substrates were tested including: the pervious concrete and Bold&Gold™ pollution control media. 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, a digital camera and data sheet.

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”.

Figures 37 – 39 shows the containers used and how the sediments were loaded onto the surfaces.

Figure 37: Half Gallon container for component testing (pervious concrete)

Figure 38: Half Gallon container for component testing (Bold&Gold™)

Figure 39: Sediment being loaded in ½ gallon containers

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.
- 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 and allow gravity to drain samples (see Figure 40).
- 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 40: Half Gallon containers 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 field conditions.

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. The configuration is illustrated below in Figure 41.

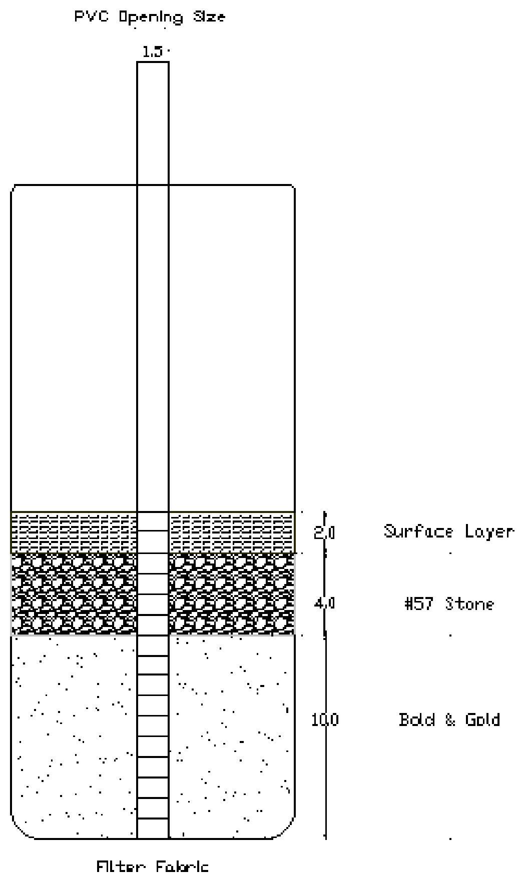


Figure 41: 55 Gallon Barrel for System testing

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. The water is then vacuumed out the 1-½ inch PVC pipe. Once initial testing is completed the surfaces inside the barrels are loaded with sediments, compacted, and then washed into the surface pores, shown in Figures 42 – 44 below.

Figure 42: Sediments being loaded on the surface and compacted into pores

Figure 43: Sediments being washed into the surface pores

Figure 44: Sediments loaded onto the surface of the pervious concrete

After porosity measurements of the loaded barrels are complete the surface is vacuumed and then retested. Figure 45 below shows the vacuumed surface of the pervious concrete.

Figure 45: Surface after vacuuming

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}:

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

Therefore:

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

Water Quality Setup

Restoring the natural hydrologic cycle using pervious pavement 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 Pervious Concrete. 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 Portland Cement Pervious Concrete. Due to many complications in the field, barrels were constructed to isolate variables and examine the quality of water that infiltrates through the Pervious Concrete system. The potential water quality benefit of adding a Bold&Gold^{TM} pollution control media layer was also examined. Between November 9th and December 15th, four 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.

A total of eight test barrels were constructed to isolate the variables of interest, the effect of Pervious Concrete 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 layer and four constructed without, labeled B&G and Fill respectively. The pervious concrete was poured in all but two barrels in the same way as it was installed in the field. The two barrels without Pervious Concrete 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 Pervious Pavement system and the Fill Pervious Pavement 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. Portland cement pervious concrete
4. Non-woven filter fabric
5. Eight 55 gallon drums
6. Eight valves
7. 17 one liter sample jars
8. Nine 5 gallon buckets
9. Watering can

Preparation

At the beginning of the test series, the barrels were 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 mesh 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. Bold&Gold™ pollution control media was then poured into the four B&G system barrels and compacted to a depth of 4 inches. Lastly, the pervious concrete was poured into all the B&G and Fill system barrels except the control barrels to a depth of 6 inches.

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 between November 9th and December 15th. 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

Laboratory Testing

Cylinders and beams used for compressive and flexural strength testing are made for one time use only. Pervious concrete samples were made from 3/8 inch aggregate, water and Type I Portland Cement. The pervious concrete mixture and the cylindrical samples for testing are in accordance with ASTM C31/C31M-03a. The pervious concrete was placed in cylinders, the surface was leveled, and a 6mil thick polyethylene plastic covering was placed over each cylindrical sample for proper curing. Ten (10) cylinders of pervious concrete, eight inches in depth and 4 inches diameter were cast. In addition, five (5) pervious concrete beams of 20 inches length and six inch by six in square cross-section were prepared to conduct flexural strength test. These were placed in beam molds and the covered with polyethylene material for curing.

Curing was done to simulate external conditions. Visual inspection of the pervious concrete mix was used to measure the consistency since no standard method exists to measure its consistency during installation. This research does not focus on the effect of the mix ratio on the strength parameters and the mix design of the concrete samples was provided by a local manufacturer (Table 1).

Table 1: Pervious concrete mix design

<table>
<tr><td>Material</td><td>Description</td><td>ASTM Standard</td><td>Specific Gravity</td><td>Weight (lb/yd^3)</td></tr>
<tr><td>Cement</td><td>Type I Portland Cement</td><td>C-150</td><td>3.15</td><td>650</td></tr>
<tr><td>Fine Aggregate</td><td></td><td>C-33</td><td>2.63</td><td>0</td></tr>
<tr><td>Coarse Aggregate</td><td>#89 Bahamas Rock</td><td>C-33</td><td>2.40</td><td>2240</td></tr>
<tr><td>Water</td><td></td><td>C-94</td><td>1.00</td><td>225</td></tr>
<tr><td>Admix 1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Admix 2</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">NOTES:</td><td>TOTAL</td><td>3115</td></tr>
<tr><td colspan="2">Design Slump: 1.0” +/- 1.0”</td><td colspan="3">Design Unit weight: 115.4 lb/ft^3</td></tr>
<tr><td colspan="2">Design Air:</td><td colspan="3">Design W/C Ratio: 0.35</td></tr>
</table>

After seven days had elapsed, the cylindrical molds were removed from ten (10) pervious concrete samples and the beam molds were removed from the five (5) beam samples. These fifteen (15) pervious concrete samples were then wrapped with the 6 mil thick polyethylene plastic. Compressive strength test were conducted on three eight (8) by four (4) inches cylinders on the 7th day after casting, while the remaining seven (7) cylinders and five (5) beams remained in the plastic confines for three more weeks. After 28 days of curing, the polyethylene plastic was removed from all the beams and the remaining cylinders and each sample was weighed.

Porosity and void ratio experiments and calculations were also performed on the seven (7) pervious concrete cylinders. The mix design, as provided by the manufacturer, for the test cell P.C sample is shown in the table above. Seventeen (17) pervious concrete cored cylindrical samples with an average depth of 7.4 inches in depth and 3.7 inches in diameter were tested. These samples were cored from our research site at the field laboratory.

Porosity and void ratio

Porosity and void ratio tests are conducted to obtain the amount of pore spaces in each cylindrical sample before they are tested for compression. The method used was that of weight of water displaced. This is in accordance with Archimedes principle and ASTM C29/29M-97. The volume of the cylindrical samples is calculated as V_T. A five-gallon bucket was filled with water up to a certain level and its initial depth was recorded as h_1. The cylinder was then gently placed in the container and then the final water level was recorded as h_2. The change in water level was recorded as ΔH. The volume of the solid displaced (V_s) was calculated with the aid of a dimensional mathematical equation developed for the five gallon container, as follows

$$V_S = 0.3904\left(\frac{\Delta H}{7.481}\right)(12^3) \qquad \text{Equation 11}$$

The volume of voids (V_V) is calculated by subtracting V_S from V_T. Subsequently, the void ratio (e) is determined by dividing V_V by V_S (V_V / V_S) and porosity (n) is calculated by dividing V_V by V_T (V_V / V_T).

Compressive strength testing

Compressive strength test was conducted in accordance with ASTM C39. After 28 days the cylinders were crushed by means of a 1-MN SATEC Universal Testing Machine. Neoprene cap was placed at the top and bottom of each cylinder before testing. This test was a stress based test, where each sample was loaded at a rate of 35 psi/sec until fail occurred. The data obtained was recorded as applied load (in pounds) and displacement (in inches).

Flexural strength testing

Flexural strength test was conducted in accordance with ASTM C78-02. This test was performed using the SATEC 1-MN load cell. After the 28 day curing period, the beams were placed on a flexural attachment which has two nose load applying points and two lower supports blocks. This test was carried out with a loading rate of 4500 lb/min till failure occurred. The modulus of rupture was measured from this flexural strength test.

Field Testing

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.

Figure 46: FWD equipment on pervious concrete section

Figure 47: FWD equipment

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:

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

Equation 12

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 13

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 119 ERIK measurements were taken for the pervious concrete 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 system types. Figure 48 below shows the cross sectional view of the embedded ring infiltrometers in the rejuvenation system (north and south) and the resulting measured infiltration rates are displayed graphically in Figures 49 - 52 below.

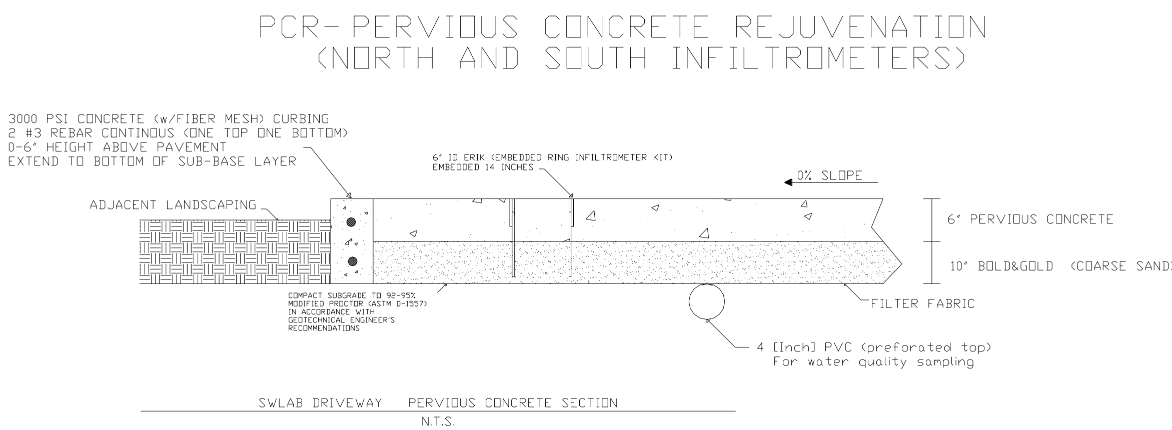


Figure 48: Pervious Concrete Rejuvenation Cross Section

(NORTH AND SOUTH INFILTROMETERS)

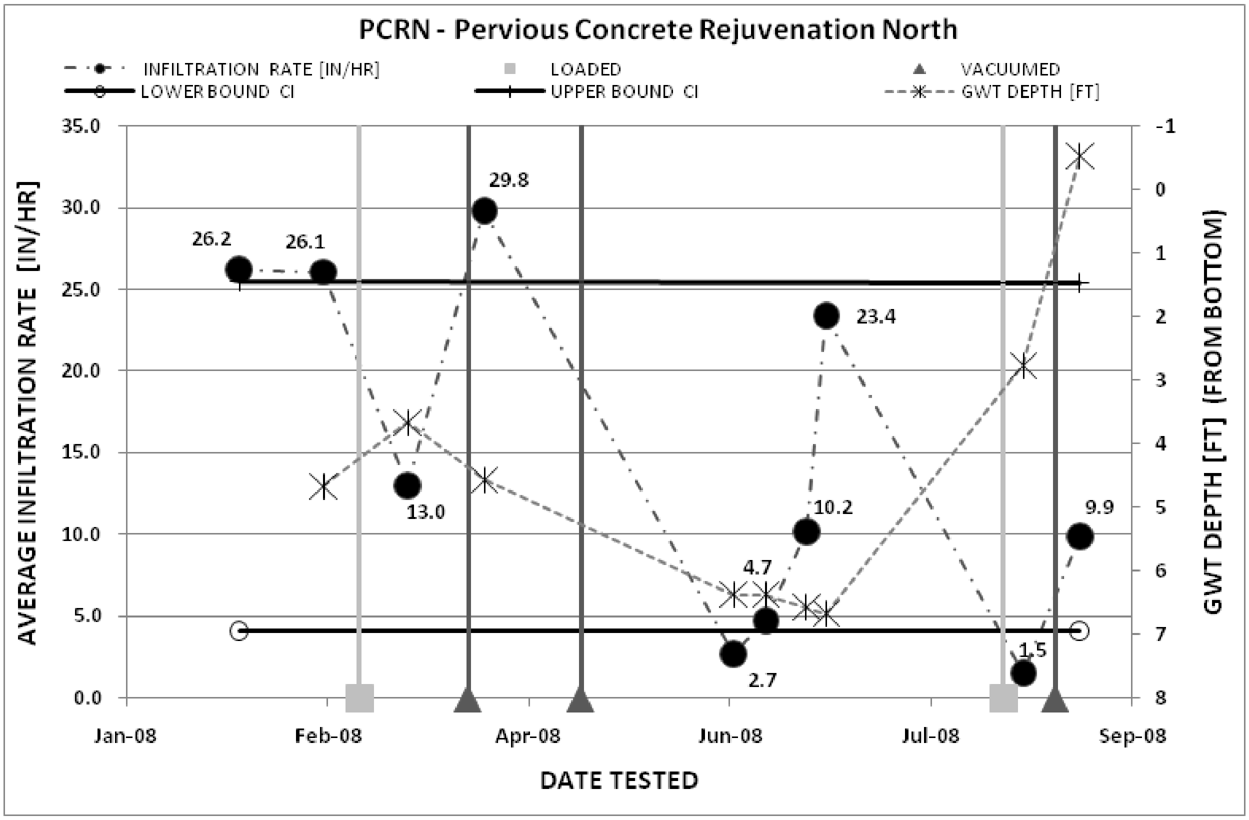


Figure 49: Infiltration results for Rejuvenation North infiltrometer

The pervious concrete rejuvenation pad's north infiltrometer initially measured average infiltration rates of 26.2 in/hr and 26.1 in/hr for the first two tests before any intentional loading took place. After the first loading of AASHTO type A-3 soil the rate decreased to 13.0 in/hr, half of the initial value and after the first vacuuming attempt the rejuvenated pervious concrete system's rate was brought up to 29.8 in/hr. The section was vacuumed a second time and then was retested again but after a month or so due to testing of other systems, and the rate dropped to 2.7 in/hr. It is not clear why the infiltration rate droped so much but could be due to site conditions or nateral loading. Three more tests were conducted within a month and the rates fluctuated from 4.7 in/hr to 23.4 in/hr. The GWT was deeper than 6 ft from the bottom of the system for all these tests so is thought to have no effect on the measured infiltration rates. The second loading of the powdered limestone seemed to cause more clogging that decreased the rate to 1.5 in/hr. However, the vacuuming restored the performance of the system back to 9.9 in/hr even when the GWT depth had risen above the bottom of the pervious concrete system.

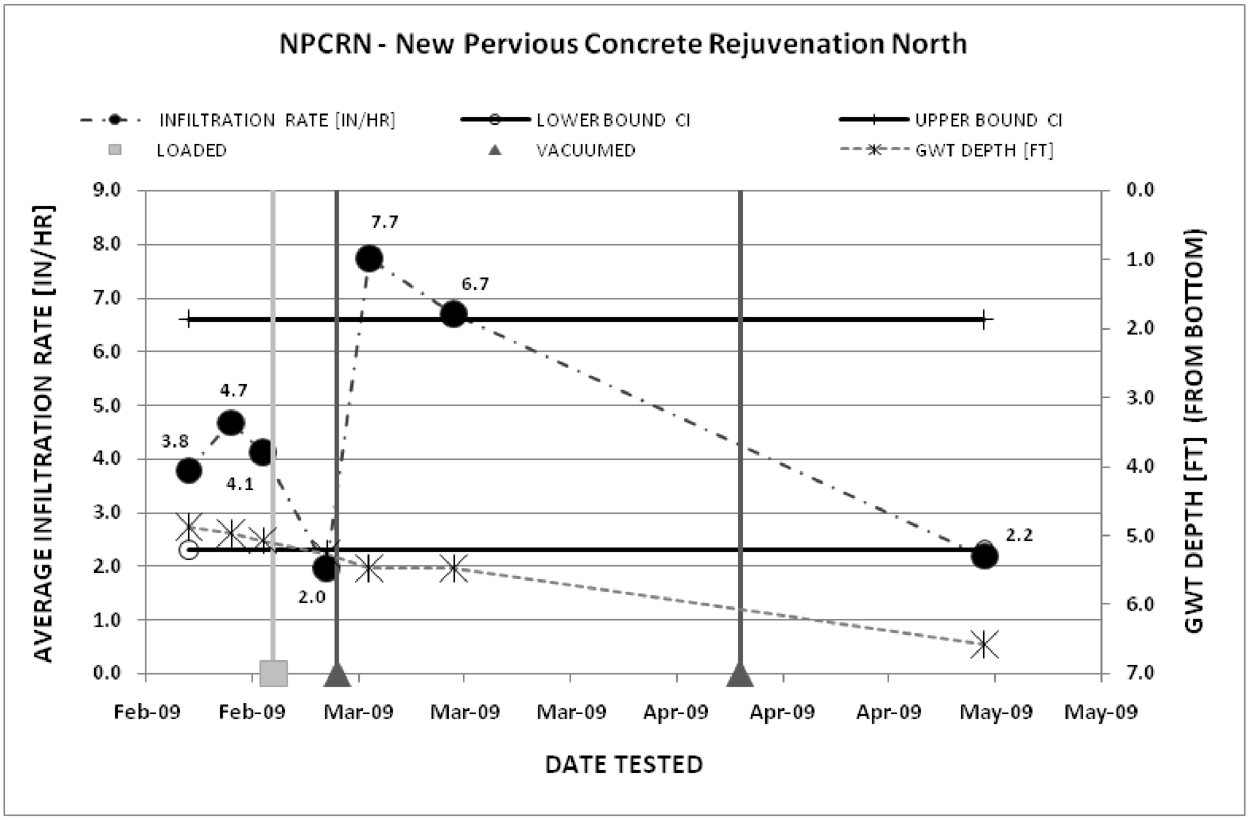


Figure 50: Infiltration results for New Rejuvenation North infiltrometer

After seven months of testing the pervious concrete rejuvenation pad was replaced with new pervious concrete to see if a different mix and placement would give similar results for the exact same location and sub-base. The new pervious concrete placement appeared to be a tighter mix than the first, with less visible surface pores either due to the mix itself or the placement of the new mix. The initial results agreed with this hypothesis given results of 3.8, 4.7, and 4.1 in/hr for the first three initial tests. The new pavement was loaded with the A-3 site soils in the same manner as above with repeated cycles of washing in and compaction. Subsequent testing indicated that the sand clogged pavement's rate dropped down to 2.0 in/hr which was lower than results given by the first pervious concrete loaded with sand. However, in both the old and new pervious concrete, the sand clogging caused the rate to decrease to about half of the initial values for infiltration. Also, similar to the first placed pervious concrete, the vacuuming rejuvenated the sand clogged system back up to a rate that was double the clogged values. After vacuuming the rate increased to 7.7 and 6.7 in/hr for the next two tests respectively. After three months the rate had fallen back to 2.2 in/hr without any intentional loading of sediments but may have encountered accidental spills from other projects in the vicinity.

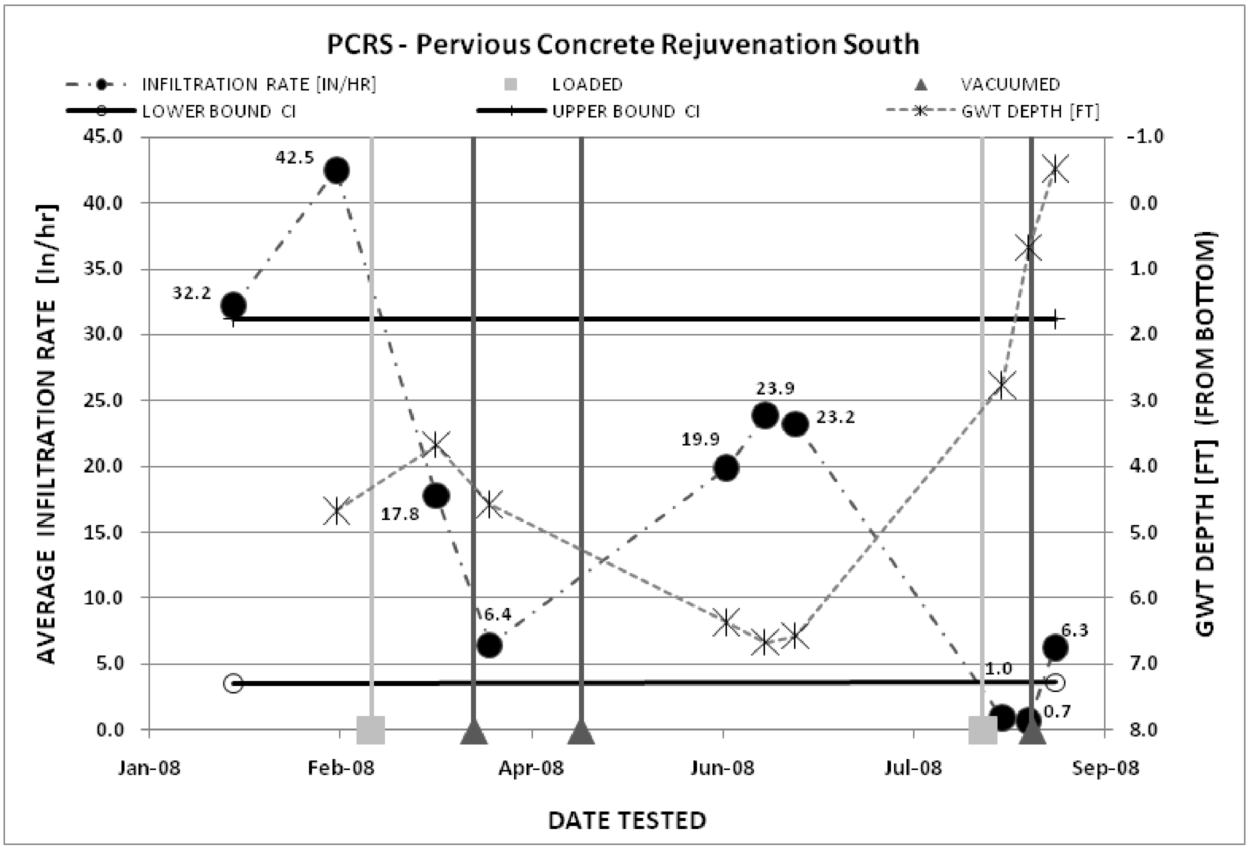


Figure 51: Infiltration results for Rejuvenation South infiltrometer

The south infiltrometer in the rejuvenation pad experienced more extreme rates of infiltration during testing than the north. The initial results of the first two tests were 32.2 and

42.5 in/hr. The sand clogging event droped the rate to 17.8 in/hr. The first vacuum attempt did not show an increase in the rate after vacuuming resulting in a 6.4 in/hr rate, but after a second attempt , the rate was increased back up to 19.9, 23.9, and 23.2 in/hr for three consecutive post vacuum tests. When the pervious concrete was clogged with the limestone powder the infiltrometer measured a decrease in rate to 1.0 and 0.7 in/hr during a time of high GWT (0-3 ft below the bottom of the system). However, with the use of a vacuum truck, the system was maintained and the rate was improved back to 6.3 in/hr.

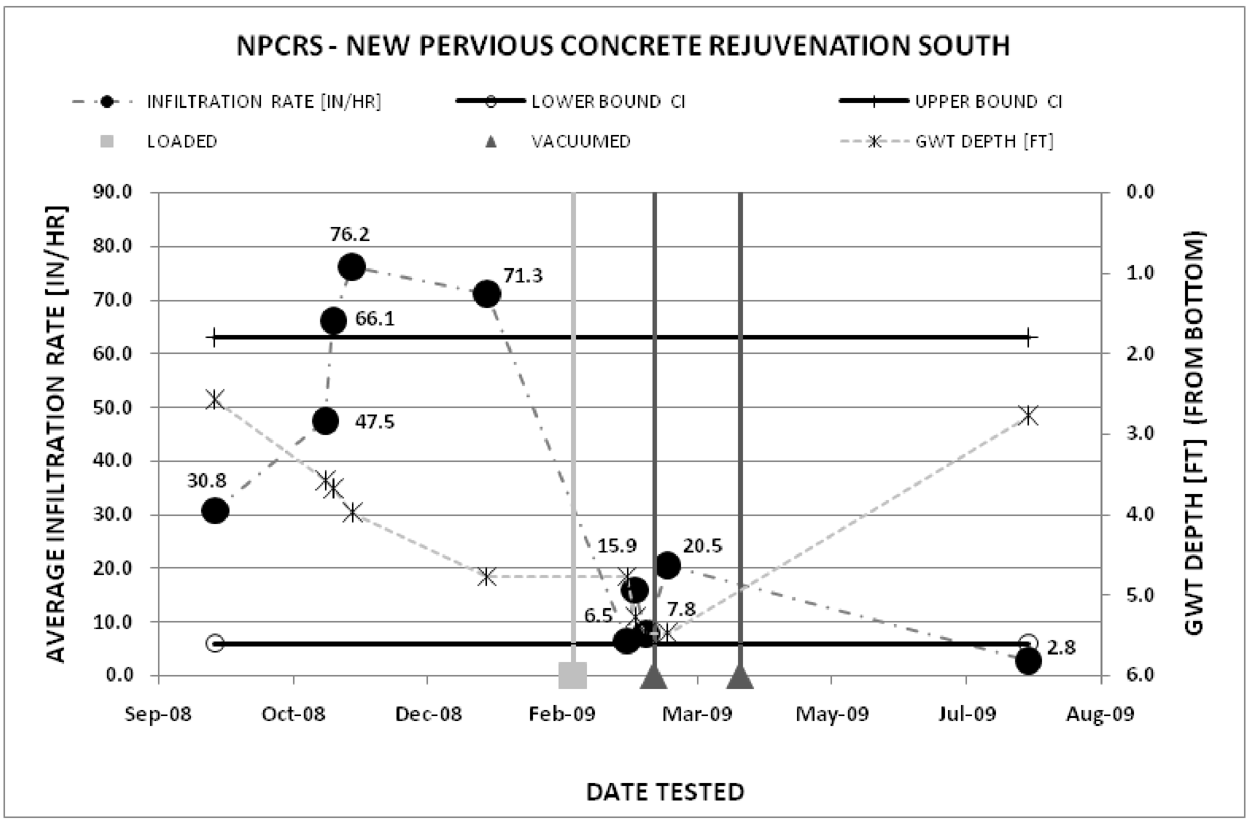


Figure 52: Infiltration results for New Rejuvenation South infiltrometer

The pervious pavement was replaced and tested for comparison of two different placements. The new pad showed initial rates of 30.8 and 47.5 in/hr when the GWT was at depths of about 2.5 and 3.5 ft below the bottom of the system respectively. The next three tests were considerably higher than the initial rates and may have been due to the GWT lowering to a depth of about 4.5 feet below the bottom of the system. Sand clogging reduced the pavements ability to infiltrate down to 6.5, 15.9, and 7.8 in/hr even during the time of low GWT. When the infiltrometer was tested soon after maintenance, the rate was restored back to 20.5 in/hr. After four months the infiltrometer was tested and showed a decline in the rate to 2.8 in/hr, but again the GWT was only 2.5 ft below the bottom of the system.

The east and west located infiltrometers illustrated in Figure 53 below, were embedded into the pervious concrete rejuvenation pad at a depth of only 4 inches. This enabled the monitoring of the performance of the pervious concrete alone with a concentration on pavement layer surface clogging. It allowed for a comparison of the results of other research that used surface infiltration tests such as the double ring infiltrometer (ASTM D3385). The results are shown graphically in Figures 54 – 55 below.

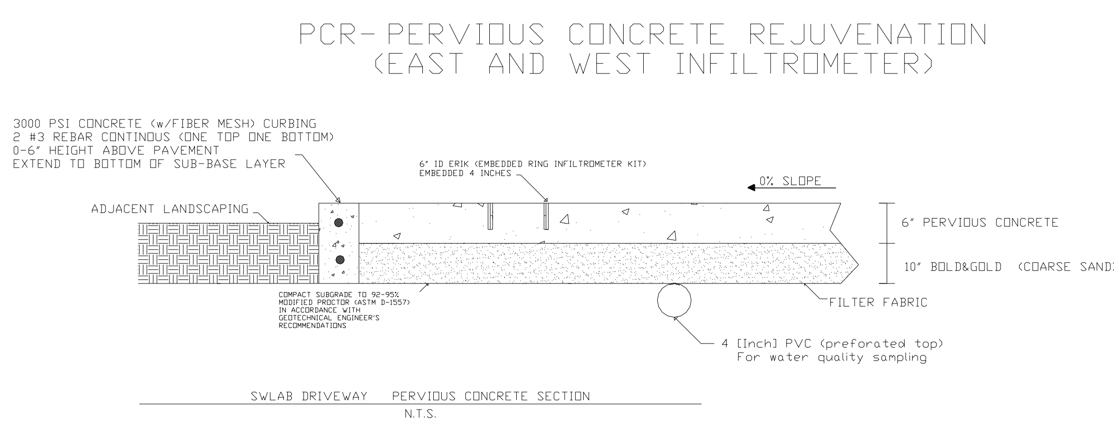


Figure 53: Pervious Concrete Rejuvenation Cross Section

(EAST AND WEST INFILTROMETERS)

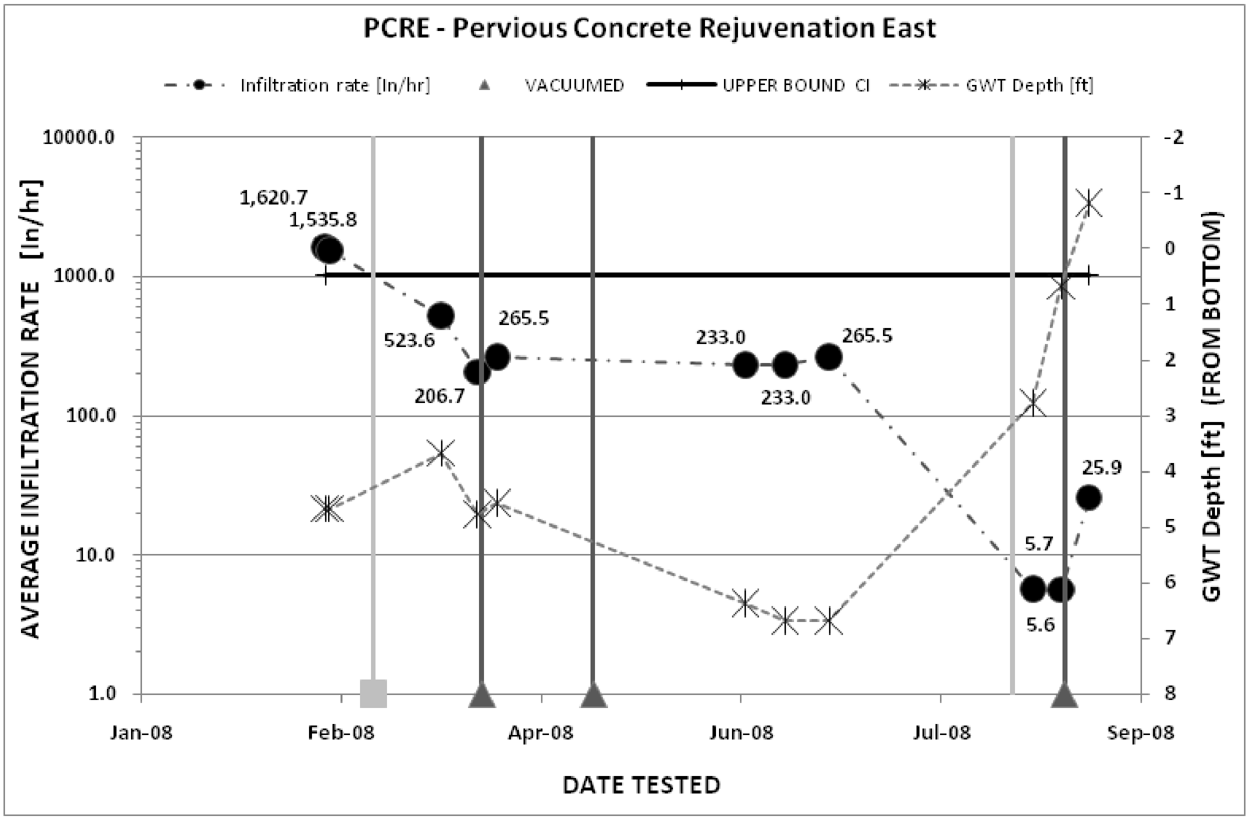


Figure 54: Infiltration results for Rejuvenation East infiltrometer

The results of the surface infiltration rates of the pervious concrete were in comparison with the results given by other researchers. The east infiltrometer measured rates of 1620.7 and 1535.8 in/hr during the initial run of surface infiltration. The sand loading event clogged the surface reducing the rate down to 523.6 and 206.7 in/hr. The first vacuum attempt showed a reduction of the surface infiltration rate to 265.5 and 233.3 in/hr during the first post vacuuming tests. Once the surfaces were clogged with the fine limestone powder, the pervious concrete performed at 5.7 and 5.6 in/hr. After vacuuming the surface the rate bounced back up to 25.9 in/hr/.

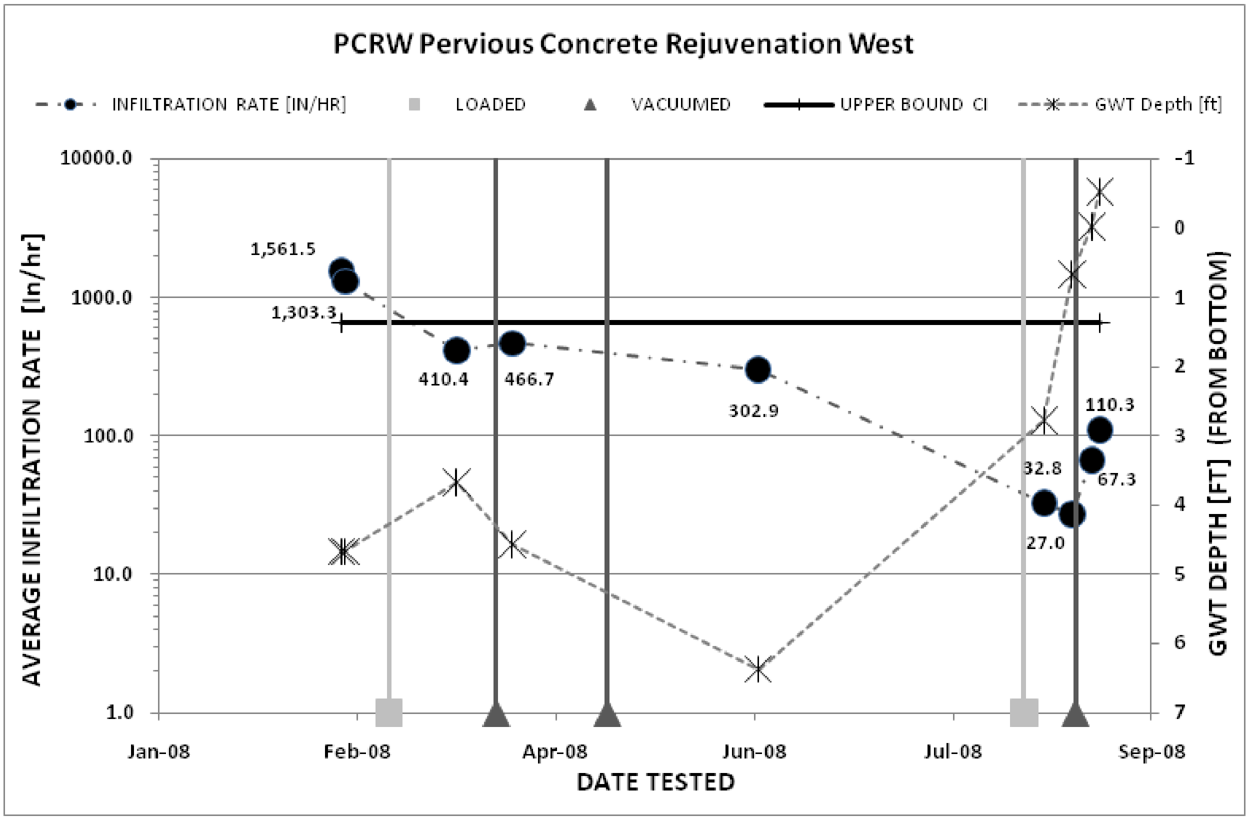


Figure 55: Infiltration results for Rejuvenation West infiltrometer

The west infiltrometer of the pervious concrete pad showed similar initial results as the east infiltrometer, 1561.5 and 1303.3 in/hr. Sand clogging and rejuvenation had a similar effect on the surface rates of this pervious pavement section as well, decreasing them to 410.4 in/hr and restoring back to 466.7 and 302.9 in/hr. The fine limestone powder again did a better job of clogging and reducing the infiltration capacity of the surface down to 32.8 and 27.0 in/hr. Performing maintenance on the pervious concrete helped to restore the infiltration rate back to 67.3 and 110.3 in/hr.

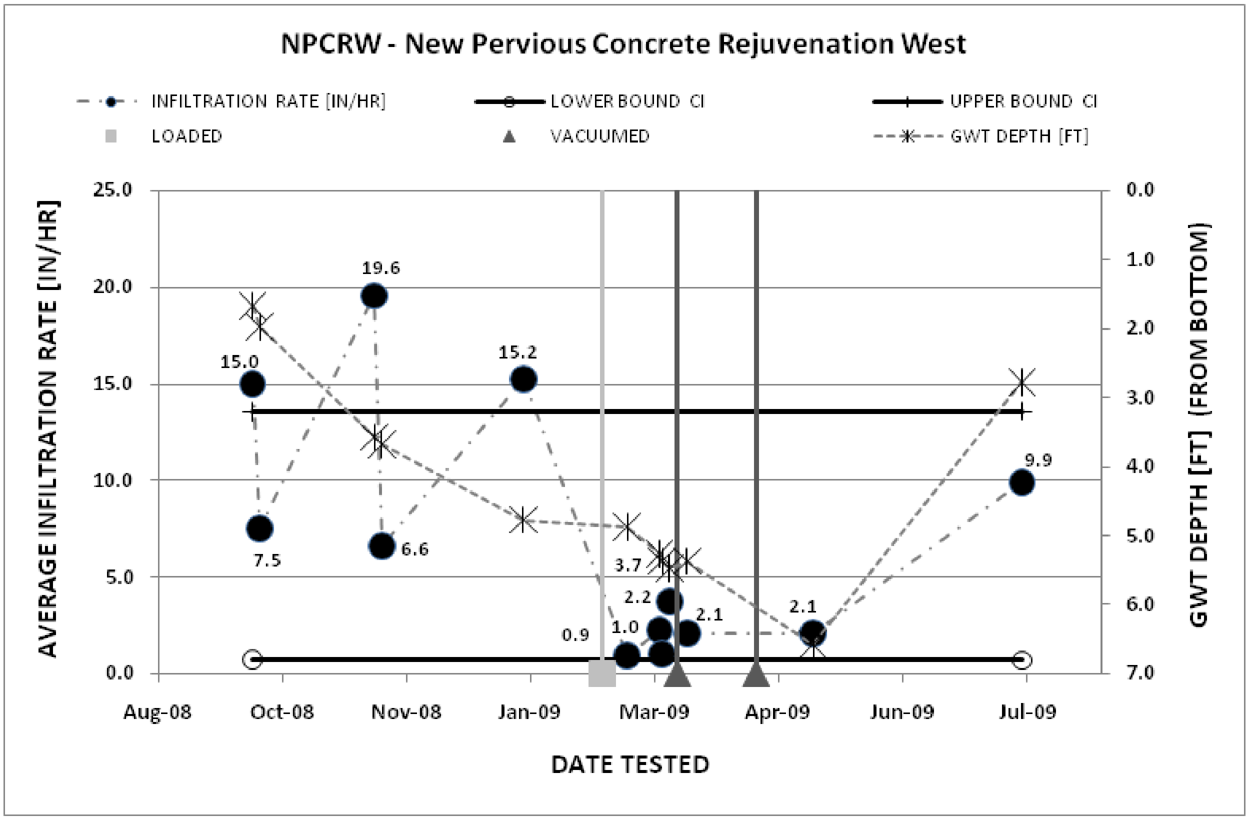


Figure 56: Infiltration results for New Rejuvenation West infiltrometer

The pervious concrete was replaced and a new 20 inch long infiltrometer was installed and the bottom extended down four inches below the bottom of the system. This infiltrometer was able to measure the rate of the pavements' surface layer, sub-base layer, and four inches of the parent earth soils below. The results from these tests are shown in Figures 56 – 60. The initial rates measured at 15.0, 7.5, 19.6, 6.6, and 15.2 in/hr respectively during the first four initial tests. The pavement was loaded with sandy soils and clogging reduced the rates to 0.9, 1.0, 2.2, and 3.7 in/hr during the four consecutive post loading tests. This increasing trend may have been due to an increasing depth to the GWT from about 5.0 ft to about 5.5 ft below the system. After maintenance was performed, the rates increased to 2.1 in/hr for the next two tests and up to 9.9 in/hr after four months.

The results from these two pervious concrete sections PCBG and PCF, having only natural loading of sediment, will be discussed first. Two ERIK's were embedded into the PCBG Pervious Concrete Bold & Gold system at the time of construction. The infiltrometer was embedded through the six inches of pervious concrete and eight more inches into the B&G sub-base which was two inches shy of the bottom of the B&G sub-base. This allowed for an infiltration rate of the system of pervious concrete and sub-base without interruption of the parent earth's typically slower rates.

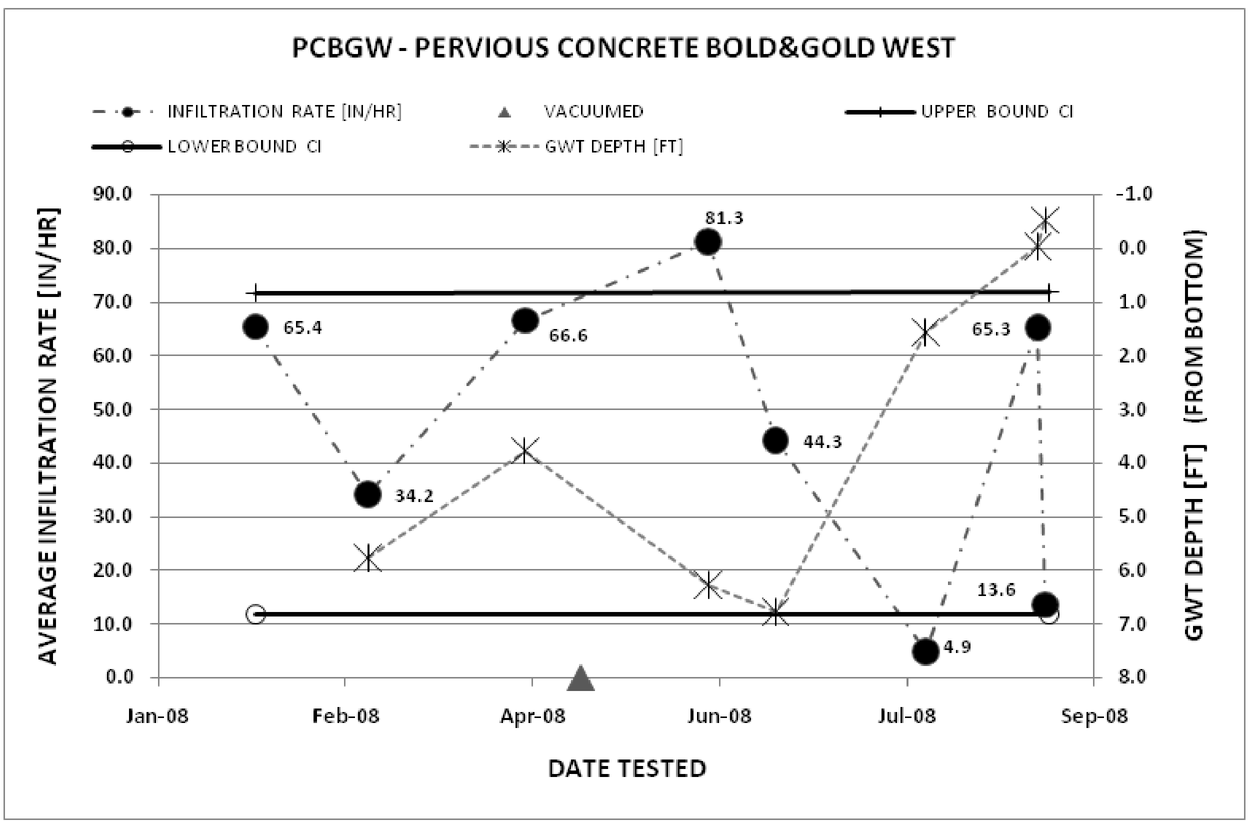


Figure 57: Infiltration results for Bold&Gold™ West infiltrometer

Initial measurements of the east and west infiltrometers (PCBGE and PCBGW) indicated rates of 60.7 (in/hr) and 65.4 (in/hr) respectively for the first test conducted. The west infiltrometer showed a range of infiltration rates of 34.2 (in/hr) to 66.6(in/hr) in the first three months of testing without much influence of the water table depth. After one vacuum sweeping was conducted, the rate increased to 81.3 (in/hr), but may have also been effected by the low ground water table (6+ ft below the bottom of the system). After a second vacuuming the rate drops down to 44.3 (in/hr) on the next test and then down to 4.9 in/hr when the water table had risen up to only 1 ft below the bottom of the system. The rate bounced up to 65.3 in/hr and then back to 13.6 in/hr and finally dropped to 0.9 in/hr after seven months of testing.

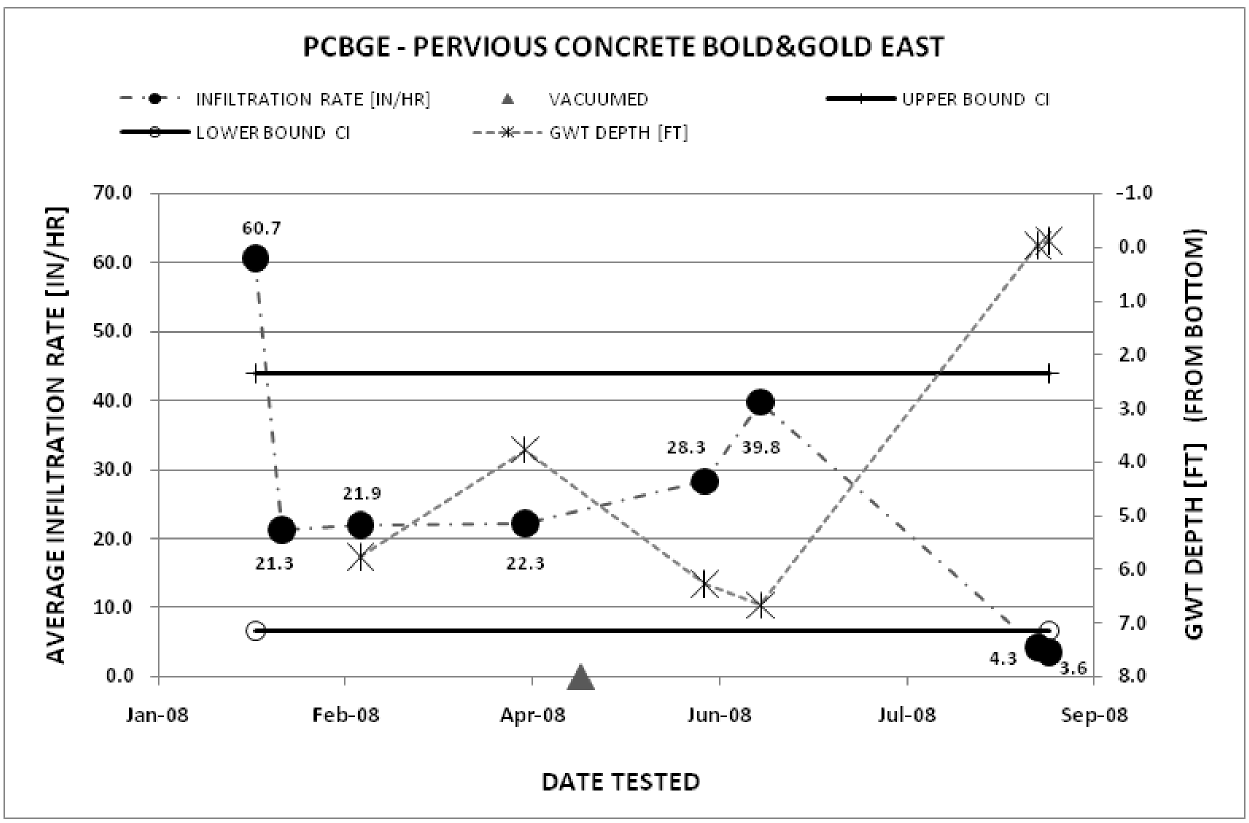


Figure 58: Infiltration results for Bold&Gold™ East infiltrometer

The east infiltrometer PCBGE showed less fluctuation in the measured rates after the initial 60.7 in/hr reading. The rate decreased to around 22 in/hr for the next five months of testing when the GWT was about 4 ft depth or lower. It was not until the GWT level was down to almost 7 ft below the bottom of the system that the infiltration rate seemed to be affected and shot back up to 39.8 in/hr. In the rainy months of August and September, and at the end of the eight months of testing with the GWT at a depth of only an inch or so from the bottom of the infiltrometer, the final results of the ERIK test showed rates at 4.3 and 3.6 in/hr. Using the results from both infiltrometers the rates have consistently stayed in the 10-50 in/hr range throughout the first 6 months of testing. Infiltration rates did not drop under 5.0 in/hr until the GWT depth below the bottom of the system was at 2 ft or lower.

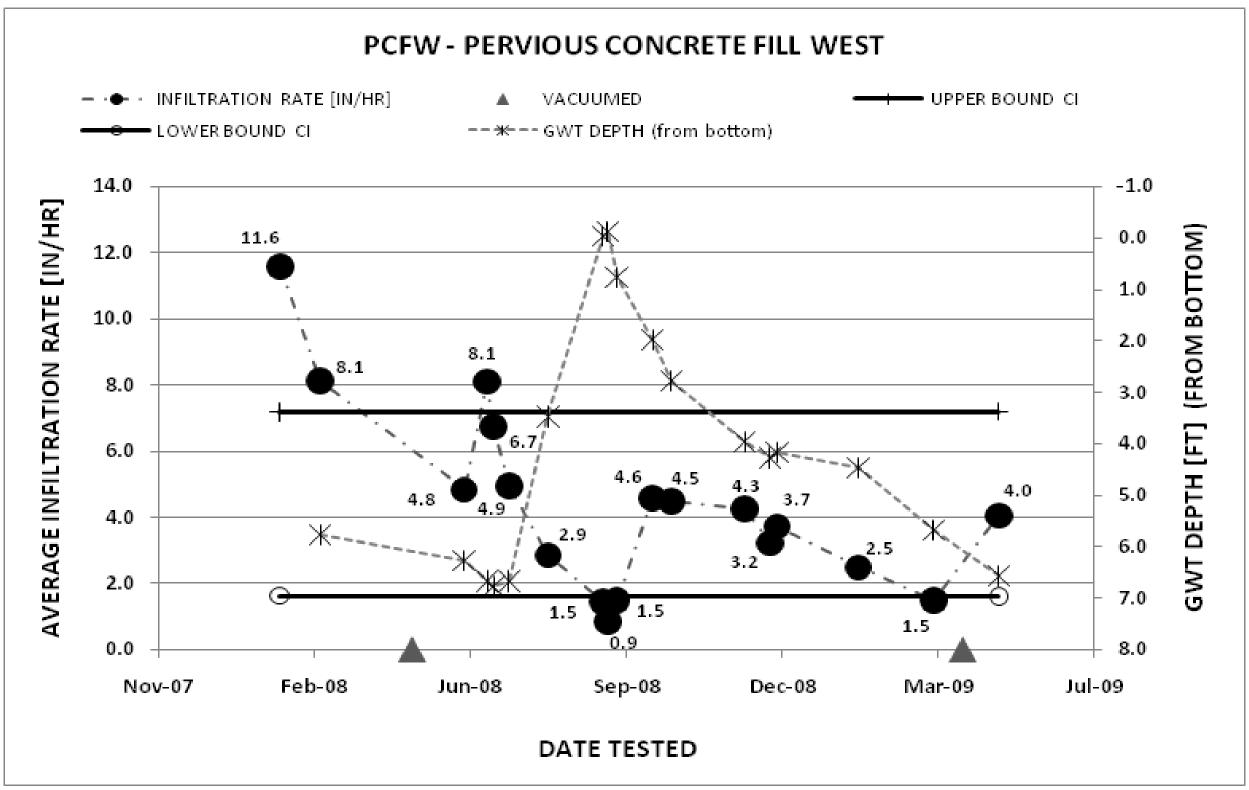


Figure 59: Infiltration results for Fill West infiltrometer

The next pervious concrete natural loading section was equipped with two infiltrometers that were embedded to a depth of 14 inches total, 6 inches of pervious concrete and 8 inches into local A-3 soils as the sub-base. The rates measured from the west infiltrometer (PCFW) were never higher than 11.6 in/hr through the A-3 soil sub-base. The west infiltrometer measured initial rates of 11.6 and 8.1 in/hr for the first and second test at relatively low GWT depths (6 ft). The system infiltrated consistently at a range of about 2.5 to 6.7 in/hr when the GWT was at about 4-6 ft below the bottom of the system. Once in September the GWT level reached an elevation of less than an inch below the bottom of the system and the infiltration rate of the system was affected by reducing the infiltration rates to 1.5 and 0.9 in/hr. After one year of service the pavement's infiltration rate fell to 1.5 in/hr but then the vacuuming rejuvenated the rate back to 4.0 in/hr.

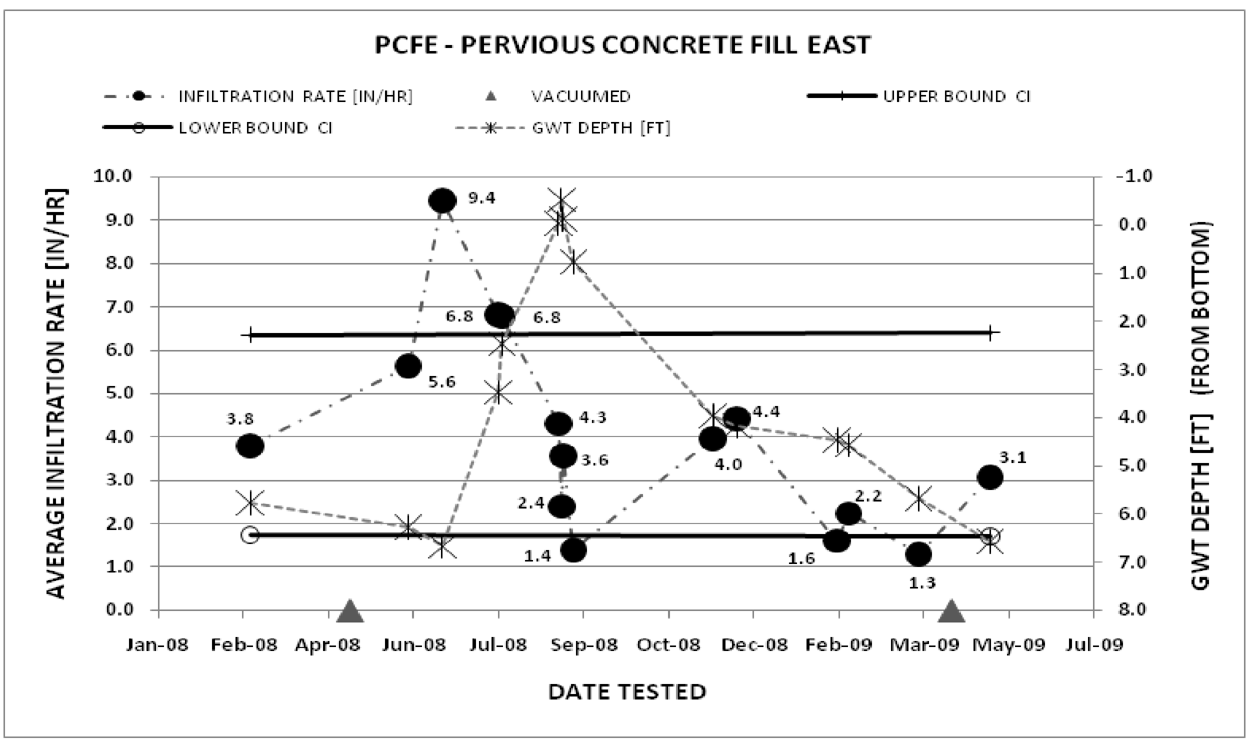


Figure 60: Infiltration results for Fill East infiltrometer

The east infiltrometer initially recorded a rate of 3.8 in/hr after installation. The pavement was vacuumed and rates increased to 5.6 then 9.4 in/hr during a period of low GWT depth. During the rainy season the GWT had risen to 3.5 ft, 2.5 ft, and eventually up to less than 1 ft below the bottom of the system. This high GWT resulted in the decrease of infiltration rates from 4.3, and 3.6 in/hr, and finally down to 2.4 and 1.4 in/hr during the next four consecutive tests. After two months the GWT receded down to lower depths (4+ ft below system) and the next to tests measured rates of 4.0 and 4.4 in/hr. Later, the GWT remained low and the rates decreased, likely from clogging of the surface down to 1.6, 2.2, and 1.3 in/hr during the next three tests. One final vacuuming was performed on this section and measured rates indicated a rejuvenation back to 3.1 in/hr.

Sustainable Storage Evaluation Results

The results of testing the porosities of the individual component materials are tabulated in Table 2 below. The total porosity of the surface layer measured in the ½ gallon containers is 31.9%. 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 and thus can be considered effective porosity. There is a slight difference in the total and effective porosities measured. As reported in the Table 2, the average effective porosity value is 27.2%. This indicates that the pervious concrete material itself dries relatively quickly recovering its storage volume. Next, the pervious concrete material is loaded with sandy sediments to induce clogging of the surface pores which resulted in an average effective loaded porosity of 23.4%. This reduction in storage is due partially to the fact that some of the volume of sediment particles is now occupying the once empty pore spaces. This also results in a larger number of smaller pore sizes that retain a larger volume of moisture in the once air filled pores. In the preloaded condition the pores were larger enough so gravity alone could more easily drain the water from the pores allowing for quicker recovery of storage capacity. It was observed during the testing that much of the sediments seemed to be trapped near the surface and only penetrated about an inch to two inches downward from the surface. After vacuuming the surfaces the sediments were extracted by the suction force with ease since much of the sediments remained near the surfaces. Porosity measurements were taken after vacuuming the surfaces and an average effective porosity of 27.8% was measured and recorded. This result confirms that the clogging sediments near the top portion were effectively removed by vacuuming. This proves the surface layer to be effective at filtering sandy sediments and preventing them from entering the sub-layers, which may cause an eventual reduction in storage capacity of the deeper storage layers. The advantage to having larger pore sizes is the ability of the surface layer to remain unclogged by allowing passage of all sediments, which helps prevent water from having a chance to become runoff before infiltrating into the pervious pavement system.

The sub-base layer material is tested using the small-scale ½ gallon containers were tested for total (over dried) and effective (gravitational drainage) porosities. The Bold&Gold™ pollution control media provided values of 38.9% total and 15.2% effective porosity averages in the small containers.

Table 2: Individual component porosity test results

Pervious Concrete PC	AVERAGE MEASURED POROSITY [%]			
MATERIAL TYPE	**Total**	**Effective**	**LOADED**	**VACUUMED**
Pervious Concrete PC	31.9	27.2	23.4	27.8
Bold&Gold	38.9	15.2		

Presented below in Figure 61 are the results for testing the amount of water storage within the complete cross section (using the 55 gallon barrels) of the pervious concrete systems including the surface layer and pollution control sub-base layer. The initial tests were conducted without introducing any sediment to the systems to investigate the total or maximum storage available.

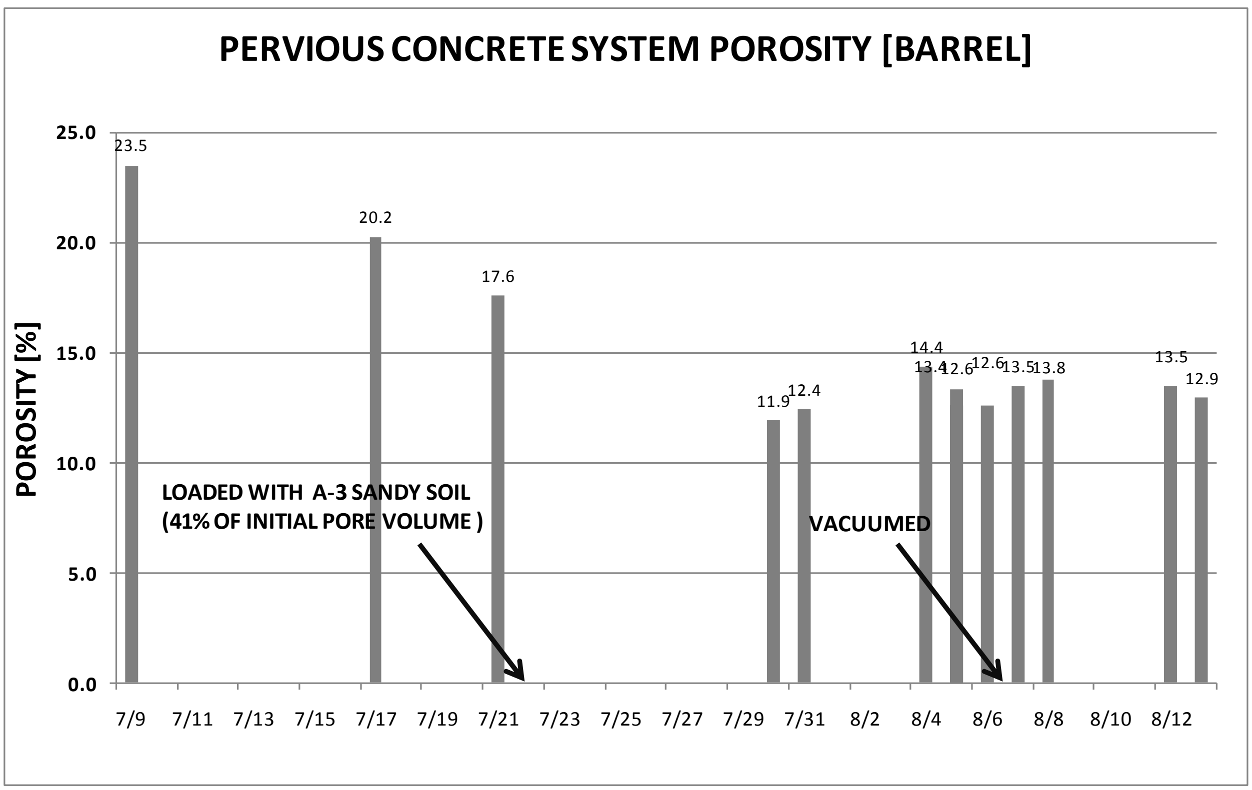


Figure 61: System porosity results using 55 gallon barrels

The initial value 23.5% 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 pervious concrete, the next two 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 micro pores in the aggregates and near the contact points, as well as the 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 two tests represent the effective porosity 20.2% and 17.6% 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 micro pores. The next five tests are conducted after loading with 41% of the initial pore volume measured by the initial test using A-3 soil on the surface of pervious concrete and washing into the pores while simultaneously pumping the infiltrated water out of the well pipe from the bottom of the stone reservoir.

After the loading takes place the resulting effective porosity was reduced ranging from 11.9% to 14.4%. After the sediments were vacuumed from the surface several tests were run. The measured values of the last three tests remained about the same as the loaded tests indicating that some of the sediments did in fact travel down to a distance that vacuuming was unable to extract. Observation of the pervious concrete the surface showed that the surface sediments were however effectively removed.

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 was determined by adding the porosity values for each component corresponding to the depths of each layer and then totaled to represent storage within the entire system. The theoretical calculation of the system's (total) storage is calculated at 5.8 inches of the entire 16 inch cross section using the total porosity values. Comparing this value to the actual barrel storage using measured total porosity values the entire 16 inch deep cross section's storage is only 3.8 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, the theoretical (effective) storage in the system is calculated to be 3.2 inches which is in agreement with the actual barrel measurement of 3.0 inches. After intentional sediment loading, the theoretical (effective) storage in the system is calculated to be 2.9 inches with the actual barrel measuring 1.9 inches. After vacuuming the surfaces the effective theoretical storage in this system is calculated and returns to 3.2 inches while the actual barrel storage is measured at 2.1 inches. It can be concluded that the actual total porosity of a complete system is about, on the average 35% less than if calculated theoretically and the actual effective porosity is about, on the average 4% 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 3 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 and total phosphate.

Table 3: 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

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 3. The pH data is also not shown here as it was not different from the values in Table 3. Examination of the replicate samples for both the Bold&Gold™ 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.

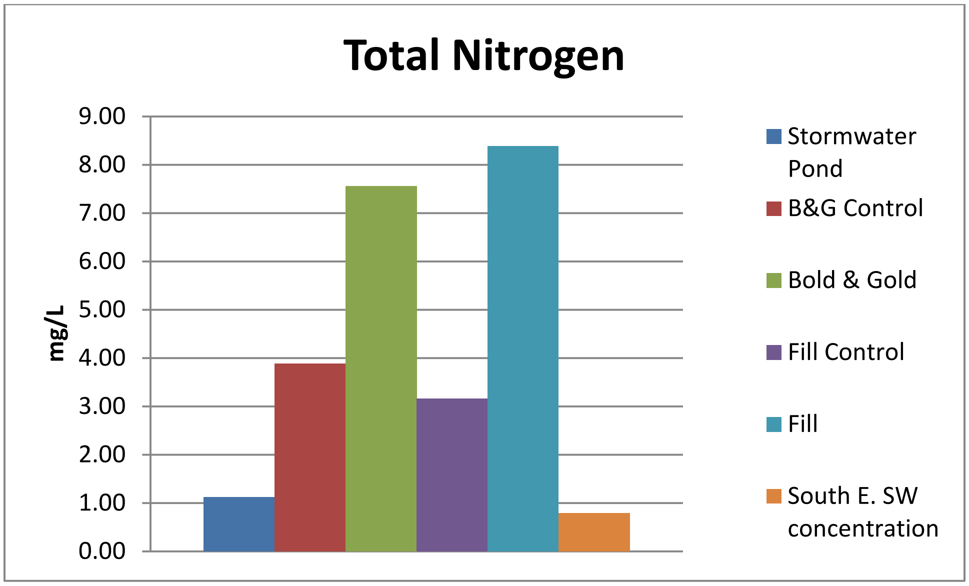


Figure 62: Total nitrogen results

Figure 62 shows the total nitrogen results for all the systems tested, the stormwater used to simulate the rain event, 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 the 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. The systems that had the Pervious Concrete were observed to have a significantly higher concentration of total nitrogen compared to the controls which might be due to the composition of the concrete or the storage conditions of the raw materials.

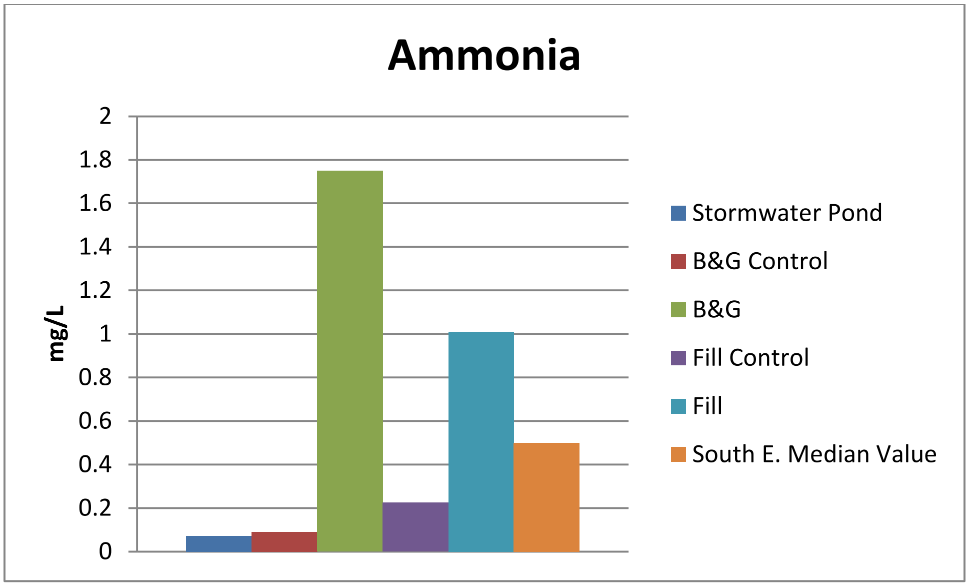


Figure 63: Ammonia results

Figure 63 shows the ammonia nitrogen concentration results for all the systems tested, the stormwater used to simulate the rain event, and the south eastern stormwater median value. After analysis of the results it was shown that there was no significant difference ($\alpha=0.05$) between the Bold&Gold^{TM} system and the fill system. This shows that the addition of the sub-base pollution control layer has no significant effect on ammonia concentration.

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 Pervious Concrete were observed to have a higher concentration of ammonia than the controls. These were all statistically different ($\alpha=0.05$). The higher ammonia concentration may be a result of the pervious concrete materials or the storage conditions of the raw materials.

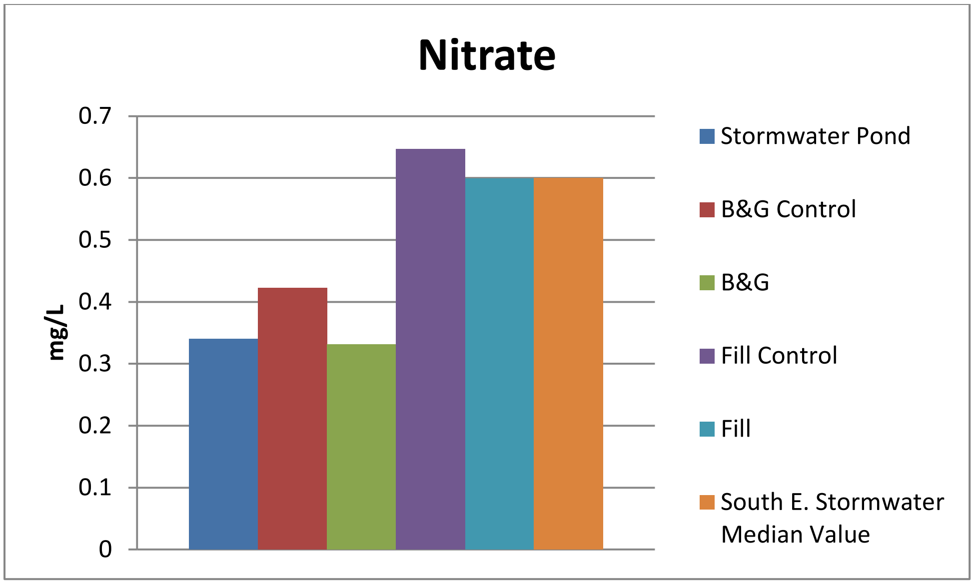


Figure 64: Nitrate results

Figure 64 shows the nitrate nitrogen concentration results for all the systems tested, the stormwater 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 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 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 test method used.

It was observed that all but one of the systems tested had higher nitrate concentrations than the stormwater used to simulate the rain event. This, again, was likely due to the fact that local soil was used to simulate the sub-base and likely leached nutrients.

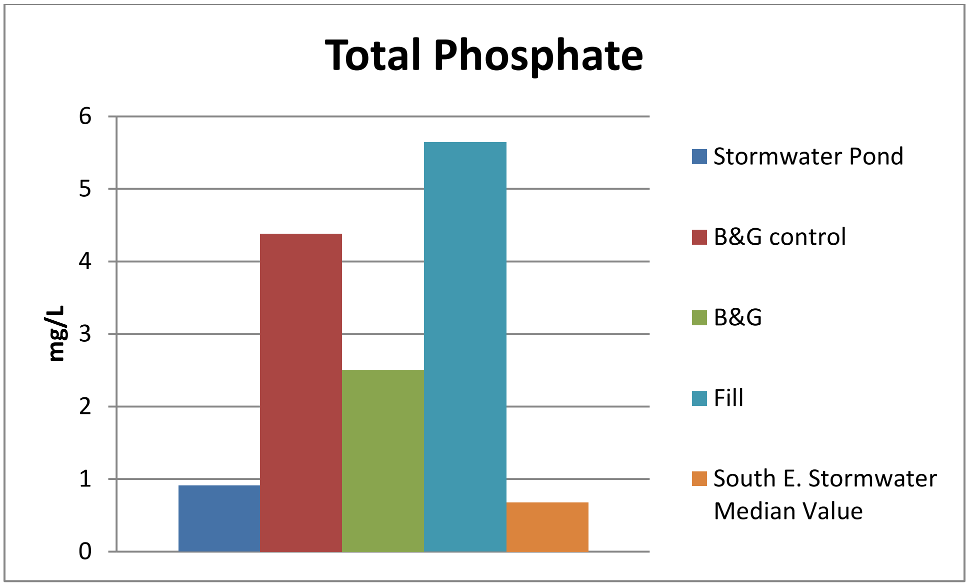


Figure 65: Total phosphate results

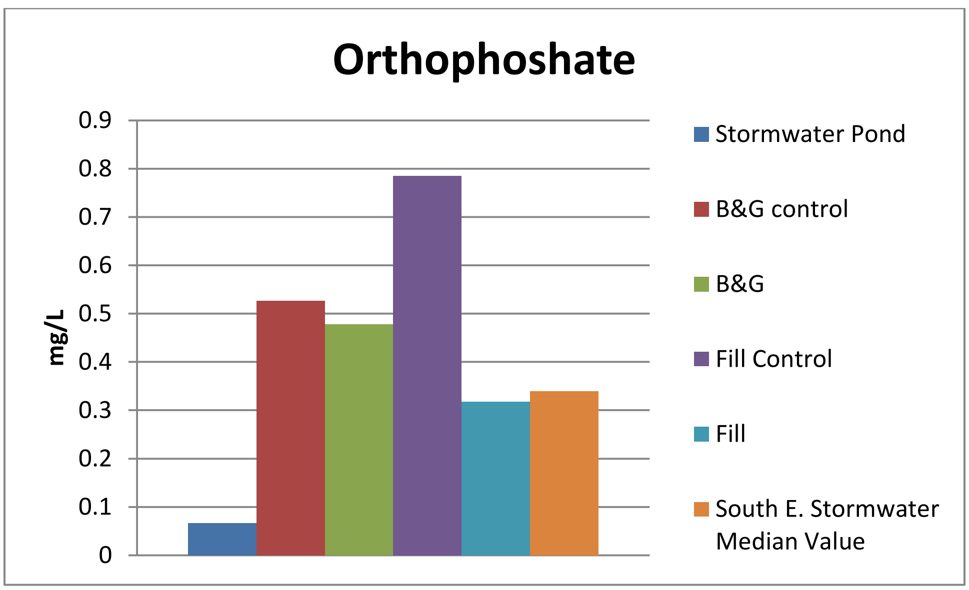


Figure 66: Orthophosphate results

Figures 65 and 66 show the total and ortho- phosphate concentration results, respectively, for all the systems tested, the stormwater used to simulate the rain event, and the south eastern stormwater median value. After analysis of the results it was shown that the B&G and Fill results for the total phosphate were significantly different (α=0.05) from each other with the B&G system having a lower concentration. The B&G Control and Fill Control systems for the orthophosphate test were also significantly different with the B&G Control having a lower concentration. This indicates that the Bold&Gold™ pollution control media may reduce the ortho- and total phosphate concentration of stormwater that infiltrates through the system.

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.

Strength Results

Laboratory Testing Results

The results of the laboratory and field tests are discussed. Relationships between the compressive strength, flexural strength, porosity are presented. In addition, a statistical analysis of the strength parameters is provided. The results of the back-calculation and forward calculations of each pervious pavement section are tabulated. The stress, strain and displacement of each layer of the pavement as determined from the KENPAVE program are also presented. Comparisons of the minimum thickness design of the flexible pavements using the AASHTO Method hand calculation and FPS 19W program are provided.

Porosity and Unit weight

As discussed in the previous chapter, tests were conducted to evaluate the porosity and compressive strength of the cylindrical pavement samples. The dry unit weight was also obtained for the different pervious pavement sections. Cored and cast-in situ pervious concrete cylinders were tested. The average depth of the core sample was 7.4 in. while the width was 3.7

in., so a correction factor was implemented when calculating the compressive strength. Samples C1 – C7 cylinders were cored from the pervious concrete driveway installed in 2005 while samples M1 – M10 were cored from PC section in the storage area which was installed in 2009.

Compressive Strength

The compressive strength values for pervious concrete samples cored from the installation at the field laboratory ranged from 988 – 2429 psi (Table 4). Sample C4 exhibited a very low compressive strength and high porosity. This range is an indication of the non-homogeneous nature of the pavement. The cylindrical concrete samples were obtained from two different production process, mix design and age.

Cast in-situ P.C cylinders of about 8 in. x 4 in. diameter size were tested. Table 5 shows the results of 28-day strengths and porosity of the test cylinders. The compressive strength values range from 364 – 1100 psi. The unit weight ranges from 93 – 105 pcf, while porosity ranges from 0.25 – 0.38. The average porosity of the 8 x 4 samples is 0.29 as shown in the Table 5. The 2σ test shows that the porosity values fall within the acceptable limits. The compressive strength range of the 8 x 4 samples is 364 – 1100 psi.

A statistical analysis was done by means of MINITAB. Statistical analysis on the results for the compressive strength is shown in Table 6 while the corresponding analysis for porosity is shown in Table 7. One (1σ) and two (2σ) standard deviations were used to find out the accuracy of the data. It was found that about 59% of the porosity data passed the 1σ (less than 67%) test while about 100% passed the 2σ test. This shows that the data provided were not within acceptable range as shown by the 1σ test. From the statistical analysis shown in Table 6, 76% of the data passed the 1σ test (greater than the 67%). This shows that the compressive strength values are within acceptable range.

Table 4: Compressive strength and porosity of cored pervious concrete cylinders.

Sample	Maximum Load at failure (lbf)	Compressive strength (psi)	Unit weight (lb/ft^3)	Porosity	Void ratio
C1	18758	1698.4	114.16	0.193	0.24
C2	26818	2428.1	121.72	0.101	0.11
C3	18072	1636.3	110.58	0.128	0.15
C4	6150	556.8	98.25	0.298	0.42
C5	19700	1783.7	116.91	0.103	0.11
C6	21598	1955.5	116.90	0.076	0.08
C7	22227	2012.5	113.18	0.131	0.15
M1	16082	1456.1	109.52	0.165	0.20
M2	18989	1719.3	111.39	0.265	0.36
M3	14300	1294.7	109.52	0.320	0.47
M4	14522	1314.8	114.28	0.201	0.25
M5	20414	1848.3	110.20	0.201	0.25
M6	15712	1422.6	113.36	0.230	0.30
M7	24437	2212.6	114.28	0.201	0.25
M8	20477	1854.0	111.26	0.093	0.10
M9	10902	987.1	104.98	0.298	0.42
M10	20248	1833.3	107.70	0.240	0.32

C – Pavement section 7 - 9
M – Pervious concrete section at storage area

Table 5: Compressive strength and porosity of 28-day pervious concrete cylinders

Sample	Size (inches)	Maximum Load (lbf)	Compressive strength (psi)	Unit weight (lb/ft^3)	Porosity	Void ratio
PC 6	8x4	6743	536.6	96.15	0.32	0.47
PC 7	8x4	10577	841.7	104.73	0.25	0.34
PC 8	8x4	5396	429.4	95.93	0.31	0.45

PC 9	8x4	7893	628.1	102.15	0.26	0.35
PC 10	8x4	13814	1099.3	103.85	0.25	0.34
PC 11	8x4	4564	363.2	92.68	0.38	0.61
PC 12	8x4	13682	1088.8	104.77	0.26	0.35

Table 6: Statistical data for compressive strength

Sample	Average Compressive strength (psi)	Standard deviation, s	Range	Proportion within 2s	Coefficient of variation, CV
C1 – C7	1724.47	578.33	(567.80, 2881.13)	1	0.34
M1 – M10	1594.28	360.88	(872.53, 2316.04)	1	0.23
C1 – M10	1647.89	450.60	(1197.28, 2098.49)	0.76	0.27 (1σ).
PC6 – PC12	712.43	302.24	(107.95, 1316.92)	1	0.42

Table 7: Statistical data for porosity

Sample	Void ratio	Porosity	Standard deviation of porosity, s	(σ-2s, σ+2s)	Proportion within 2s	Coefficient of variation, CV
C1 – C7	0.18	0.147	0.076	(-0.005, 0.299)	1	0.52
M1 – M10	0.29	0.221	0.066	(0.089, 0.353)	1	0.30
C1 – M10	0.25	0.191	0.078	(0.113, 0.268)	0.59	0.41 (1s)
C1 – M10	0.25	0.191	0.078	(0.035, 0.347)	1	0.41
PC6 – PC10	0.42	0.29	0.05	(0.20, 0.39)	1	0.16

Flexural Strength

The main aim of these tests was to obtain the ability of each beam sample to resist bending. Only the cast in-place 28-day P.C. beam samples were tested. The modulus of rupture obtained from this test can be used in the design of rigid pavements. Failure occurred at the middle third section of the beam. Once again, the errors may have occurred as a result of batch mixing, fabrication, sampling method and compaction. This test is very sensitive to mix design, moisture content, sample preparation, handling and curing process (ASTM, 2004b).

Flexural strength values for pervious concrete as discussed in some literature ranges from 450 – 620 psi. The flexural strength range of conventional concrete is between 500 – 800 psi. Table 8 shows that the modulus of rupture ranges from 198 – 279 psi. The lower values obtained in the current study may be attributed to factors such as weaker bonding agent (cement paste) used and improper mix design. The 2σ test in Table 9 shows that the modulus of rupture values falls within acceptable range. The average modulus of rupture of the beams was 246 psi. This value is almost half of that specified in some literature.

Table 8: Modulus of rupture from flexural strength test of cast in-situ pervious concrete

Sample	Maximum Load, P (lbf)	Modulus of Rupture, M.R (psi)
B1	2003	197.3
B2	2699	256.0
B3	2493	243.0
B4	2680	256.5
B5	2797	278.1

Table 9: Statistical data for modulus of rupture

Sample	Average Modulus of rupture (psi)	Standard Deviation, s	Range	Proportion within 2s	Coefficient of variation, CV
B1 – B5	246.2	30.09	(185.99, 306.36)	1	0.12

The comparison between the compressive strength test and flexural strength conducted in this research and values obtained from past literature is summarized in Table 10. From previous NRMCA reports (NRMCA, 2005), the compressive strength range of PC is in the range of 500 – 4000 psi with a typical range of of 2,000 – 2,500 psi. The flexural strength of PC is in the range of 150 – 550 psi (NRMCA, 2005). The compressive strength of cored pervious concrete cylinders obtained from three field locations were in the range of 1643 – 2495 psi previously found in literature (Crouch, 2006).

Table 10: Comparison between the strength laboratory test and literature

Pavement Type	Compressive strength (psi)		Flexural strength (psi)	
	Test	Literature	Test	Literature
Cored Pervious Concrete (8x4)	1725	1643 - 2500	-	-
28-day Pervious concrete (8x4)	365 - 1100	500 – 4000 2000 (typical)	247	150 - 550

Field (FWD) Testing Results

As previously stated, back-calculation of the moduli values was done by means of the software Modulus 6.0. For a clearer analysis, each pavement type will be discussed for each load application and the result of the resilient moduli and the measured deflection will be summarized in a table. This analysis treats the pavement system as a deflection basin.

Meanwhile, for rigid pervious pavement surfaces, the FWD deflection basin was compared to that of conventional concrete surface as shown in Table 11. As expected, the pervious concrete FWD deflections were greater than that of conventional concrete because its surface has pore spaces and it is not as rigid as the conventional concrete.

Table 11: Comparison between the pervious concrete and conventional concrete

Pervious Concrete							
Load (lb)	Sensor spacing (in.)						
	0	8	12	18	24	36	60
6000	15.76	13.49	12.17	10.24	8.71	5.94	2.53
9000	22.66	19.53	17.69	15.05	12.72	8.62	3.63
12000	30.30	26.11	23.74	20.14	17.10	11.61	4.90
Conventional Concrete							
Load (lb)	Sensor spacing (in.)						
	0	8	12	18	24	36	60
6000	3.95	3.65	3.46	3.17	2.85	2.19	1.29
9000	5.88	5.48	5.19	4.74	4.29	3.32	1.96
12000	7.33	6.81	6.43	5.88	5.32	4.14	2.45

The FWD deflection basin for the pervious concrete is shown in Figure 67. The FWD deflection from the load of 12000 lb is greater than that of 6000 lb and 9000 lb. This deflection basin is not as parabolic as that of flexible pavements.

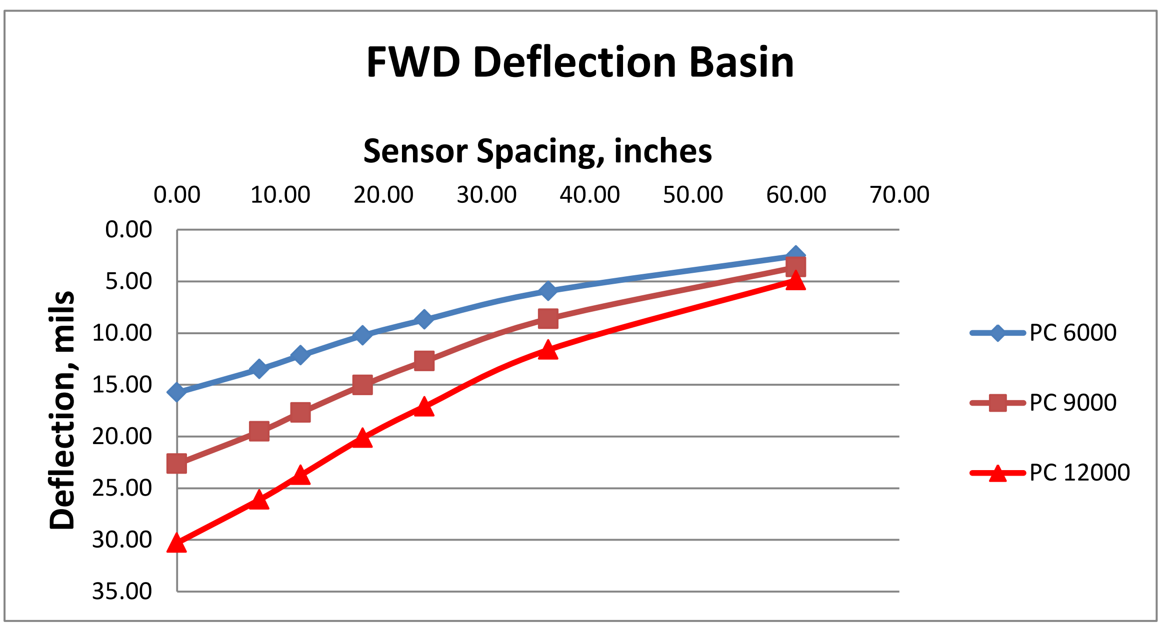


Figure 67: FWD deflection basins for pervious concrete

Meanwhile, the FWD deflection basin for the conventional concrete is shown in Figure 68. This concrete slab had no reinforcement installed. This deflection basin is not as parabolic as that of conventional asphalt because of its rigidity.

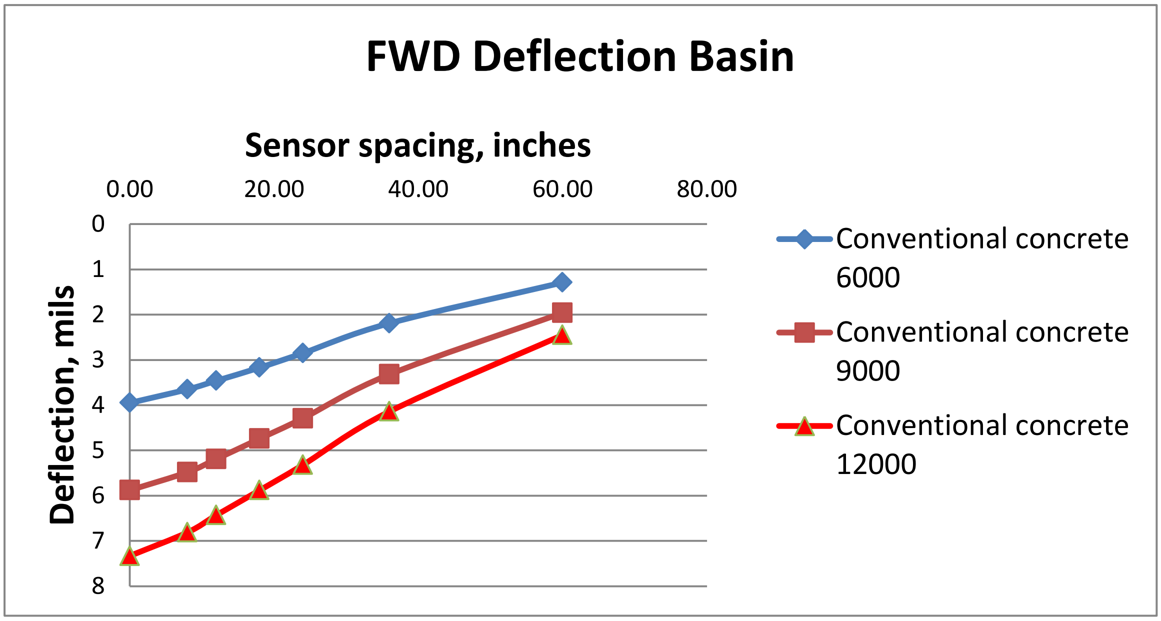


Figure 68: FWD deflection basin of conventional concrete

Table 12 compares the back-calculated surface elastic moduli for the various pervious pavements with value stated in past literature. The in-situ elastic modulus of pervious concrete ranges from 740 – 1350 psi compared to 725 – 2900 psi published in literature (Rohne, et al., 2009). The conventional concrete resilient modulus ranges from 3000 – 7700 psi. Modulus 6.0 does not give precise result when used to calculate the elastic moduli of rigid pavements.

Table 12: Comparison of back-calculated in-situ elastic moduli

Pavement Type	Back-calculated Elastic Moduli (psi)	
	Test	Literature
Pervious Concrete	740 – 1350	725 - 2900
Conventional Concrete	3000 - 7700	2000 - 6000

CONCLUSIONS AND OBSERVATIONS

General Observations

Observations made during the installation of the pervious concrete are included below. There was noticeable amount of raveling at the surface of the pavement throughout the section caused by heavy vehicle loads and turning movements (semi-trucks, dump trucks, heavy construction equipment, etc.) soon after installation. This raveling was reduced as time went on as the few loose particles were removed and all that was left were the intact particles. Some cracking was noticed in the pavement sections that were typical of conventional concrete, and is concluded that the pervious concrete should be designed at a greater thickness than 6 inches to be able to handle the heavy vehicle loads.

In conclusion the pervious concrete pavement systems studied are able to perform well considering the high level of sediment accumulation on the surfaces throughout the 22-month study period. Out of one hundred and nineteen tests conducted on the above sections only thirteen tests recorded rates below 2.0 in/hr. This study reveals that even under these intense sediment loading conditions that 89.1% of the measured infiltration rates stayed above the state recommended minimum 2.0 in/hr for all the sections tested. The pervious concrete pavement systems can be expected to perform above 2.0 in/hr under normal “light to medium” sediment accumulation conditions without any maintenance and the infiltration rate can fall below 2.0 in/hr if under intense “heavy” sediment loading. These systems, however, can be rejuvenated by a standard vacuum sweeper truck to rates above 2.0 in/hr. The above mentioned intense sediment loading may be experienced by a pavement system located near highly disturbed soils, coastal areas, or near the end of the pavements service life only.

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 in removing the clogging sediments in the surface pores when done during a rain storm, shortly after a rain storm, or when the surface is saturated by ponding water on the surface.

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 a standard vacuum truck can 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 section 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 is less than the calculated theoretical storage found by measuring each of the individual components. 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 pervious concrete system is about 12%.

Water Quality

This study examined the quality of water that infiltrates through two pervious concrete systems, a system containing a Bold&Gold™ 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 a little higher than the concentrations measured in stormwater in the Orlando Florida area. 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 pervious concrete system as the specified product. The cross section for this system consists of a 10 inch deep layer of Bold&Gold™ pollution control media and a 6 inch deep layer of pervious concrete on top. There is a non-woven filter fabric separating the parent earth soil from the Bold&Gold™ 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 0.75. 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 10 minute duration. Using the rational method, it is determined that the rainfall excess flow rate is 6.3 cfs and multiplying that by the 10 minute duration gives a runoff volume of 3,780 cubic feet, or 107,038 liters. Therefore, the TN mass leaving the system is 84.6 grams and the TP mass leaving the system is 72.8 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 pervious concrete system specified would have a TN mass reduction of 23.4 grams (22%) and a TP mass reduction of 20.1 grams (22%) for a one acre parking lot.

The above analysis and example problem shows that there is a water quality benefit to using the pervious concrete system. This benefit is only realized, however, through taking into account the stormwater runoff volume reduction achieved. 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

The test and analysis of the structural properties the existing driveways at the Stormwater Management Academy laboratory shows the in-situ strength parameters of pervious concrete pavements was conducted in this study. The compressive strength values for pervious concrete samples cored from the installation at the field laboratory ranged from 988 – 2429 psi while the compressive strength range of the 8 x 4 cast in place samples was in the range 364 – 1100 psi. Flexural strength values for pervious concrete as discussed in literature ranges from 450 – 620 psi. The flexural strength range of conventional concrete is between 500 – 800 psi. From the testing in this project, the modulus of rupture ranges from 198 – 279 psi. The lower values obtained in the current study may be attributed to factors such as weaker bonding agent (cement paste) used and improper mix design.

Pervious concrete was found to have a range of modulus of elasticity of 740 – 1350 psi. This is comparable to the elastic modulus value of 725 - 2900 psi specified in literature. Typical elastic moduli for conventional concrete ranged from 2000 – 6000 psi. There are no exact mix designs for pervious pavements that will produce high mechanical properties. Laboratory testing is one of the methods of establishing a range of values which will lead to an acceptable design.

It should be emphasized that the use of pervious pavements should be limited to areas with low volume traffic. The accumulated 18 kip equivalent single axle load (ESAL) of approximately 412,000 was estimated as the load the pavement will be subjected to during its design life. The summary tables at different reliability levels show the effect of traffic loading on the structural capacity of the pavement. In rigid pavements, at a given degree of certainty and traffic load, as the modulus of subgrade reaction increases the minimum thickness of the rigid pervious pavement decreases.

As expected, the pervious concrete FWD deflections were greater than that of conventional concrete because its surface has pore spaces and it is not as rigid as the conventional concrete. The in-situ elastic modulus of pervious concrete ranges from 740 – 1350 psi compared to 725 – 2900 psi published in literature (Rohne, et al., 2009). The conventional concrete resilient modulus ranges from 3000 – 7700 psi. Modulus 6.0 does not give precise result when used to calculate the elastic moduli of rigid pavements.

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Final Report

Pervious Pavements - Installation, Operations and Strength
Part 2: Porous Asphalt Systems

Work Performed for the Florida Department of Transportation

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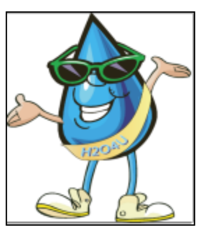

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation. Furthermore, the authors are not responsible for the actual effectiveness 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 are designed to have enhanced pore sizes in the surface layer compared to conventional pavement types, encouraging flow of water through the material. 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. This research project investigated the infiltration rates, rejuvenation techniques, sustainable storage of the components and complete systems, water quality, and the strength properties of porous asphalt pavements. The work was conducted at the field labs of the Stormwater Management Academy at UCF.

Porous asphalt section showed noticeable amount of raveling at the surface under day-to-day loads after installation. The asphaltic binder never seemed to "set up" especially during the high temperatures causing the sediments on the surface to stick to the asphalt. Compared to other sections, there was noticeable ponding and runoff from porous asphalt sections even under low intensity short duration events. This pavement type also experienced the highest decline of infiltration rate under sediment loading and it was not possible to improve the infiltration rates using vacuuming. This system is not recommended as an effective pervious system, particularly for the mix design used at our research facility and under the high temperature climates like Florida.

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INTRODUCTION

Porous 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).

Porous 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 recycled automobile tire chips (used in construction of the surface layer), tire crumbs (used in blending of the pollution control media), and crushed concrete aggregates, can contribute to earning LEED^{TM} points. Porous 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 system is measured in the laboratory and is based on Archimedes's principles of water displacement. Barrels containing the porous asphalt system were constructed and water quality samples collected and 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 Porous Asphalt pavement 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 the flexible 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.

Pervious pavement systems offer designers and planners an effective tool for managing stormwater. These systems manage stormwater by increasing the rate and volume of infiltration and the reduction of runoff volume. By reducing runoff from pavement surfaces, a reduction in the amount of pollutants carried downstream by runoff water can be achieved to minimize non-point source pollution.

The porous asphalt system is designed to have larger pore sizes in the surface layer compared to conventional asphaltic pavement types, created to encourage maximum flow of water through the material. Additionally, sediments may also flow freely through the material possibly reducing water infiltration rates and the potential water storage volume in the rock reservoir layer below. The performance of pervious pavement 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 induced erosion. How fast a permeable pavement system will infiltrate stormwater throughout its service life will change through periodic sediment accumulation on the surface and the frequency of maintenance.

This report presents the infiltration rates due to high levels of sediment 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 porous asphalt pavement systems. The new draft statewide stormwater rule in Florida suggests that the minimum vertical infiltration rate 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, stone support/reservoir layer, pollution control layer, and finally the parent earth below the system 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 clogging. This is done to test the effectiveness of vacuum cleaning as a rejuvenation method for porous asphalt systems. The results of this study will provide designers, regulators, and contractors with an understanding of how well these pervious pavement systems perform, as per infiltration of water, and the effectiveness of the proposed maintenance method of vacuum sweeping 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 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 & 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 stormwater's capability of 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 causing serious problems to the structure. The only sure way to keep water from accumulating in the structural section is to drain it using a layer of very high permeability (33 in/hr to 333 in/hr or even greater) material under the full width of traffic lanes which 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) that 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 pervious pavement systems can also function as parking areas as well as on-site stormwater control (Dreelin et. al., 2003). Smith (2005) compares porous pavement systems to infiltration 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 porous pavement systems, trees have 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 pervious 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 stone reservoir/sub-base of the pervious pavement system is designed to store rainwater and allow it to percolate into sub-soils restoring the natural ground water table levels that 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 use and implementation of pervious pavement systems include technical uncertainty in the long term performance, lack of data, social perception, adoption, and maintenance (Abbot and Comino-Mateos, 2003).

Literature Review

Water has often been described as the "enemy" of asphalt (Cahill, 2003). Runoff from impervious surfaces finds their way into dense asphalt surface and erodes it. Therefore immense effort has being taken to prevent this occurrence. Pervious asphalt (PA) is an effective way of curbing this problem. Pervious asphalt, otherwise known as porous asphalt, is a well-known pavement material for stormwater management purposes. This type of pavement is made up of asphalt cement (binder) and coarse aggregates. It is different from dense asphalt concrete because of its use of single sized aggregates. Like most pervious pavements, it has little or no fine aggregates in its mixture.

According to Cahill (2003), porous asphalt does not usually require additives or proprietary ingredients, even though it has been observed that polymers or fibers help to improve its durability and shear strength. Like most pervious pavements, this type of pavement is mostly used as parking lots, driveways, walkways.

Nevertheless, the major issue with porous asphalt is that of clogging (Ferguson, 2005). Clogging is normally caused by the asphalt binder. In some cases, the binder is too fluid or the bond between the binder and the single sized aggregates is weak, thereby making the binder gradually drain downwards from the surface through the pore space resulting into a clogging layer inside the pavement structure. This phenomenon mostly occurs in hot regions like Florida. The permeability of this pavement is adversely affected and also unbound surface particles are easily seen.

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 reduce 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. An embedded ring device developed to monitor influences of sub-layer clogging does reveal this phenomenon. 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 a 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).

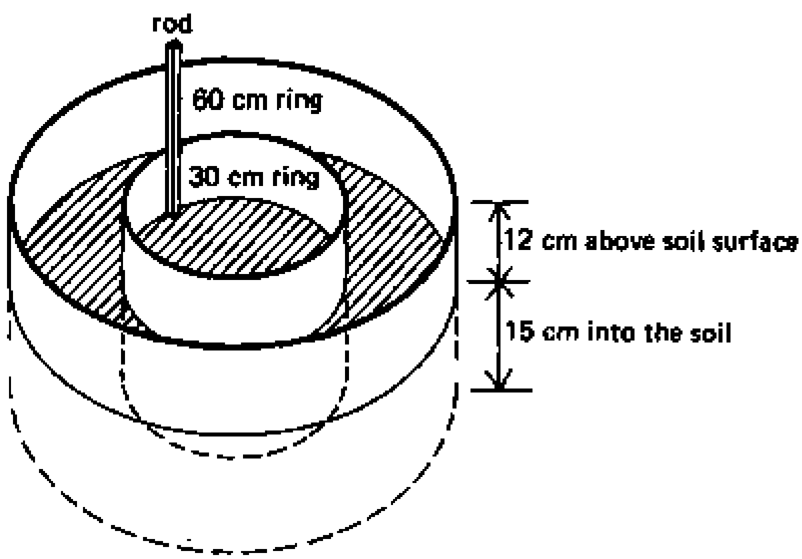
Field Infiltration Methods

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 subsoil exfiltrator 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 well as other factors. It should be noted that tests at the same site are not likely to give identical results. The results are recommended primarily for comparative use (ASTM D3385, 2009). The testing procedure is as described by the ASTM standard test method for infiltration rate of soils in field using double-ring infiltrometer ASTM D3385. A typical double-ring infiltrometer set-up for field testing is presented in Figure 1 (Brouwer, et al. 1988).



(Courtesy: Brouwer, et al. 1988)

Figure 1: Double Ring Infiltrometer (*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 a 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 x 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. The long-ring Erik, on the other hand, 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. 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. The plan and section views of the ERIK embedded ring as installed in a permeable pavement system are presented in Figure 2.

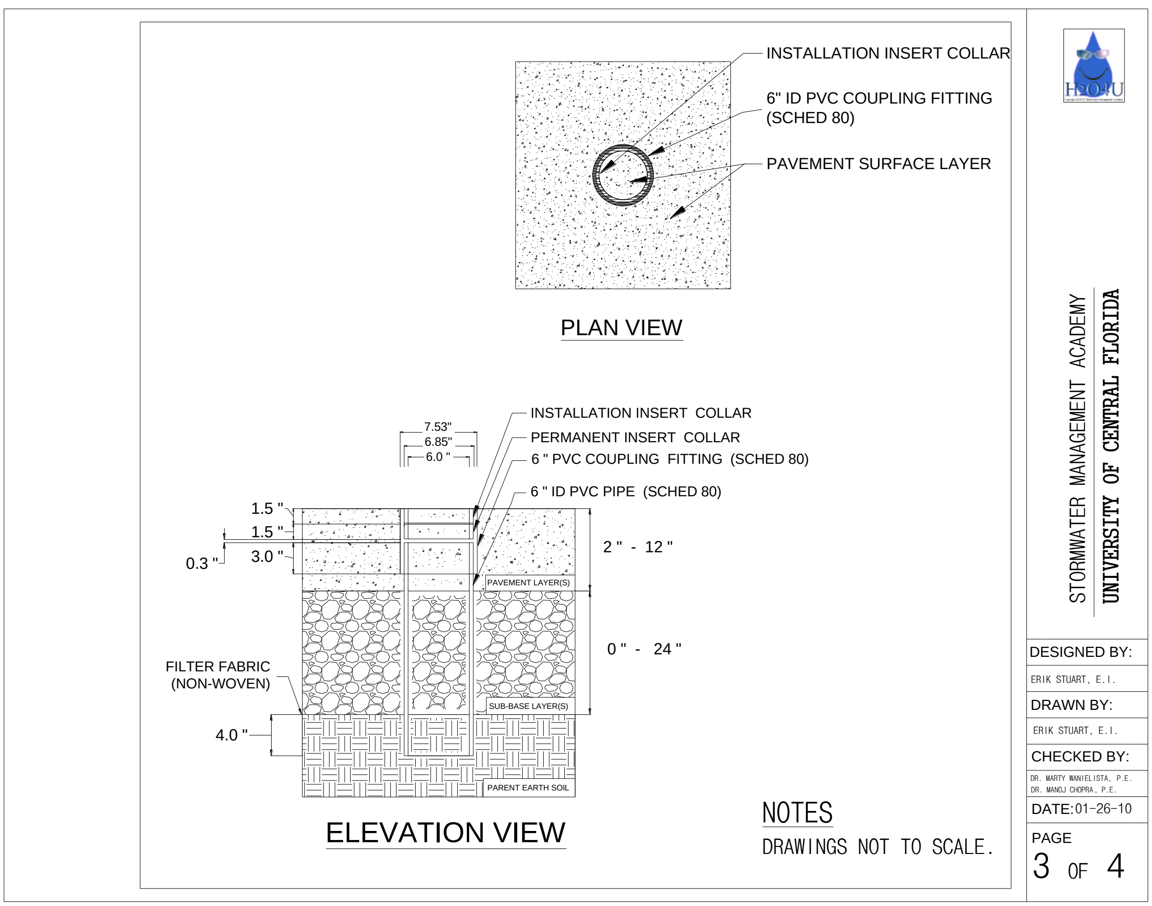


Figure 2: ERIK monitoring tube

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. 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; nor 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.

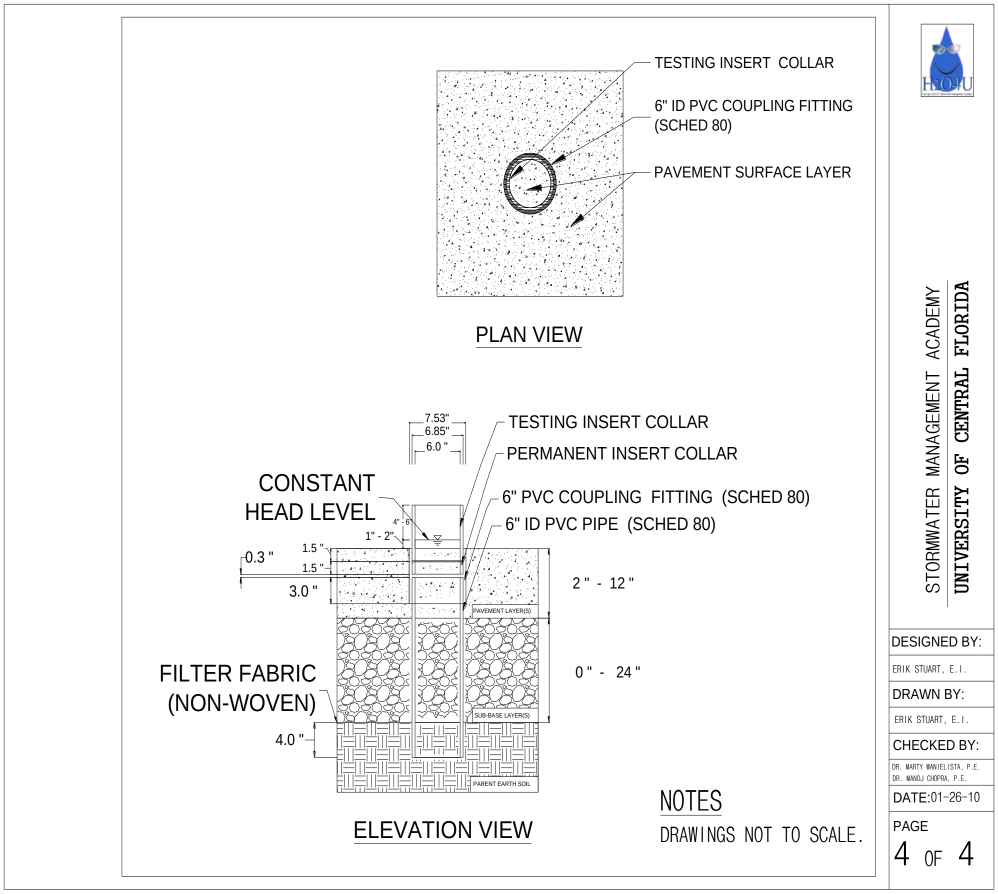


Figure 3: ERIK embedded ring installed

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 measure

ed. The plan and elevation views of the monitoring device are presented in Figure 4.

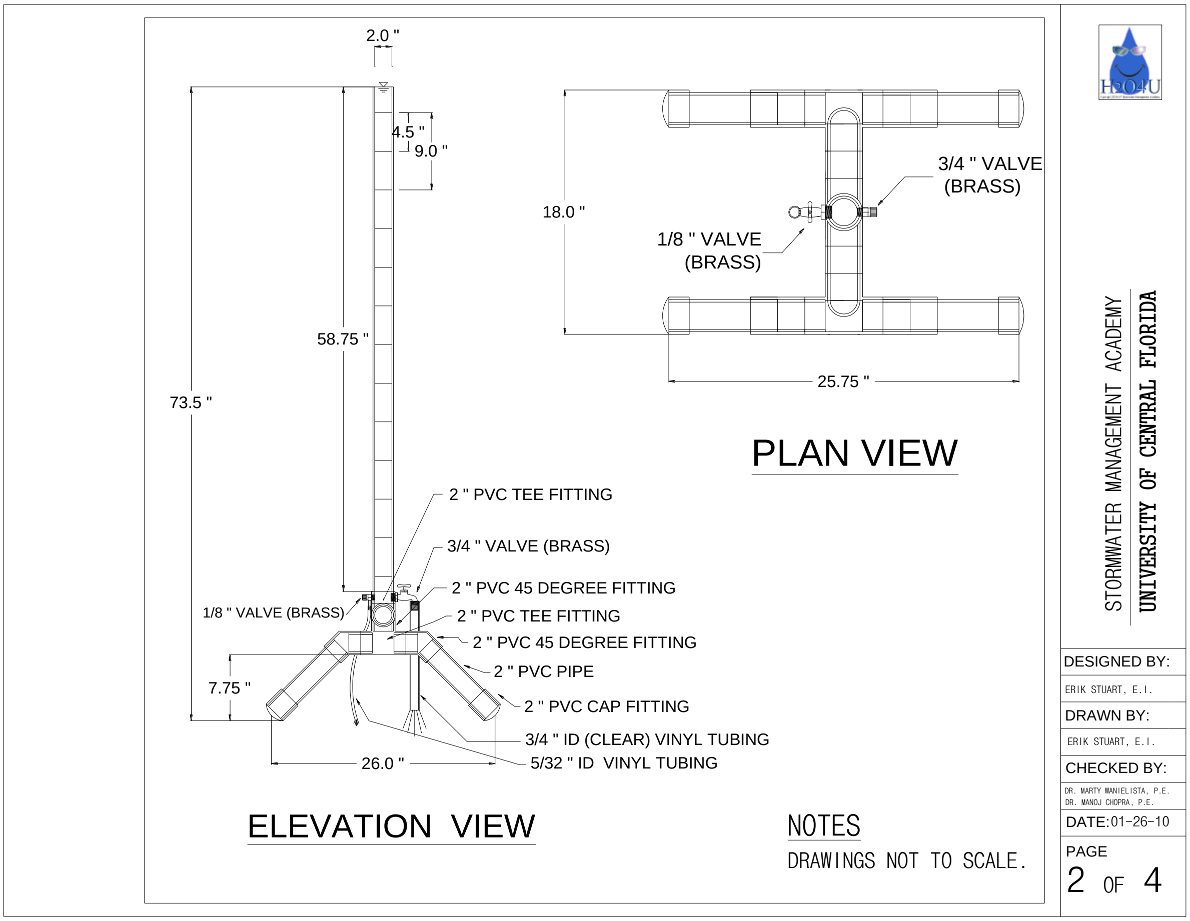


Figure 4: ERIK monitoring cylinder reservoir

PAVEMENT INSTALLATION AND SETUP

The porous asphalt test section is approximately 1500 sq ft with three equal sections denoted as rejuvenation, fill, and Bold&Gold^{TM}. The entire pad is surrounded with flush perimeter curbing (installed after surface layer placement) which only extends about 4 inches deep and no partitioning between the different sections. The surface layer is 4 (four) inches thick of porous asphalt placed on 4 (four) inches of #57 recycled crushed concrete for all sections. The rejuvenation and fill pads both utilized the local A-3 soil as fill for the 8 inches of sub-base, while the Bold&Gold^{TM} pad used the Bold&Gold^{TM} made with the same A-3 soil as the sand component of the mix. All sections were installed with filter fabric separating the parent earth soils from the bottom of the sub-base layer.

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 into piles where the loaders could place in their final positions before leveling and compacting. 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.

Embedded ring infiltrometers are placed flush with the final surface elevation and extends down 4 inches for the "shallow", and 14 inches for the "deep" infiltrometers. The inside of the embedded rings are constructed with the same layers and thicknesses as the rest of the section. The surface layer is then placed with standard equipment shown in the following Figures 5 and 6 below.

Figure 5: Installation of Pavement layer

Figure 6: Surface layer installed similar to conventional asphalt

These steps were all done according to the manufacturer's specifications. Figures 7 and 8 depict the final pavement systems.

Figure 7: Final layout pavement sections

Figure 8: 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 testing, 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 9 below). The sediments were then washed into the pores using a garden hose (see Figures 10 and 11 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 9: The A-3 sediments spread evenly over entire Rejuvenation section

Figure 10: Washing in A-3 soils with garden hose

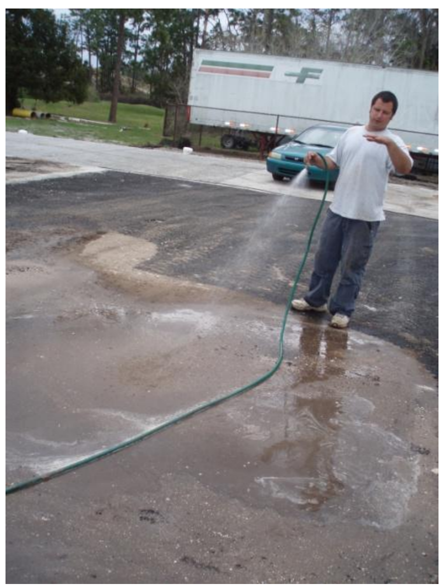


Figure 11: Washing in sediments using garden hose

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, see Figures 12 – 14.

Figure 12: Post sediment loading ERIK testing on “deep” infiltrometer

Figure 13: Post sediment loading ERIK testing on "short" infiltrometer

Figure 14: Post sediment loading ERIK test (close up)

It was noticed that the vacuum force was unsatisfactory at completely detaching and removing the soils in a dry and hardened state. Water was then added to the surface to aid in cleaning the pavements surface which helped a little. The performed maintenance using a standard vacuum truck and the removal of some of the surface debris performed is shown in Figures 15 - 19. However upon closer investigation, qualitatively the sediments appeared to become stuck to the pavements surface. This may be due to the high temperatures causing the asphaltic binder to melt and allow clogging sediments to adhere and eventually become part of the mix that originally was free of fines. Once the surfaces were vacuumed, post-rejuvenation ERIK measurements were continued on the porous asphalt systems.

Figure 15: Porous asphalt surface after vacuuming

Figure 16: Porous asphalt surface after vacuuming

Figure 17: Porous asphalt surface after vacuuming

Figure 18: Close up of Porous asphalt surface after vacuuming

Figure 19: Number 57 stones that were embedded into surface of porous asphalt after driving over by vehicles

Sustainable Storage Evaluation Setup

Sustainable Void Space

The sustainable void spaces or pore volume that could be occupied by 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 20 - 22.

Figure 20: Half Gallon container for component testing of Porous Asphalt

Figure 21: Half Gallon container for component testing of Porous Asphalt

Figure 22: Half Gallon container for component testing of Porous Asphalt

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 conducted on the samples without disturbing or changing the structure of the materials. Also washing and compacting of sediments into the materials to simulate loading in the field and vacuuming to simulate rejuvenation in the field could be done while testing the storage values at the different levels of clogging and rejuvenation see Figure 23 below.

Figure 23: Half Gallon containers being loaded with sediments

Laboratory Porosity

In accordance with this understanding, a variety of substrates were tested including: the porous asphalt and the crushed concrete (#57 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 Half 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 (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, a digital camera, and data sheets 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 24.

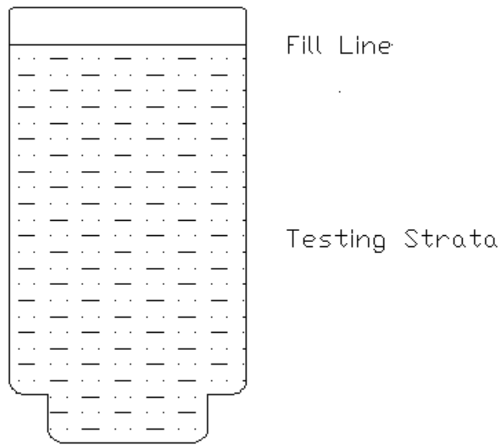


Figure 24: Half Gallon plastic jar cross section for component testing

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, Valava & Montes, 2005).
- Add the cap to the bottom of the ½ gallon jar and 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 to allow gravity to drain samples (see Figure25).
- 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 25: Half Gallon containers 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.

Referring to the cross section drawing in Figure 26, 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.

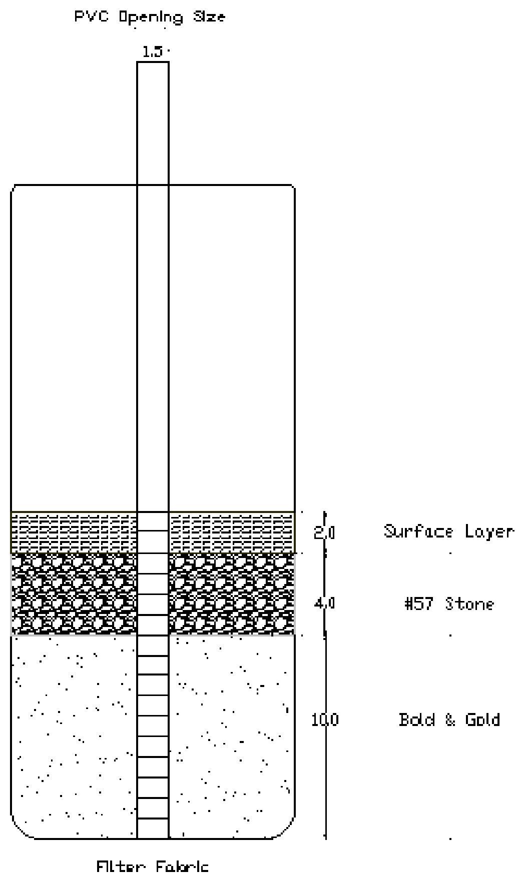


Figure 26: 55 Gallon Barrel for System testing

The procedure for the complete system porosity 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:

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

The above procedure is used to test the system barrels initially, after sediments are loaded and washed into the surface pores (see Figures 27 and 28), and after the surfaces have been vacuumed (see Figure 29).

Figure 27: System testing in 55 gallon barrel

Figure 28: Sediment being washed into the porous asphalt system

Figure 29: Porous asphalt system post vacuum

Water Quality Setup

Restoring the natural hydrologic cycle using pervious pavement 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 Pervious Asphalt. 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 porous asphalt. Due to complications in the field, barrels were constructed to isolate variables and examine the quality of water that infiltrates through the pervious pavement system. The potential water quality benefit of adding a Bold&Gold™ pollution control media layer was also examined. Between May 27th and July 8th 2010, 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.

Porous asphalt is one type of pervious pavement aimed to lower the environmental impact of stormwater runoff. Porous asphalt, like other pervious pavements, helps to replenish water tables and aquifers instead of needing storm sewer systems because of its open structure (NAPA, 2010). Made of bituminous asphalt, screened to prevent small particles from entering the mixture, porous asphalt has an approximate void space of 16%. This allows an effortless permeability which aids in runoff prevention. Unlike many pervious pavements, one advantage porous asphalt has on its competitors is its easy application. It uses the same mixing and application equipment as traditional impervious pavement (Lake Superior, 2010). In rainy weather, it has been noted that porous asphalt reduces aquaplaning, increases skid resistance, and reduces splash and spray behind vehicles (Maurex, 1990). Porous asphalt is also more durable than other pervious pavements on the market, according to Koster (1990), very positive results came from the application of porous asphalt to roads with high-speed traffic.

Over the years, the Netherlands have begun transitioning their roads to a pervious asphalt system. Although the pavement has its disadvantages including a shorter life span, clogging of voids, and high salt dosages during snow fall, tremendous positive results in the environmental footprint have been noted. For instance, research has shown that the runoff volume has significantly decreased as well as the pollutant concentration of the runoff that is generated. In addition, the heavy metal concentration is a factor of 5 lower than runoff from traditional impervious asphalt (Berbee, et al, 1999).

A total of eight test barrels were constructed to isolate the variables of interest, the effect of pervious asphalt 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 layer and four constructed without, labeled B&G and Fill respectively. All eight barrels had the #57 stone sub-base layer installed in the same manner. The porous asphalt was then installed in all but two barrels in a manner that mimicked the field installation. The two barrels without porous asphalt 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 porous asphalt system and the Fill porous asphalt 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. Porous Asphalt
5. Eight Valves
6. Eight 5 Gallon Buckets

7. Stormwater Pond Water
8. Watering Can
9. 1 L Sample Containers
10. Non-woven Filter Fabric

Preparation

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. Bold&Gold^{TM} pollution control media was then poured into the four B&G system barrels and compacted to a depth of 4 inches. Next, #57 Stone was placed into all 8 barrels at a depth of 4 inches, then leveled and compacted. Lastly, the porous asphalt was poured into all the B&G and Fill system barrels except the control barrels. 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 containers were labeled to match each barrel, two containers 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 May 27th to July 8th. 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.

Figure 30: FWD equipment

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. Figure 30 shows a FWD test on a porous pavement section.

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:

$$E_n = \frac{q_a f_i \sum_{i=1}^{s} \left(\frac{f_i}{f_i \omega_i{}^m} \right)^2}{\sum_{i=1}^{s} \left(\frac{f_i}{f_i \omega_i{}^m} \right)}$$

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 60 ERIK measurements were taken for the porous asphalt 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 31 below shows the cross sectional view of the embedded ring infiltrometers (east and west) and the resulting measured infiltration rates are displayed graphically in Figures 32 and 33 below. The results shown below are for the Rejuvenation section.

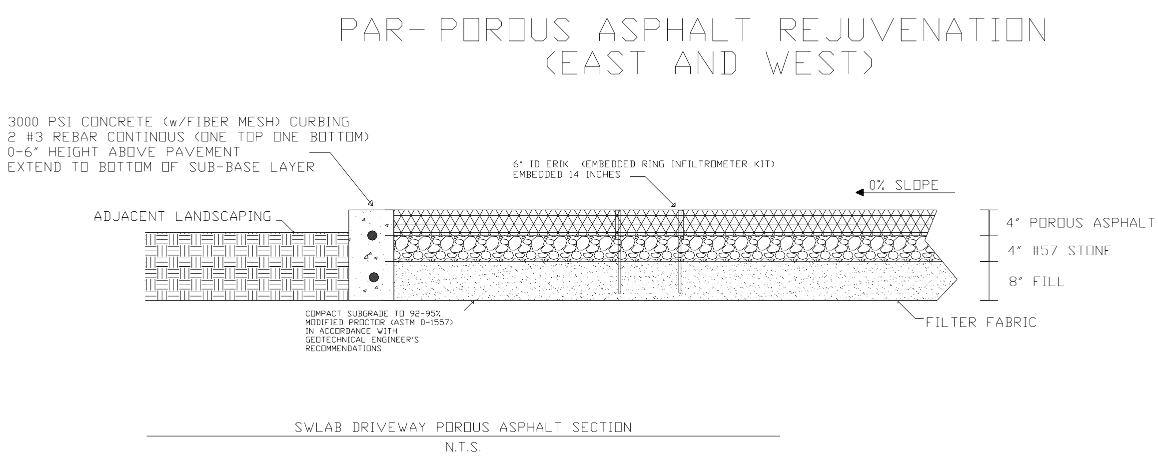


Figure 31: Porous Asphalt Rejuvenation Cross Section (East and West infiltrometers)

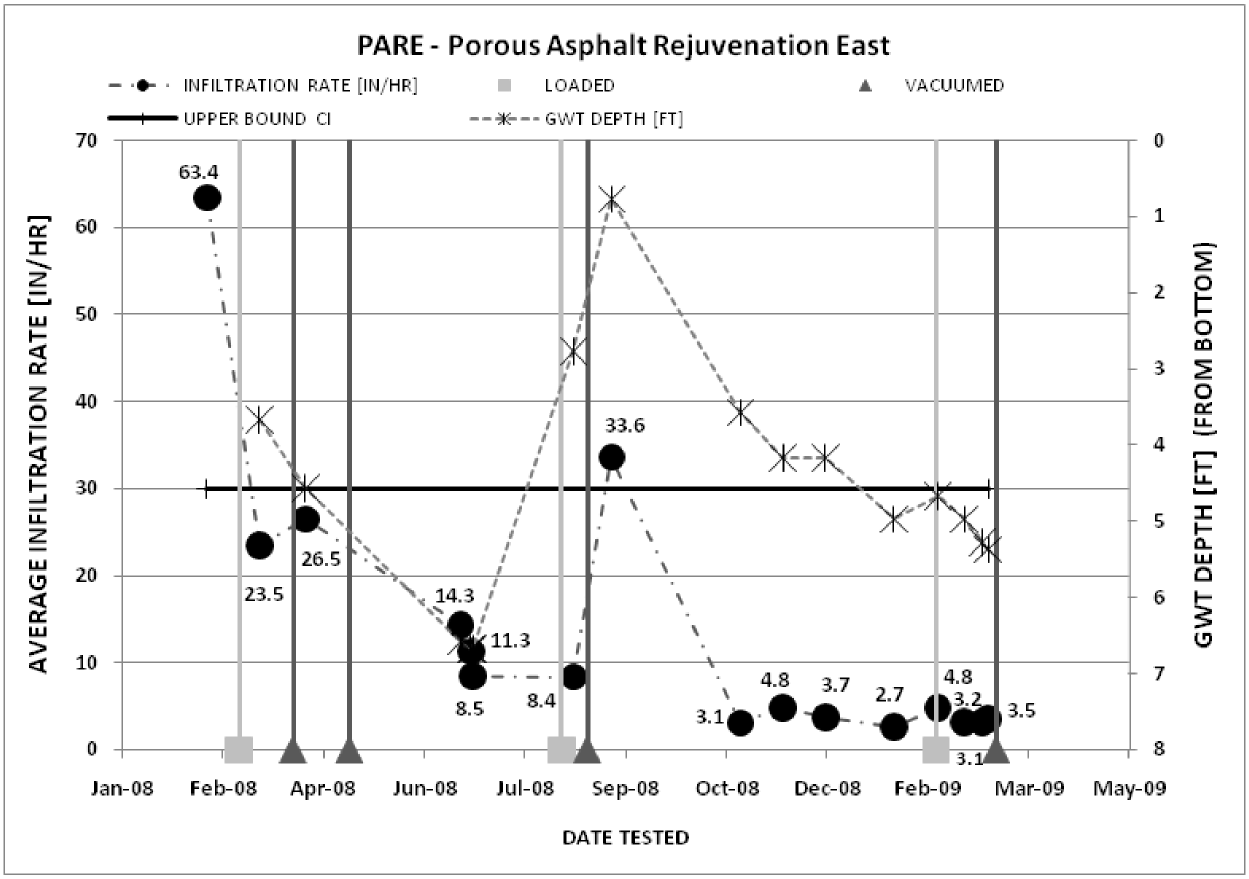


Figure 32: Infiltration Rate (ERIK) Results for the Rejuvenation Section East Infiltrometer

The porous asphalt sections were each equipped with two 14 inch long system infiltrometers in the east and west locations, and one 4 inch long surface infiltrometer located in the middle of the pad. The rejuvenation section used local A-3 soils for the sub-base layer beneath the porous asphalt and #57 stone layers. The initial rate of 63.4 in/hr was measured initiallyfrom the East infiltrometer and then the system was loaded. The rate decreased to 23.5 in/hr after sandy sediments were applied, washed, and compacted into the pavement. The first vacuum attempt only increased the rate to 26.5 in/hr and the successive vacuuming led to a decrease in the measured rates to 14.3, 11.3, and 8.5 in/hr. The system was then loaded with limerock fines in which the measured rate only decreased to 8.4 in/hr. In vacuuming the limerock fines, the rate did increase to 33.6 in/hr but the next four tests measured values of 3.1, 4.8, 3.7, and 2.7 in/hr during the next four months of testing. The porous asphalt was finally loaded again with the sandy soils and resulted in a decrease in the measured rates of 4.8, 3.2, 3.1, and 3.5 in/hr.

Figure 33 below presents the results for the West infiltrometer in the same pavement section.

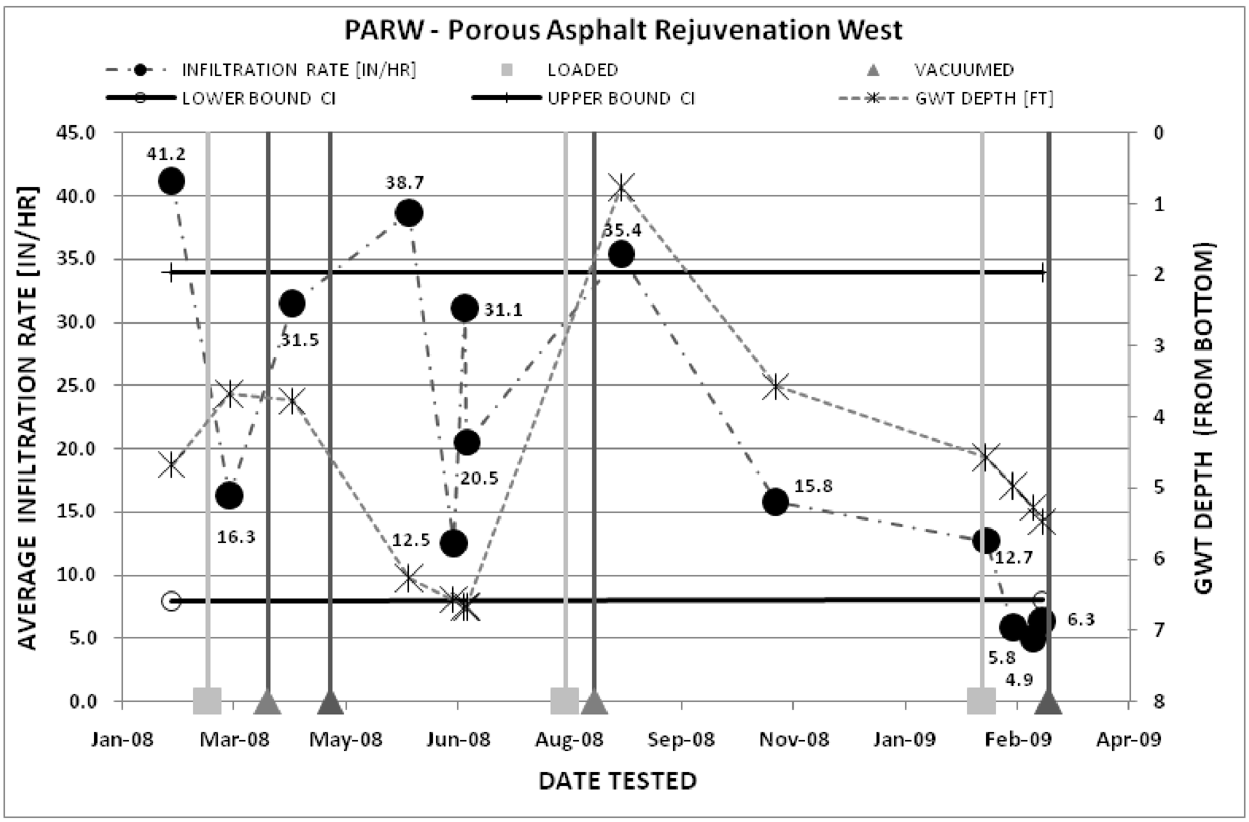


Figure 33: Infiltration Rate (ERIK) Results for the Rejuvenation Section West Infiltrometer

The West infiltrometer measured initial and loaded rates very similar to the identical East infiltrometer located in the same section. The initial rate is 41.2 in/hr and after being subjected to the excessive sediment loading the rate fell to 16.3 in/hr. Both East and West infiltrometers experienced a 60% reduction from the initial rate to the sediment loaded rate. Vacuuming appeared to help improve the measured infiltration rate with the next five tests reported rates ranging from 12.5 - 38.7 in/hr. During the rest of the study period with two more cycles of loading and vacuuming the rates measured ranged from 4.9 – 35.4 in/hr. This infiltrometer indicates the rates remained above 2.0 in/hr throughout the study period.

The “short” infiltrometer that is only embedded four inches into the surface layer is shown in Figure 34 below.

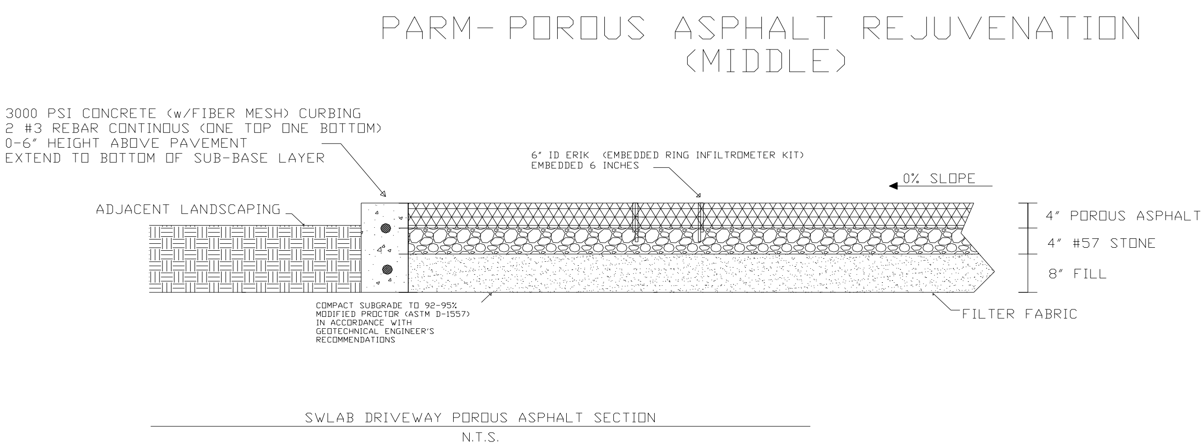


Figure 34: Porous Asphalt Rejuvenation Cross Section (Middle infiltrometer)

The results for the short infiltrometer are displayed below in Figure 35.

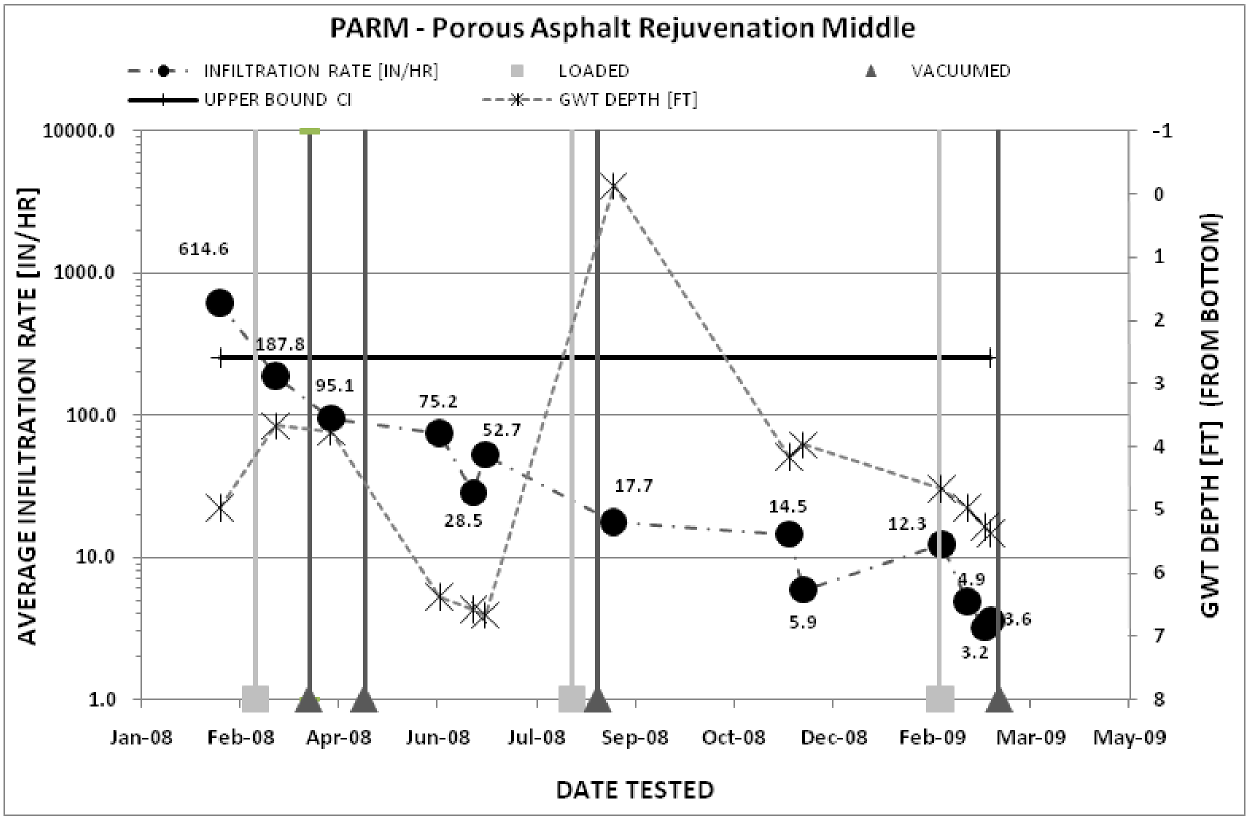


Figure 35: Infiltration Rate (ERIK) Results for the Rejuvenation Section Middle Infiltrometer

The Middle infiltrometer on the same pad which tested the surface materials infiltration measured an initial rate of 614.6 in/hr. Once the surface was clogged with sediments the rate was measured as 187.8 in/hr, and post vacuuming rate measured at 95.1 in/hr. This indicates that the surface layer has been clogged and the vacuum was not able to restore the rate but actually reduced the rate maybe due to the vacuum truck weight compacting sediments into the surface pores. The surface was vacuumed again and did not result in an increase of the infiltration rate, the measured rates were 75.2, 28.5, and 52.7 in/hr during the next three tests. The surface was then clogged with the limerock fines and had a greater impact on the performance of the system. The infiltrometer measured post-loaded rates at 12.3, 4.9, 3.2, and 3.6 in/hr.

The next section analyzed is the Bold&Gold^{TM} section equipped with only one functional "long" infiltrometers in the east location and the "short" infiltrometer located in the middle of the section.

Below Figure 36 shows an illustration of the "deep" infiltrometer located in the east location of the section and the measured infiltration results are displayed in Figure 37.

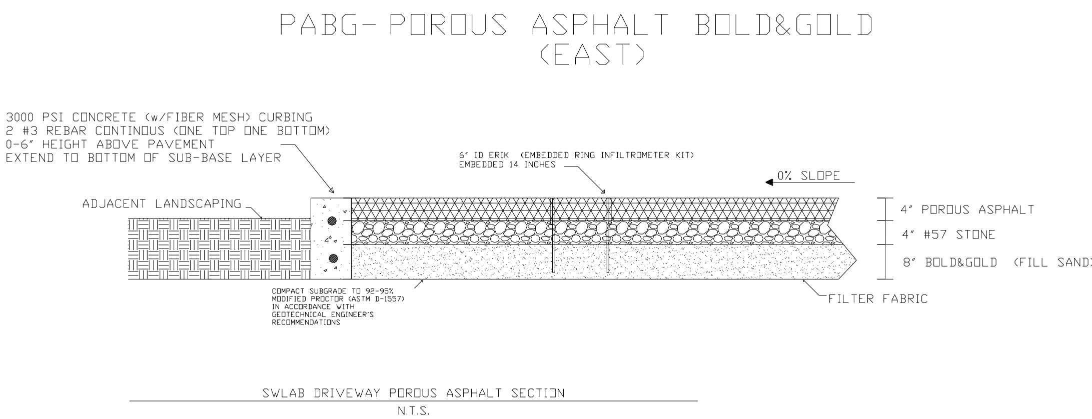


Figure 36: Porous Asphalt Bold&Gold^{TM} Cross Section (East infiltrometer)

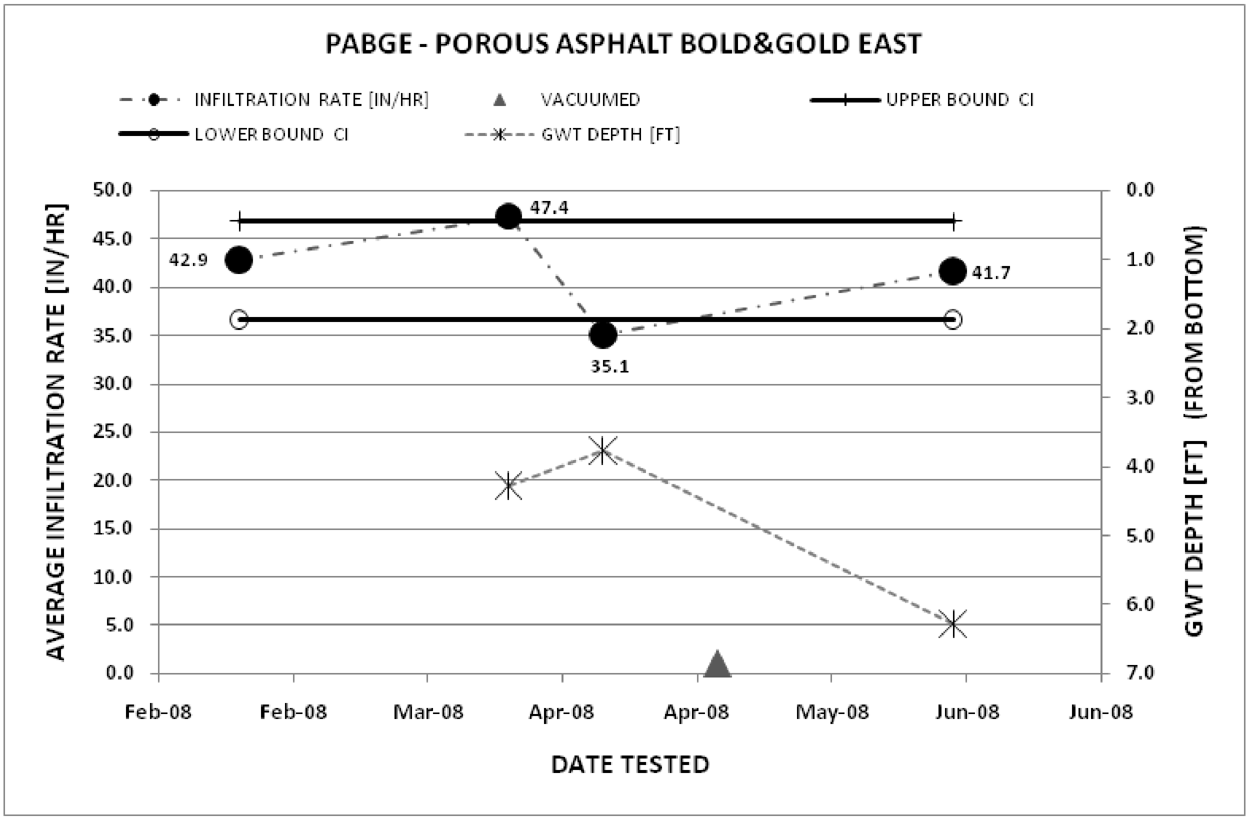


Figure 37: Infiltration Rate (ERIK) Results for the Bold&Gold^{TM} Section East Infiltrometer

The infiltrometer measured initial rates of 42.9, 47.4, and 35.1 in/hr over the first two months of service under natural sediment loading conditions. The surface was vacuumed once and the post-vacuumed rate was measured at 41.7 in/hr. This infiltrometer was then damaged by a skid steer loaders bucket scrapping the surface and cracking the schedule 40 PVC pipe. This lead to the use of schedule 80 PVC to be used for the infiltrometers in case of snow plows or any other equipment causing damage to the infiltrometers.

Next the Bold&Gold^{TM} system equipped with the "short" infiltrometer is illustrated in the cross sectional drawing in Figure 38. The measured infiltration results are presented in Figure 39 below.

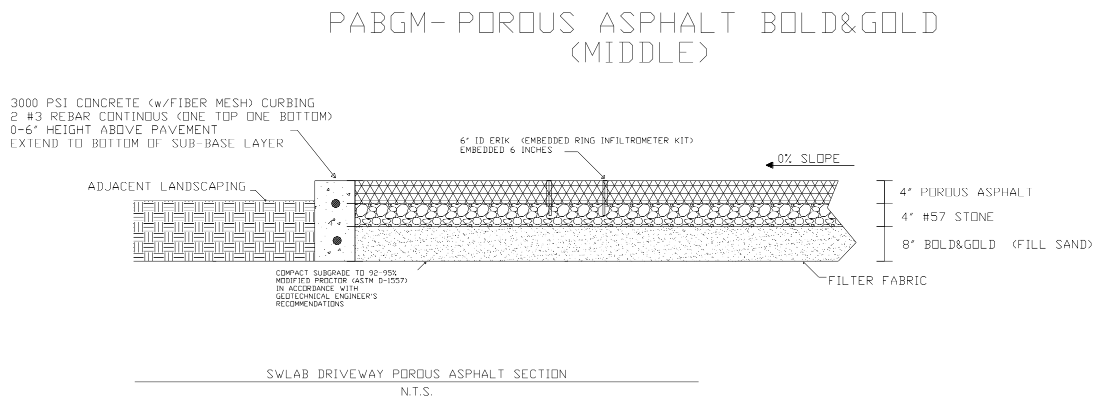


Figure 38: Porous Asphalt Bold&Gold™ Cross Section (middle infiltrometer)

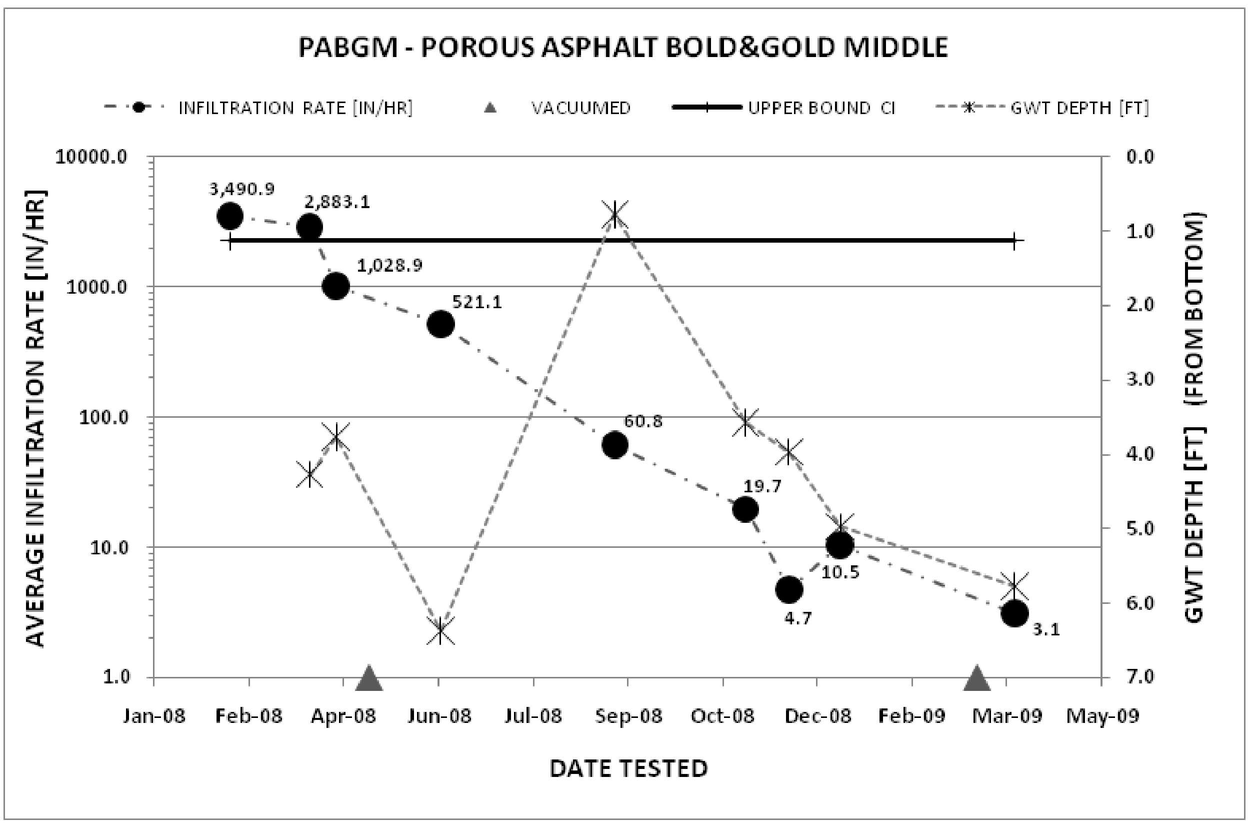


Figure 39: Infiltration Rate (ERIK) Results for the Bold&Gold™ Section Middle Infiltrometer

The short infiltrometer measuring the infiltration rate of the surface layer reported initial rates of 3490, 2883, and 1028 in/hr. After vacuuming the measured rate continued to decline from 521 in/hr down to 4.7 in/hr during the next four tests. The surface was vacuumed once more and the rate continued to fall to 3.1 in/hr showing no sign of the vacuum restoring the measured infiltration rates. This indicates that sediments might be sticking to the surface layer thus making the vacuum not effective in rejuvenating the system.

The Fill section is analyzed next which included one “deep” infiltrometer shown in the drawing in Figure 40. The east infiltrometer was damaged so only the results for the west are presented. Figure 41 below shows the graphical resluts of the infiltration test regime. The “short” infiltrometer of the Fill section is illustrated in Figure 41 below.

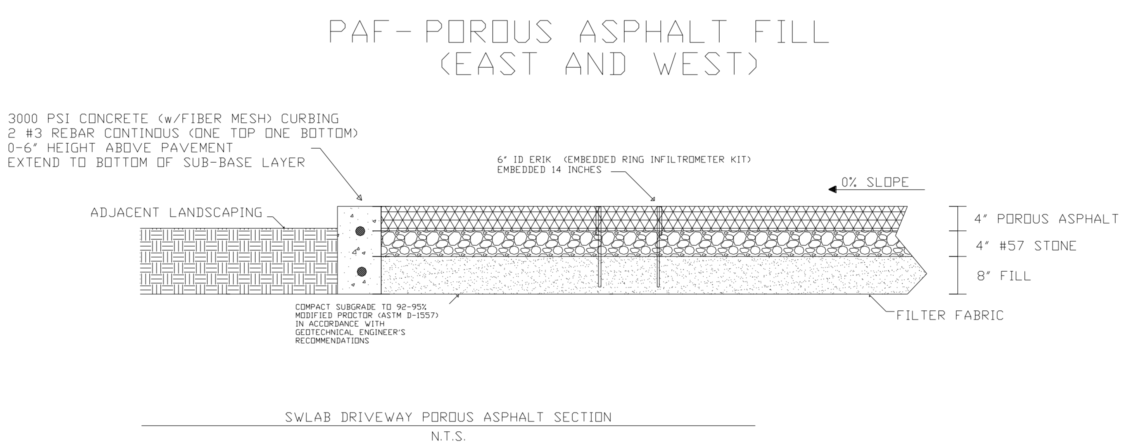


Figure 40: Porous Asphalt Fill Cross Section (West infiltrometer)

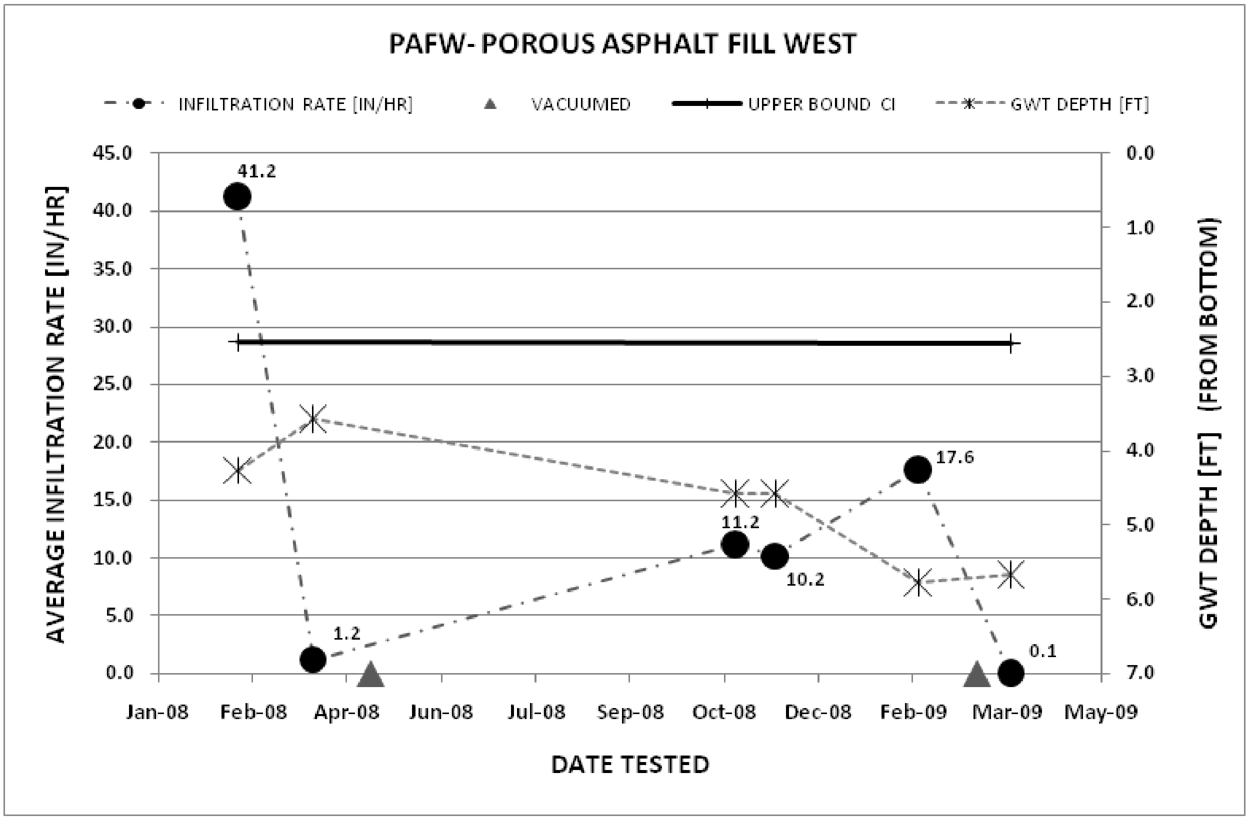


Figure 41: Infiltration Rate (ERIK) Results for the Fill Section West Infiltrometer

The initial rate measured was 41.2 in/hr and after only about a month the rate fell to 1.2 in/hr with only natural sediment loading. After vacuuming and allowing about five months to pass the next three measured rates were 11.2, 10.2, and 17.6 in/hr. The surface was vacuumed again and when retested the rate fell down to 0.1 in/hr. This rate can signify that the system has become clogged to the extent that will not allow stormwater to infiltrate as intended. The rate is measured at an order of magnitude below 2.0 in/hr, and can be concluded that this system has failed.

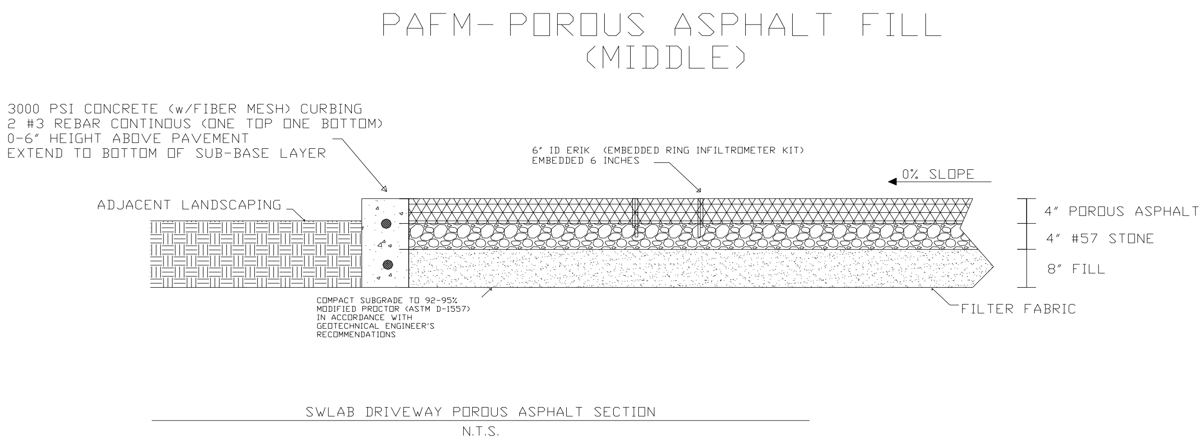


Figure 42: Porous Asphalt Fill Cross Section (Middle infiltrometer)

The results for the short infiltrometer are presented below in Figure 43.

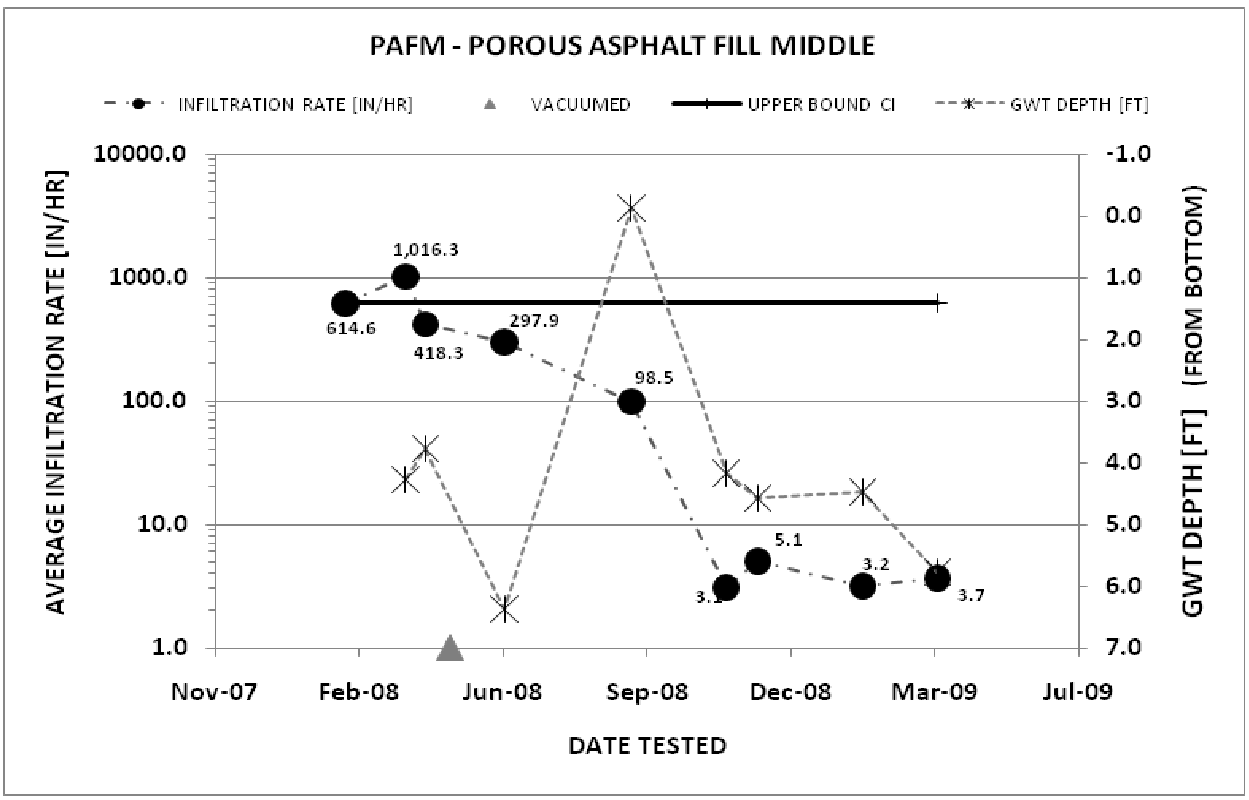


Figure 43: Infiltration Rate (ERIK) Results for the Fill Section Middle Infiltrometer

The above graph shows the initial measured rates ranging from 418 – 1016 in/hr for the first three tests conducted. After vacuuming was conducted the measured rate dropped to 297 in/hr down to 3.2 in/hr over the next six tests conducted over the next eight months of testing. The steady decline in the measured rates for the porous asphalt sections indicates that the pavement continues to clog with sediments in a way that the vacuum is ineffective in removing.

Sustainable Storage Evaluation Results

Sustainable Storage Strength Evaluation

The porosity testing results of the individual component materials are tabulated in Table 1 below. The total porosity of the surface layer measured in the ½ gallon containers is 35.2%. 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 and thus can be considered effective porosity. The average effective porosity value is 32.4% which is a slight reduction from the total porosity measured (almost a 3% reduction) as reported in Table 1 below. This is due to dead end pores which do not allow the water to drain through the asphalt and evaporation.

Next, the porous asphalt material is loaded with sandy sediments to induce clogging of the surface pores which resulted in an average effective loaded porosity 19.6%. It should be noted that the depth of material in the samples in the ½ gallon containers is much more (about 8 inches) than in the field (4 inch thickness). This difference may result in less effective sediment removal in the bottom section of the test sample by the vacuum than may be achieved in the field as the vacuum effectiveness decreases with depth. The noted reduction in porosity is due partially to the fact that some of the volume of sediment particles is now occupying the once empty pore spaces and because a larger number of smaller, air-filled pores retain a larger volume of moisture due to gravity causing water to drain from the pores.

It was observed during the testing that much of the sediments were retained near the top one to two inches of the surface. This observation agrees with the data that shows that much of the empty pore spaces remained free from sediments. After vacuuming the surfaces little of the sediments were extracted by the suction force due to the extent of sediment sticking to the asphaltic material. The sediments near the surface were not easily removed by the vacuums' suction force. Porosity measurements were taken after vacuuming the surfaces and an average effective porosity of 20.2% was recorded.

These results confirm that the clogging sediments did in fact stay near the surface and were not able to be vacuumed from the surface. This proves the surface layer to be effective at filtering sandy sediments and preventing them from entering the sub-layers, which may cause an eventual reduction in storage capacity of the deeper storage layers. The disadvantage is that the surface clogs easily and cannot be restored to allow infiltration and storage into the sub-layer of the system.

The sub-base layer materials were tested using the small scale ½ gallon containers and were tested for total (over dried) and effective (gravitational drainage) porosities. The #57 crushed concrete aggregates provided values of 47.1% total and 41.4% effective porosity averages in the small containers.

Table 1: Individual component material porosity

Porous asphalt PA	AVERAGE MEASURED POROSITY [%]			
MATERIAL TYPE	Total	Effective	LOADED	VACUUMED
Porous asphalt PA	35.2	32.4	19.6	20.2
(#57) Crushed concrete	47.1	41.4		
Bold&Gold	38.9	15.2		

Presented below in Figure 44 is the results for testing the amount of water storage within the complete cross section (using the 55 gallon barrels) of the porous asphalt system including the surface layer, stone support/reservoir layer, and pollution control sub-base layer. The initial tests were conducted without introducing any sediment to the surface to investigate the total or maximum storage available.

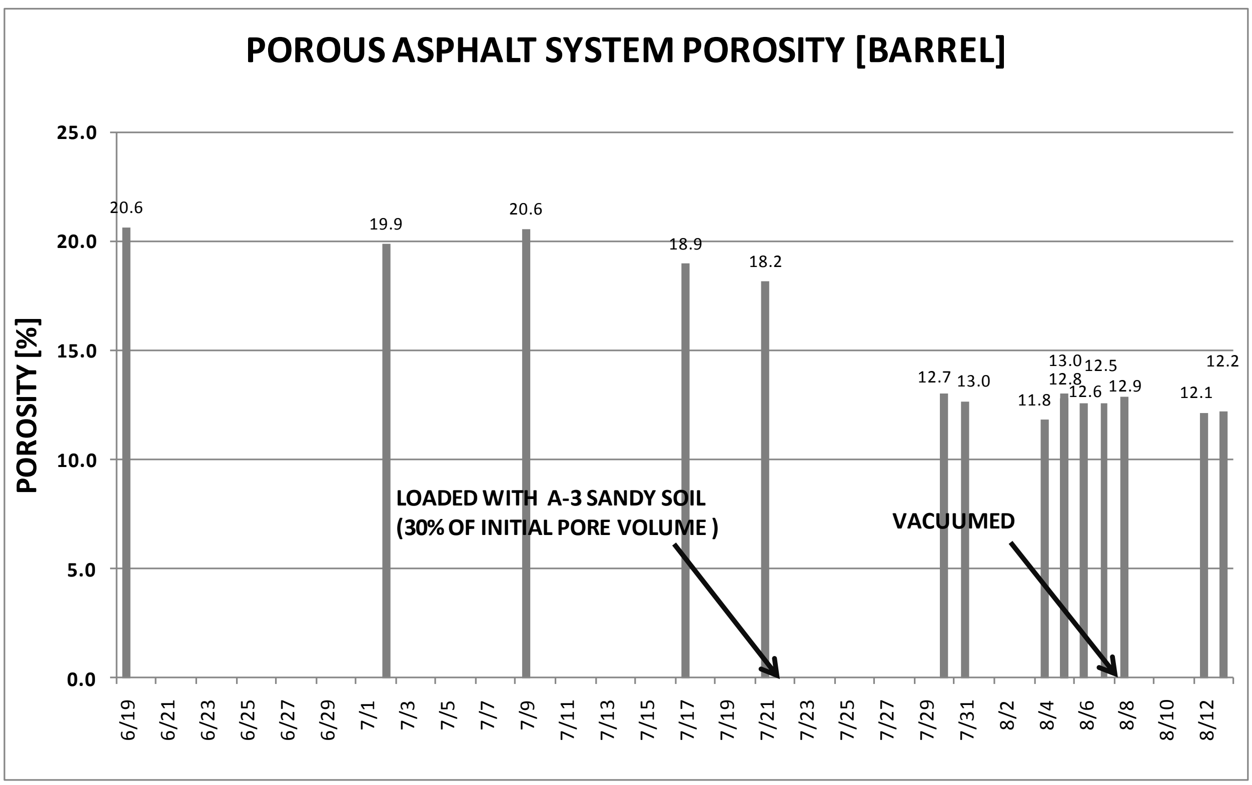


Figure 44: Porous Asphalt System Porosity Results

The first value 20.6% porosity 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 range of (18.2% - 20.6%) 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 30% of the initial pore volume measured by the initial test using A-3 soil on the surface of porous asphalt 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 45 below).

Figure 45: Washing loaded sediments into pores while pumping infiltrated water out through well pipe

After the loading takes place the porosity reduced down to 12.7% as the effective porosity when the system was re-tested. 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, subsequent tests were measured to be about 12% showing that the vacuum is unable to recover and the storage lost by loading with sediments.

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 is calculated at 7.2 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 3.3 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 after intentional sediment loading, the theoretical effective storage in the system is calculated to be 4.0 inches with the actual barrel measurement of 1.9 inches. After vacuuming the surfaces the effective theoretical storage in this system is calculated remains at 4.0 inches while the actual barrel storage is measured at 1.9 inches. It can be concluded that the actual total porosity of a complete system is about, on the average 54% less than if calculated theoretically and the actual effective porosity is about, on the average 29% 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.

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

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 above. Examination of the replicate samples for both the Bold&Gold™ 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.

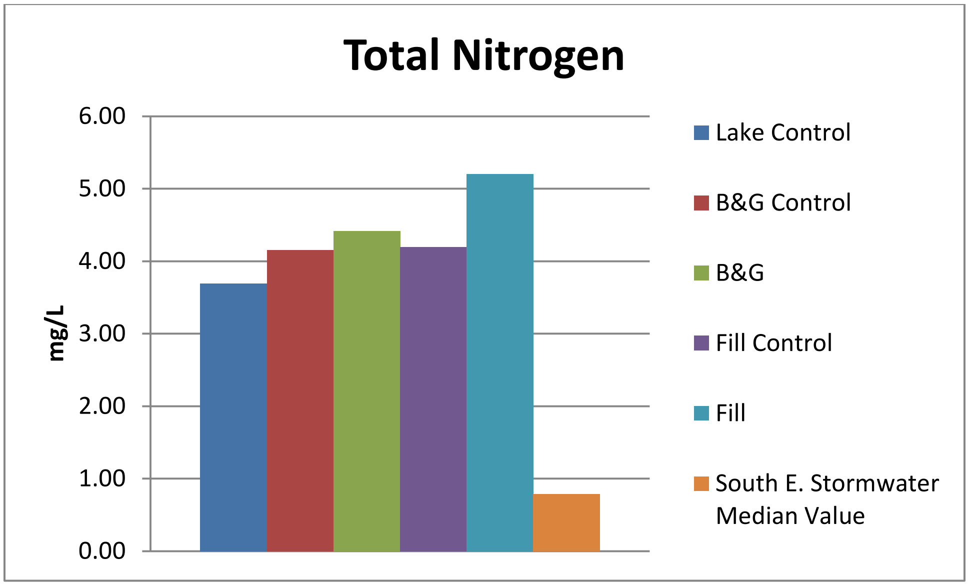


Figure 46: Total Nitrogen Results

Figure 46 shows the total nitrogen results for all the systems tested, the stormwater used to simulate the rain event, and the south eastern stormwater median value. After analysis of the results it was shown that the B&G 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 a slightly higher total nitrogen 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 parent earth and likely leached nutrients. It should be noted that all the systems tested as well as the stormwater pond water had total nitrogen concentrations higher than the south eastern stormwater median value for total nitrogen. Since none of the systems tested were significantly different (α=0.05) from the stormwater pond water used to simulate the rain events these results show that the porous asphalt system has no effect on total nitrogen concentration in stormwater.

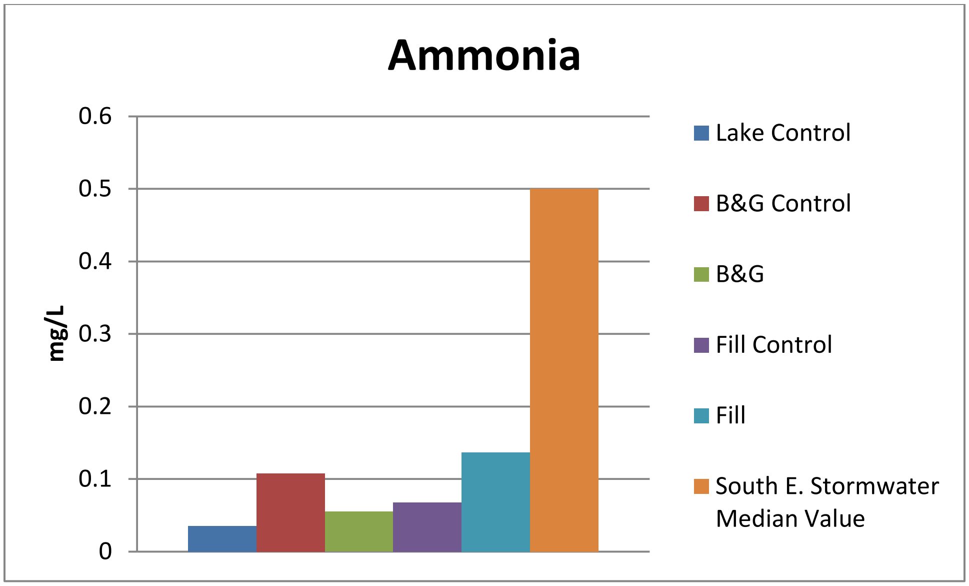


Figure 47: Ammonia Results

Figure 47 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 B&G system was significantly different (α=0.05) from the Fill system. This shows that the addition of the sub-base pollution control layer lowered 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 the 0.5 mg/L which is the south eastern stormwater median value. This decrease is not viewed as significant and was likely a result of chemical conversions that took place in the soil matrix.

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 parent earth and likely leached nutrients.

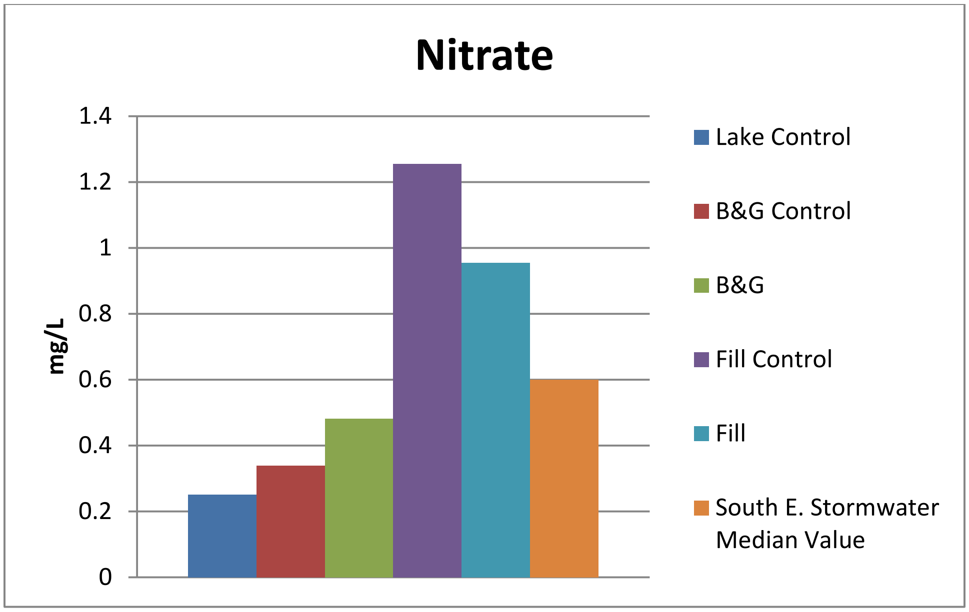


Figure 48: Nitrate Results

Figure 48 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 there was a significant difference (α=0.05) between the B&G control and Fill control systems. Although this was the case for the controls, the B&G and Fill systems were not significantly different. 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 both the B&G control and the B&G systems were lower than the Fill control and the Fill systems.

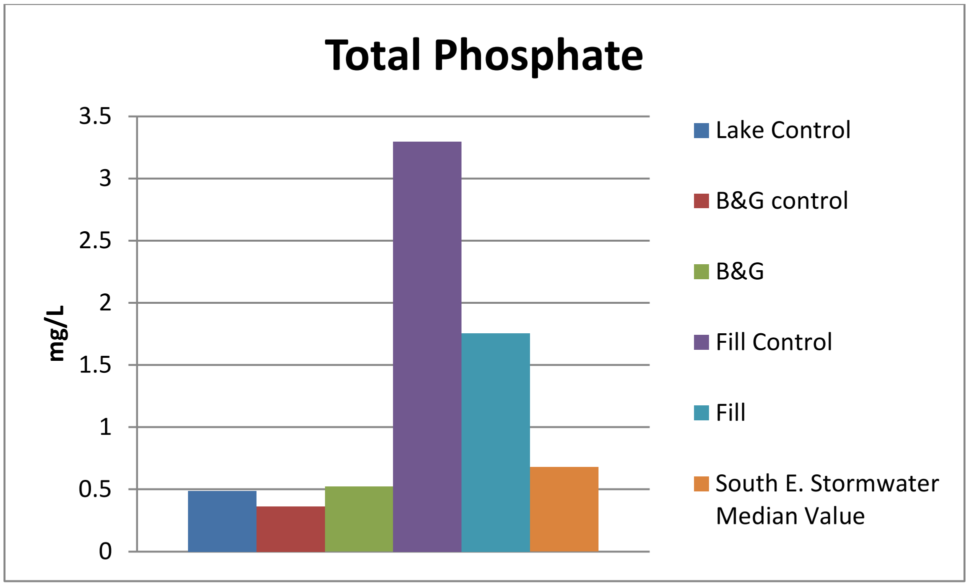


Figure 49: Total Phosphate Results

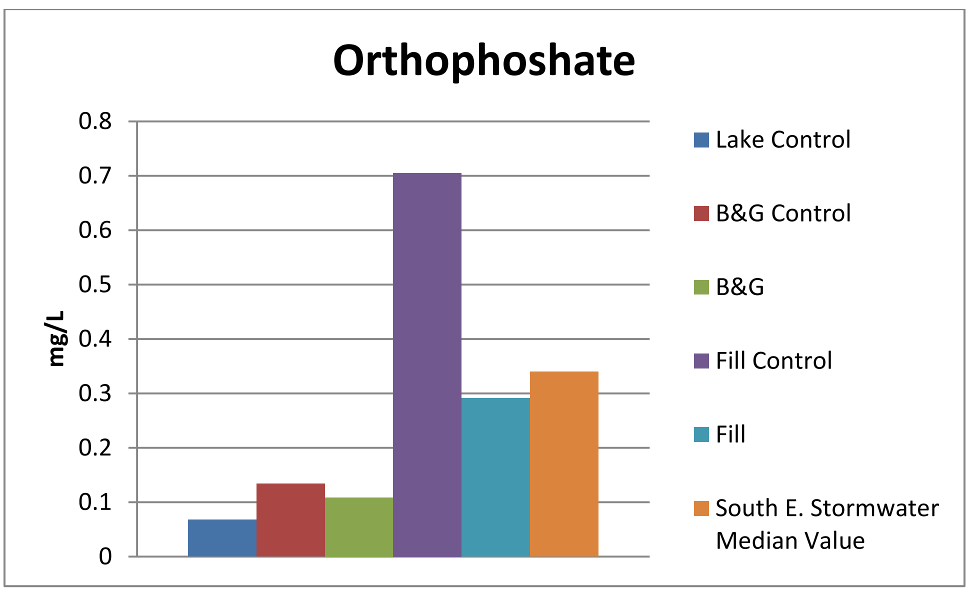


Figure 50: Orthophosphate Results

Figures 49 and 50 show the ortho- and total phosphate concentration results, respectively, 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 B&G and the Fill controls were significantly different (α=0.05) from each other for both ortho- and total phosphate. In addition, the B&G and the Fill systems were also significantly different for total phosphorous. This shows that the use of a B&G pollution control media layer does show a significant reduction in ortho- and total phosphate concentrations compared to the Fill system.

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 parent earth and likely leached nutrients.

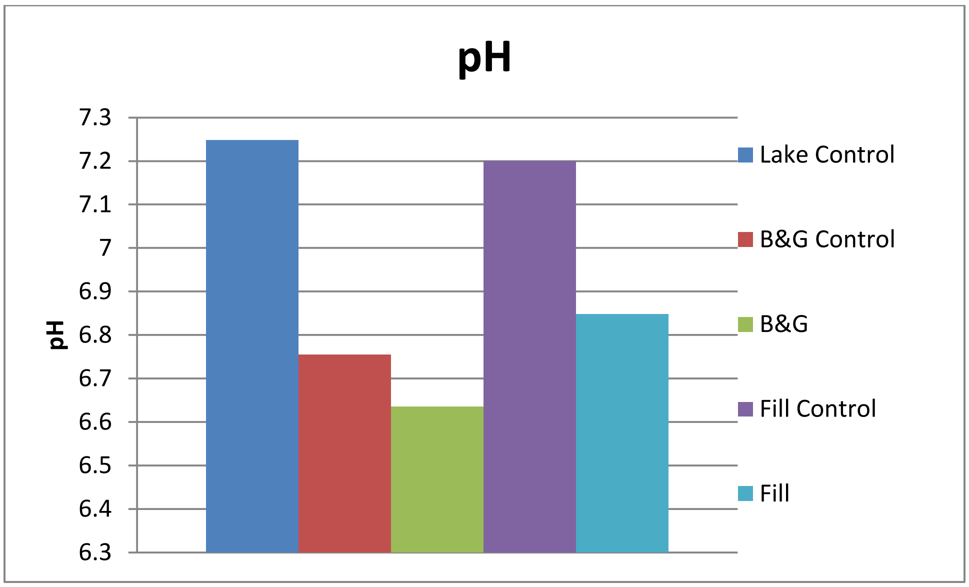


Figure 51: pH Results

Figure 51 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 show that the infiltrated water has sufficient buffering capacity.

FWD Strength Test Results

Back-calculation of the elastic moduli values was done by means of the software Modulus 6.0. The result of the resilient moduli and the measured deflection will be summarized. This analysis treats the pavement system as a deflection basin.

Table 3 shows the comparison between the back-calculated moduli for the 3 porous asphalt types and the conventional asphalt pavement in the field. It is observed here that the elastic moduli range from 535 – 1002 ksi for porous asphalt while the elastic modulus of the conventional asphalt is 904 ksi. For an impact load of about 9000 lb the back-calculated elastic moduli range of porous asphalt is between 485 – 1028 ksi and that of conventional asphalt is about 794 ksi as shown in Table 4.

Table 3: Back-calculation Moduli for P.A and Conventional Asphalt for 6000 lb load

Pavement	PAF	PAR	PABG	Asphalt Inlet	Neptune Drive
$E_{surface}$ 6000 (ksi)	709.4	1001.6	534.2	903.7	111.5
E_{base} 6000(ksi)	72.6	64.1	50	74.6	13.2
$E_{subbase}$ 6000(ksi)	37.6	63.2	36	0	0
$E_{subgrade}$ 6000(ksi)	16.5	13.2	12.3	10.7	20.9
Abs error/sens (%)	0.76	1.14	0.59	1.4	3.06

Table 4: Back-calculation moduli for PA and conventional asphalt for 9000 lb load

Pavement	PAF	PAR	PABG	Asphalt Inlet	Neptune Drive
$E_{surface}$ 9000(ksi)	721.4	1027	484.1	793.1	148.5
E_{base} 9000(ksi)	45.1	64.8	75.1	77.9	11.5
$E_{subbase}$ 9000(ksi)	57.1	49.4	27.9	0	0
$E_{subgrade}$ 9000(ksi)	15.6	12.8	12.1	10.8	19.8
Abs error/sens (%)	0.85	0.65	0.45	1.3	3.68

As seen in Table 5, the back-calculated elastic moduli for the pervious asphalt ranges from 461 – 987 ksi while the conventional asphalt is about 851 ksi when an impact load of 12000 lb is applied on the pavement.

Table 5: Back-calculation moduli for PA and conventional asphalt for 12000 lb load

Pavement	PAF	PAR	PABG	Asphalt Inlet	Neptune Drive
$E_{surface}$ 12000(ksi)	692.2	986.1	460.1	849.5	178.1
E_{base} 12000(ksi)	59.8	60.8	76.9	75	10.3
$E_{subbase}$ 12000(ksi)	35.2	59.8	25	0	0
$E_{subgrade}$ 12000(ksi)	15.1	12.3	11.7	10.5	19.3
Abs error/sens (%)	0.55	0.72	0.56	1.36	3.99

As previously discussed, three points were tested on every pavement section and three load applications 6000 lb, 9000 lb and 12000 lb) were impacted at every point. The average surface layer modulus value of PAF is 707.7 ksi, that of PAR is 1004.9 ksi and PABG is 492.8 ksi. Conventional Asphalt roadway on Neptune drive had an average elastic modulus value of 184.3 ksi while the asphalt inlet asphalt concrete surface had a modulus value of 849.5 ksi. The low modulus value of Neptune drive can be attributed to the numerous alligator cracking and rutting visible on this layer.

The FWD deflections obtained from a representative pervious asphalt section was compared to that of a conventional asphalt surface. This comparison of the pavement response at the seven sensor locations for the two pavement surfaces is shown in Table 6. The deflection of conventional asphalt is greater than that of porous asphalt. This shows that when the load is dropped on porous asphalt surface, the response in each sensor is not that of the pavement system but instead it is the rebound displacement when rubber loading plate rebounds from the flexible pavement surface.

Table 6: Comparison between deflections of PA and conventional asphalt

Porous Asphalt							
Load (lb)	Sensor spacing (in.)						
	0	8	12	18	24	36	60
6000	10.33	8.15	6.58	4.99	3.83	2.51	1.38
9000	16.10	12.69	10.25	7.80	6.05	4.02	2.13
12000	21.01	16.71	13.64	10.43	8.11	5.36	2.85
Conventional Asphalt							
Load (lb)	Sensor spacing (in.)						
	0	8	12	18	24	36	60
6000	22.15	13.03	7.92	4.88	3.23	1.89	1.02
9000	31.37	19.36	12.25	7.57	4.94	2.73	1.53
12000	41.06	26.13	16.92	10.58	6.78	3.62	2.14

The FWD deflection basins for the different impact load applied on the surface of the pervious asphalt is shown in Figure 52. The greater impact load (12000 lb) produced more deflections. Meanwhile, the falling weight deflectometer (FWD) deflection basins for the various impact load applied on the surface of the conventional asphalt is shown in Figure 53. As expected, the greater impact load (12000 lb) produced higher deflections.

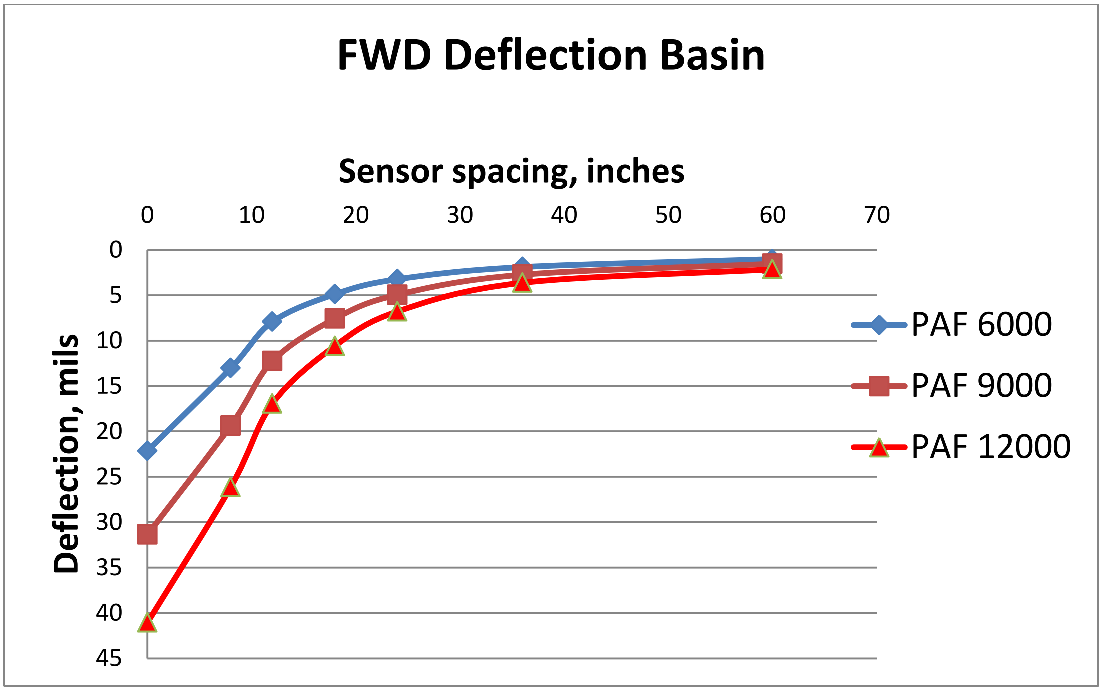


Figure 52: FWD Deflection basins for porous asphalt

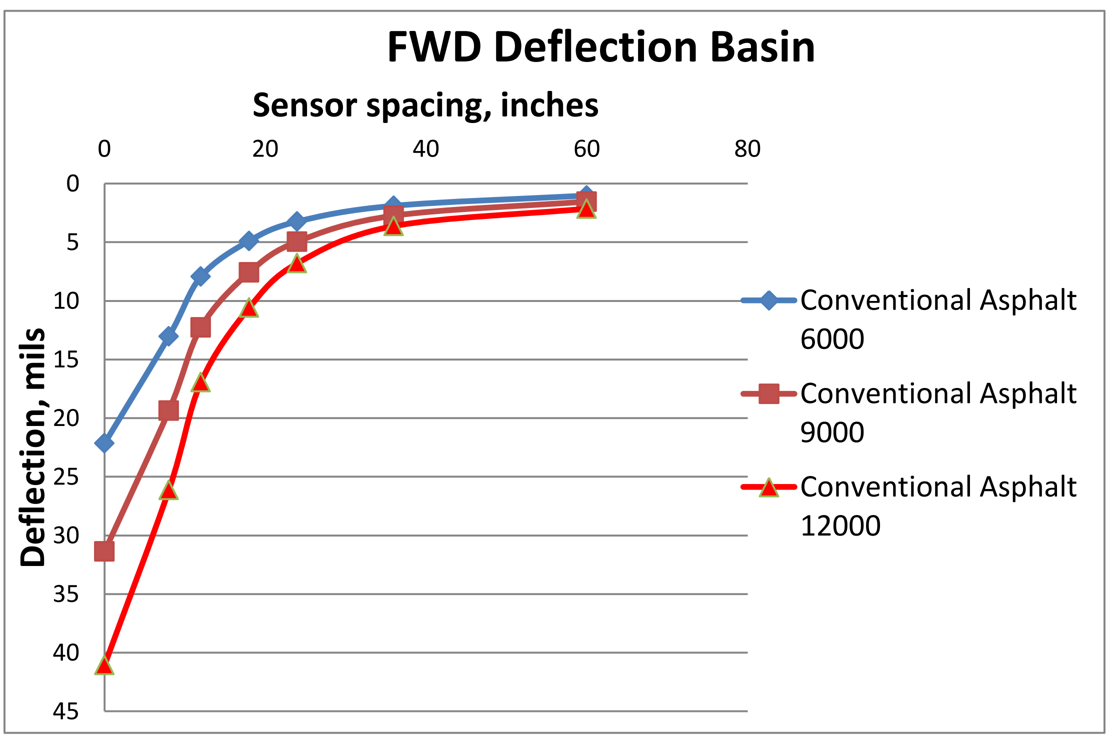


Figure 53: FWD deflection basins for conventional asphalt

CONCLUSIONS AND OBSERVATIONS

General Observations

Observations made during the installation of the pavement sections are included below. There was a noticeable amount of raveling at the surface of the pavements throughout the sections that was caused by heavy vehicles (semi-trucks, dump trucks, heavy construction equipment, etc.) after installation. Also observed was the surface sealing when sediments deposited on the pavement would stick to the asphaltic binder that never seemed to "set up" especially during the high temperatures throughout the summer. There was one incident where a small amount of diesel fuel was spilled on the surface of the porous asphalt and resulted in the pavement breaking down into almost a liquid state. The affected area became very soft and excessive raveling was noticed were the diesel fuel contacted the asphalt and eventually a pot hole formed. During rainfall, even low intensity short duration events caused significant ponding and runoff from the porous asphalt sections compared to the other pervious/permeable pavements at the site.

Infiltration Rates

The determination of porous asphalt infiltration rate was conducted for normal operations, intentional sediment loading, and rejuvenation of the system. During the study period, the ERIK device was used 60 times and 95% of the runs provided values above the minimum of 2.0 in/hr for all three sections measured by the infiltrometers. However the porous asphalt system experienced the lowest measured rate of all the pavements tested (0.1 in/hr). The infiltration graphs for the porous asphalt systems all experienced a gradual declining trend even after the surfaces were vacuumed and the rates should have been restored above the clogged condition rates.

The results from this study indicate that porous asphalt pavement systems will not perform as intended over long periods of time. Maintenance by the use of a vacuum sweeper truck will not improve the infiltration rate when used in during a dry or saturated wet surface condition.

The amount of sediment loading depends on the site location and its exposer to sediments being brought onto the pavement's surface by natural (wind and water laid sediments) or unnatural causes (ie. Tire tracking of sediments, spills, etc.).

It should be noted that the vacuum suction strength is not sufficient in removing the sediments that are stuck to the asphaltic binder near the surface.

This permeable pavement system is not recommended as an effective infiltration BMP that will perform well throughout its service life. If the infiltration performance is degraded due to sediments bonding to the surface, standard vacuum trucks will be unsuccessful at improving the capability to infiltrate stormwater above 2.0 in/hr stated as the minimum rate recommended 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 porous asphalt systems is about 12%.

Water Quality

This study examined the quality of water that infiltrates through two porous asphalt systems, a system containing a Bold&Gold™ pollution control media 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. 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 porous asphalt system as the specified product. The cross section for this system consists of a 4 inch deep layer of #57 limerock and a 4 inch deep layer of porous asphalt 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 0.77. 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 10 minute duration. Using the rational method, it is determined that the rainfall excess flow rate is 6.47 cfs and multiplying that by the 10 minute duration gives a runoff volume of 3,881 cubic feet, or 109,898 liters. Therefore, the TN mass leaving the system is 86.8 grams and the TP mass leaving the system is 74.7 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 porous asphalt system specified would have a TN mass reduction of 21.2 grams (19%) and a TP mass reduction of 18.2 grams (20%) for a one acre parking lot.

The above analysis and example problem shows that there is a water quality benefit to using the porous asphalt system. This benefit is only realized, however, through taking into account the stormwater runoff volume reduction achieved. 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

The average surface layer modulus value of PAF is 707.7 ksi, that of PAR is 1004.9 ksi and PABG is 492.8 ksi. Conventional Asphalt roadway on the existing control section on Neptune drive had an average elastic modulus value of 184.3 ksi while the asphalt inlet asphalt concrete surface had a modulus value of 849.5 ksi. The low modulus value of the older control section can be attributed to the numerous alligator cracking and rutting visible on this layer.

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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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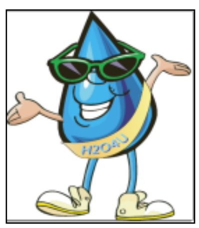

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Disclaimer

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™ 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 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).

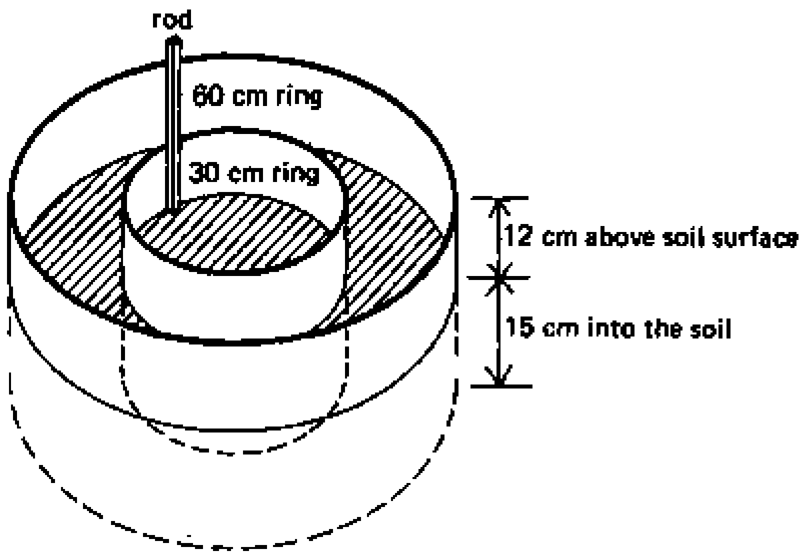
Field Infiltration Methods

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 subsoil 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. A typical double-ring infiltrometer set-up for field-testing is presented in Figure 1 (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. The plan and section views of the ERIK embedded ring as installed in a permeable pavement system are presented in Figure 2.

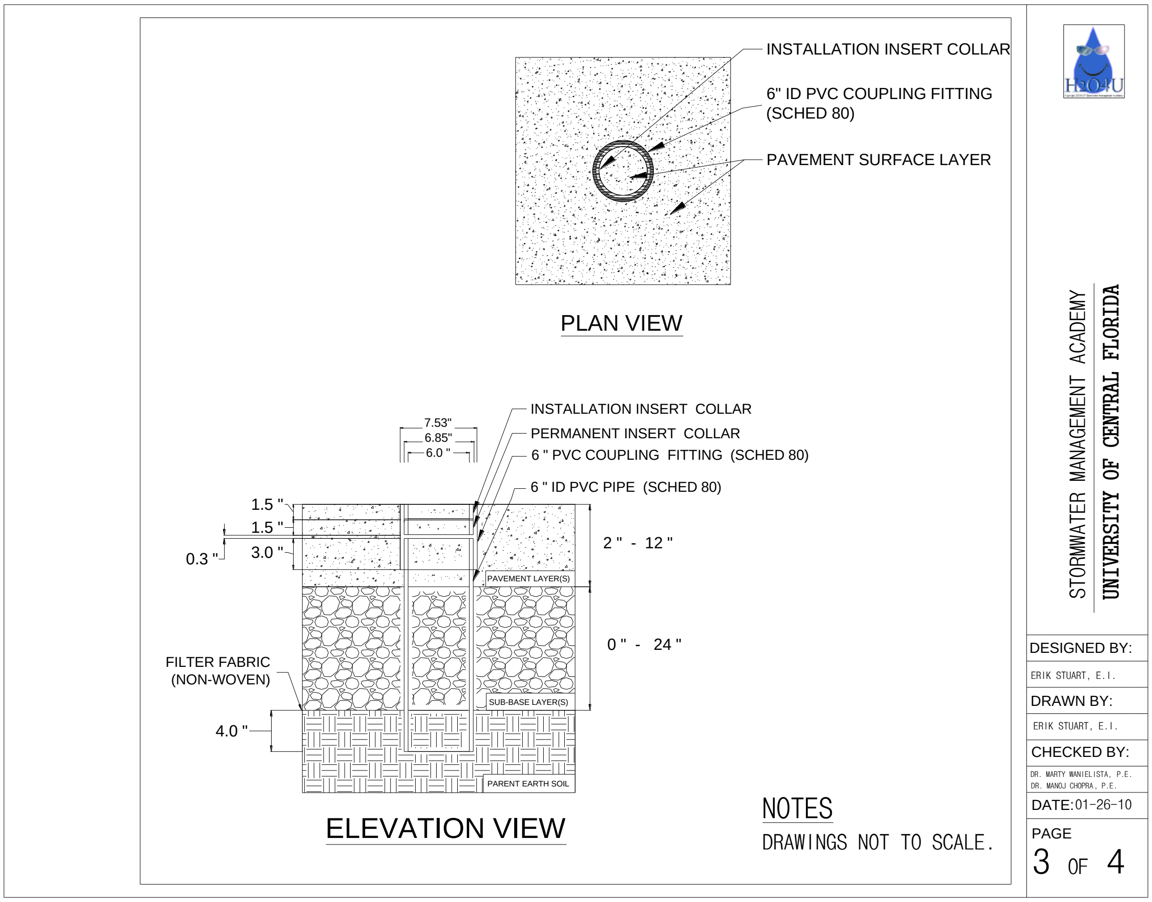


Figure 2: ERIK monitoring tube

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.

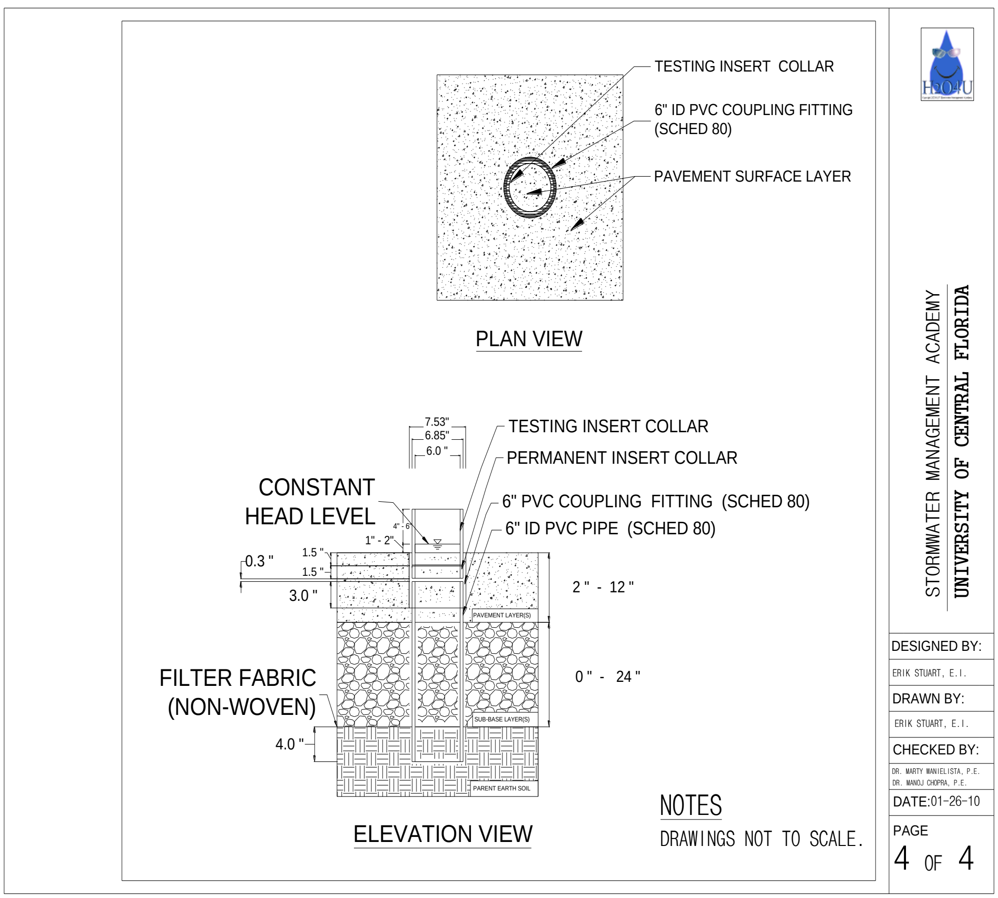


Figure 3: ERIK embedded ring installed

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 Figure 4.

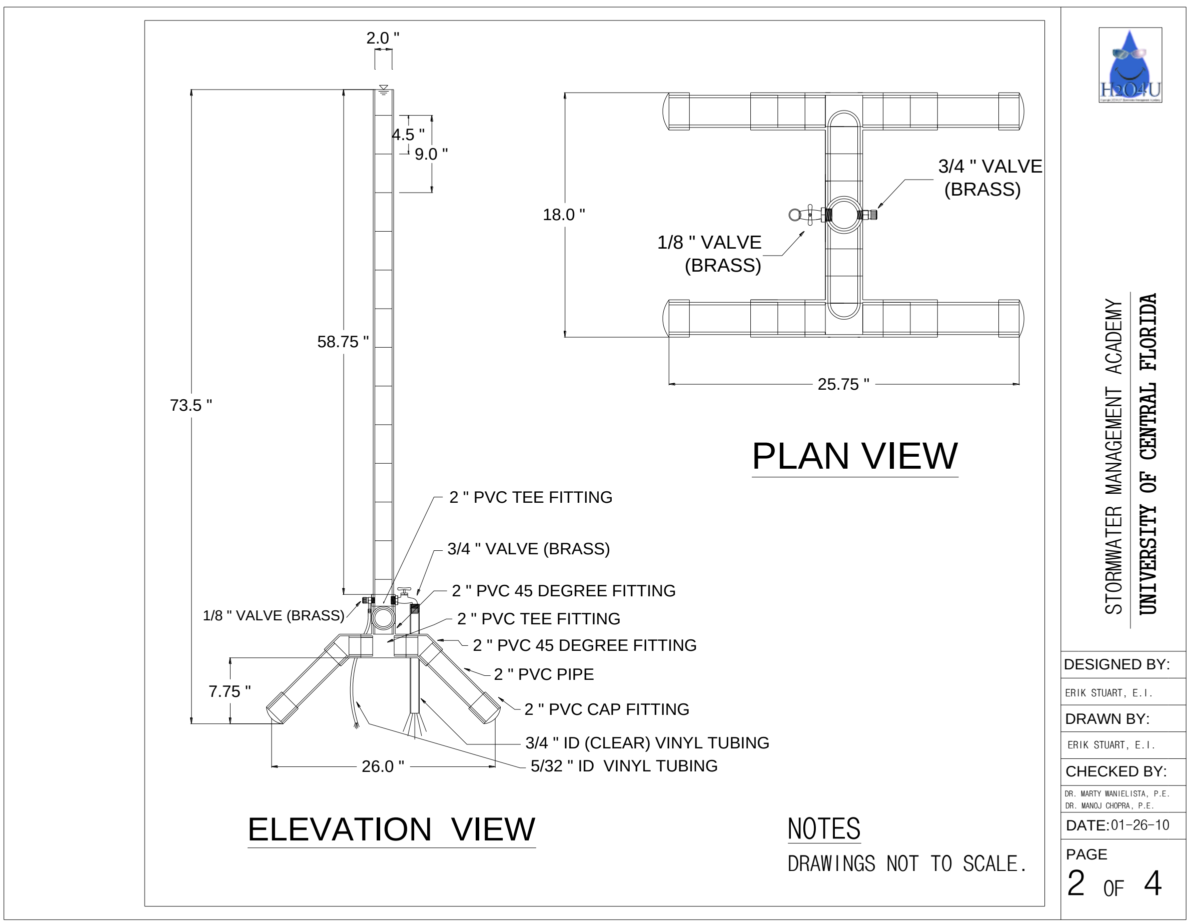


Figure 4: ERIK monitoring cylinder reservoir

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 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.

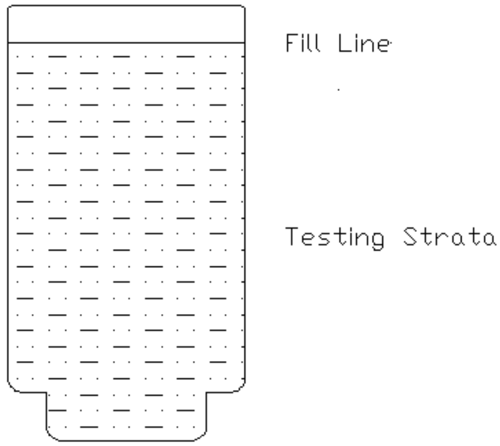


Figure 16: Half Gallon plastic jar cross section for component testing

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:

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

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.

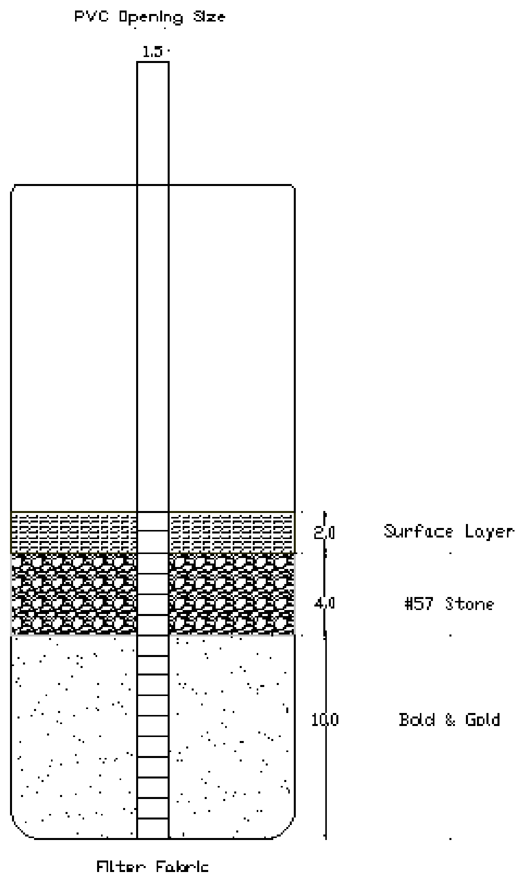


Figure 18: 55 Gallon Barrel for System testing

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™

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™ 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™ 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 20^{th} to September 10^{th} 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:

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

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:

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

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 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.

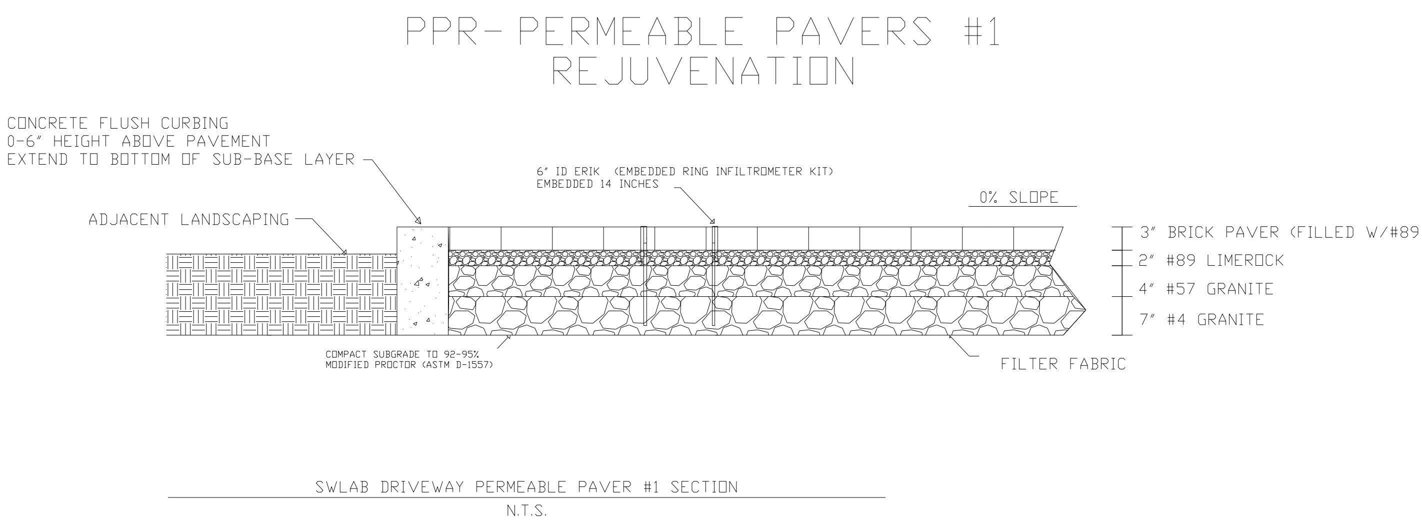


Figure 27: Permeable Pavers Rejuvenation Cross Section

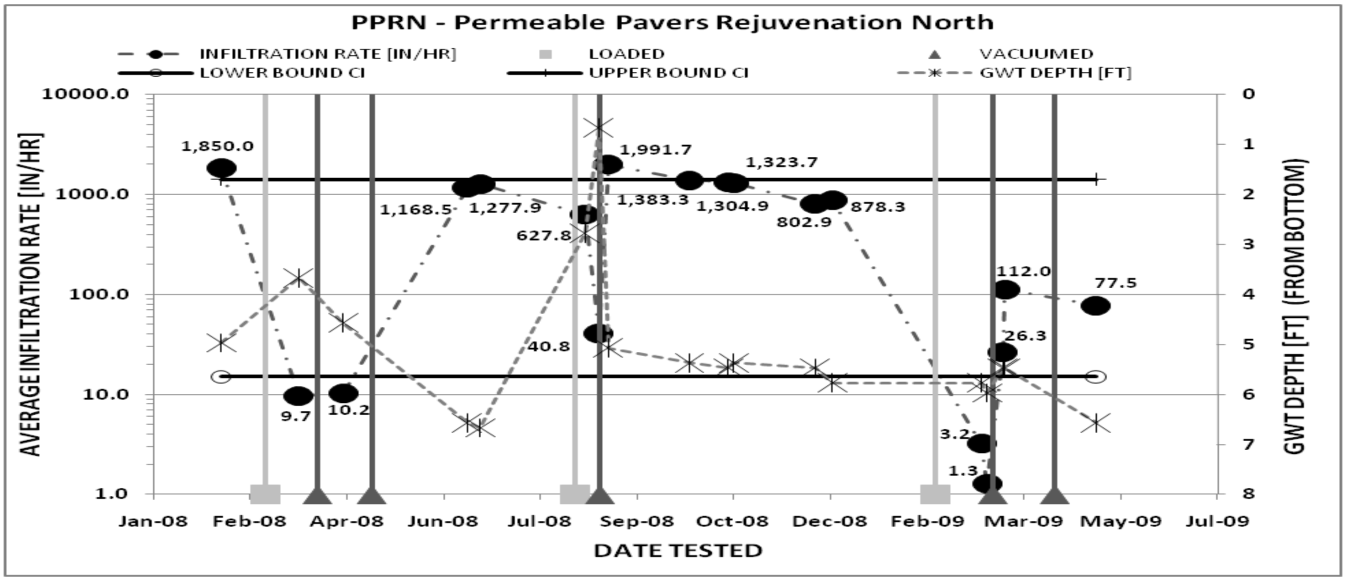


Figure 28: Infiltration Rate (ERIK) Results for the Permeable Pavers Rejuvenation North Section Infiltrometer

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.

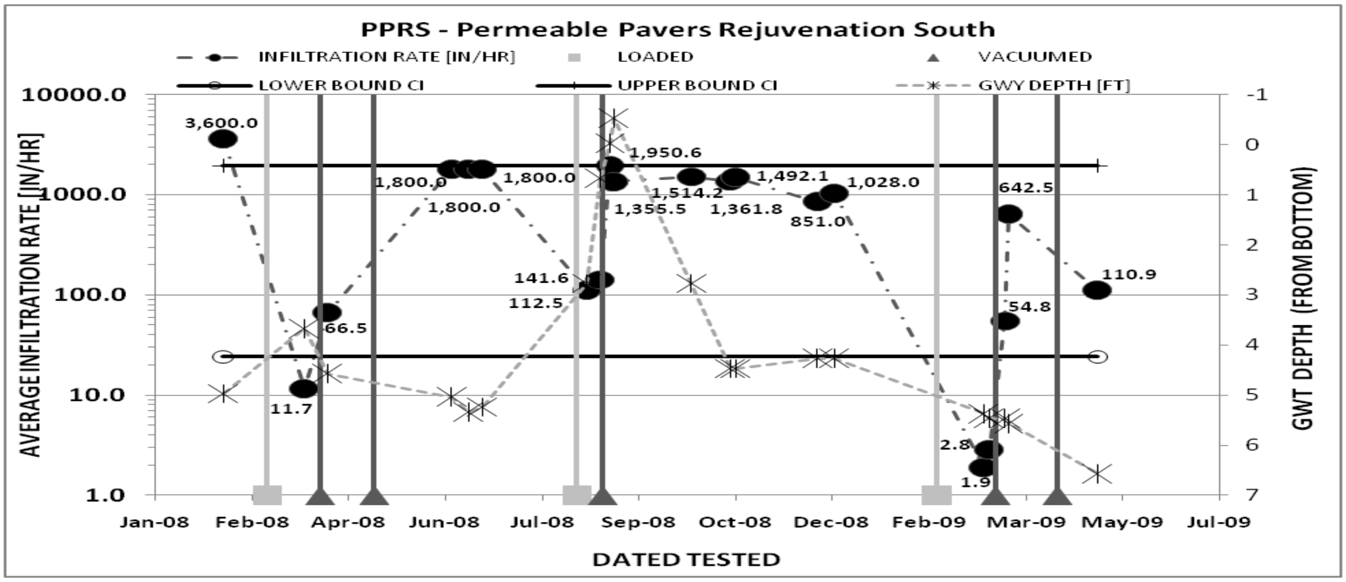


Figure 29: Infiltration Rate (ERIK) Results for the Permeable Pavers Rejuvenation South Section Infiltrometer

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

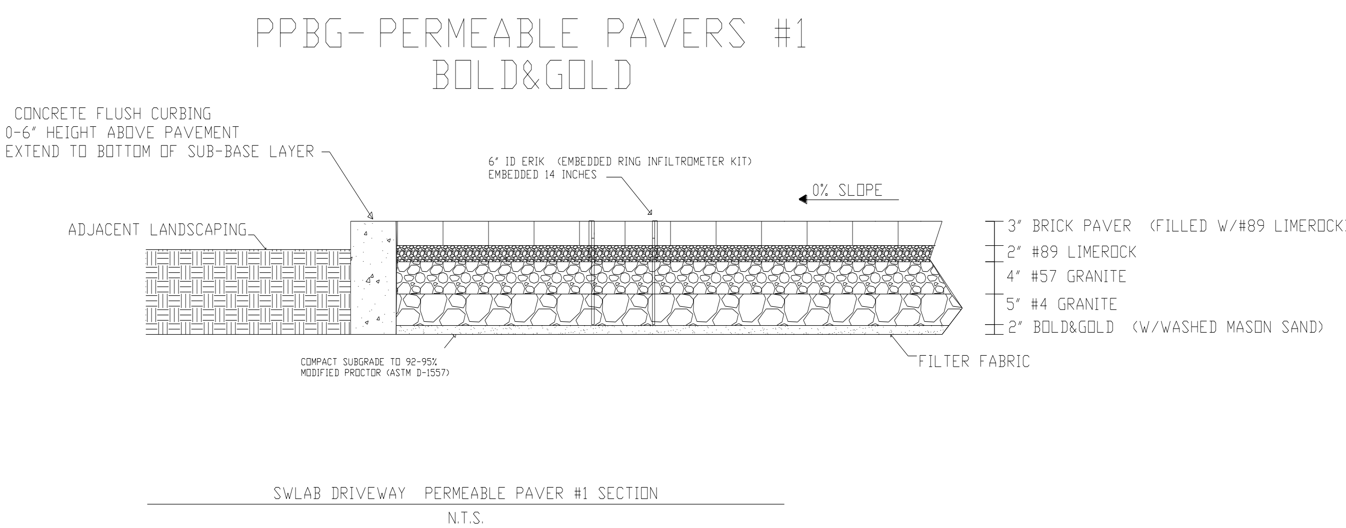


Figure 30: Permeable Pavers Bold&Gold Infiltrometer Cross Section

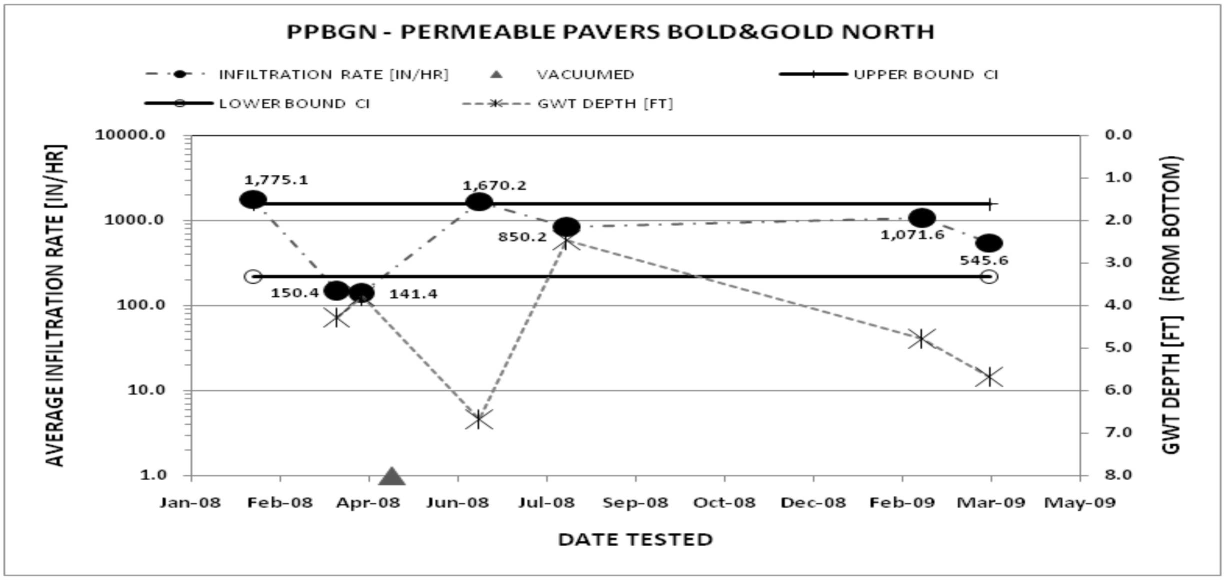


Figure 31: Infiltration Rate (ERIK) Results for the Permeable Pavers Bold&Gold North Section Infiltrometer

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.

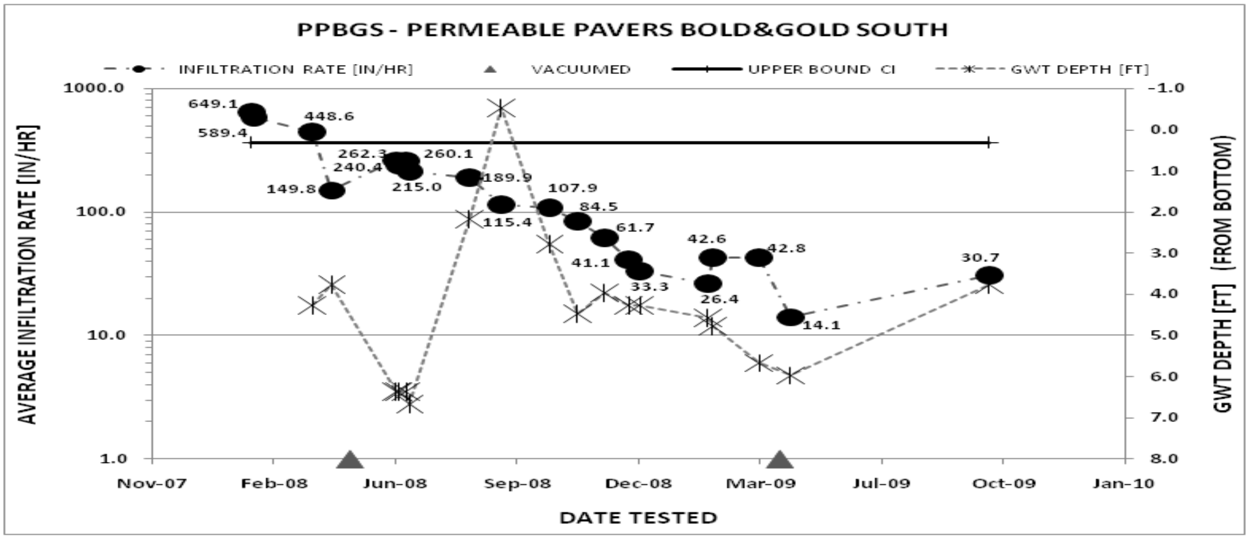


Figure 32: Infiltration Rate (ERIK) Results for the Permeable Pavers Bold&Gold South Section Infiltrometer

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).

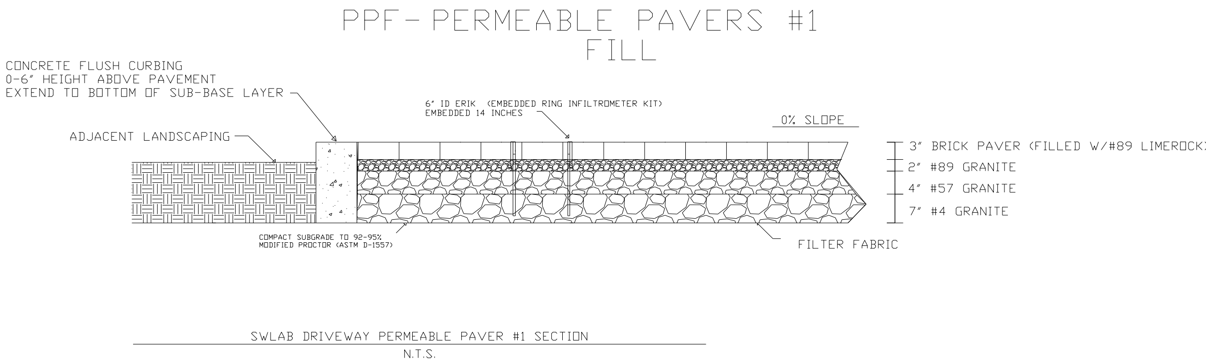


Figure 33: Permeable Pavers Fill Infiltrometer Cross Section

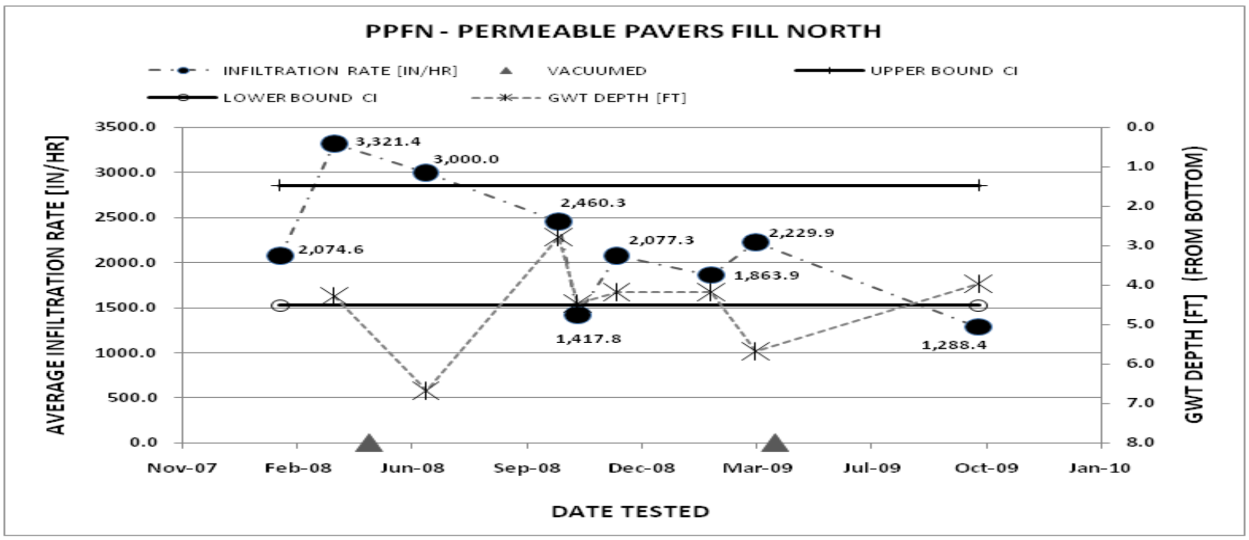


Figure 34: Infiltration Rate (ERIK) Results for the Permeable Pavers Fill North Section Infiltrometer

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.

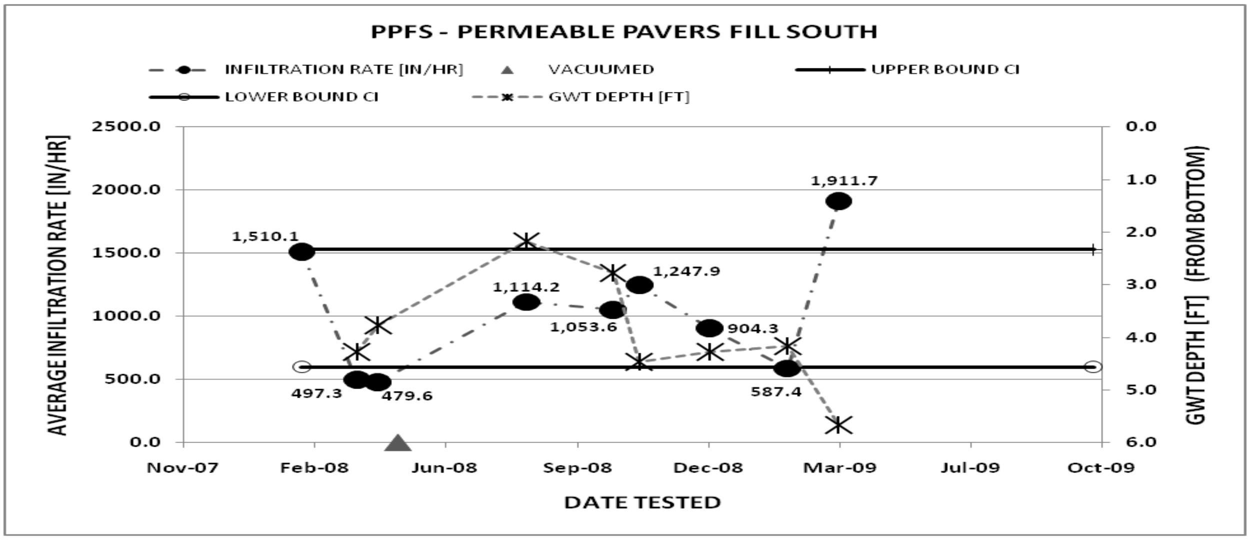


Figure 35: Infiltration Rate (ERIK) Results for the Permeable Pavers Fill South Section Infiltrometer

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 permeable pavers including the surface layer, bedding layer, and stone reservoir sub-base layers. The first five initial tests were conducted without introducing any sediment to the systems to investigate the total or maximum storage available.

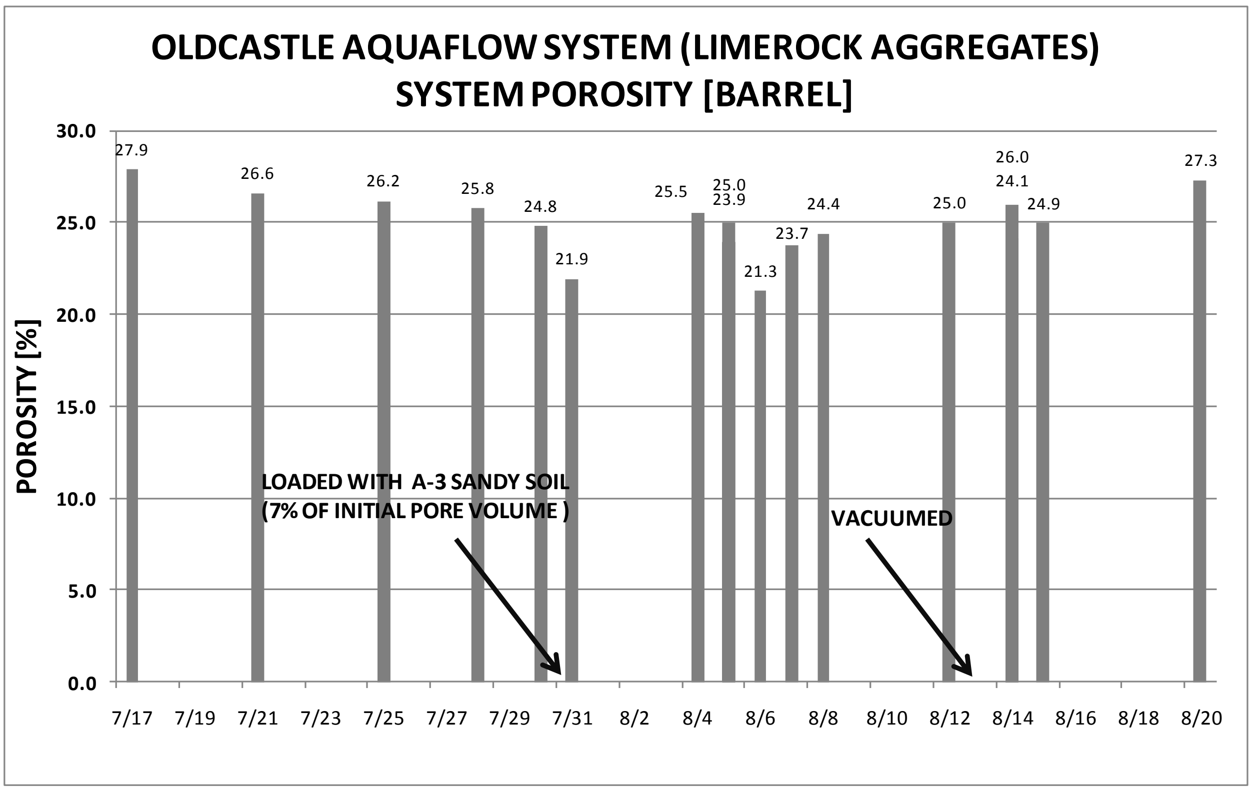


Figure 36: System porosity results using 55 gallon barrels (#4 granite)

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.

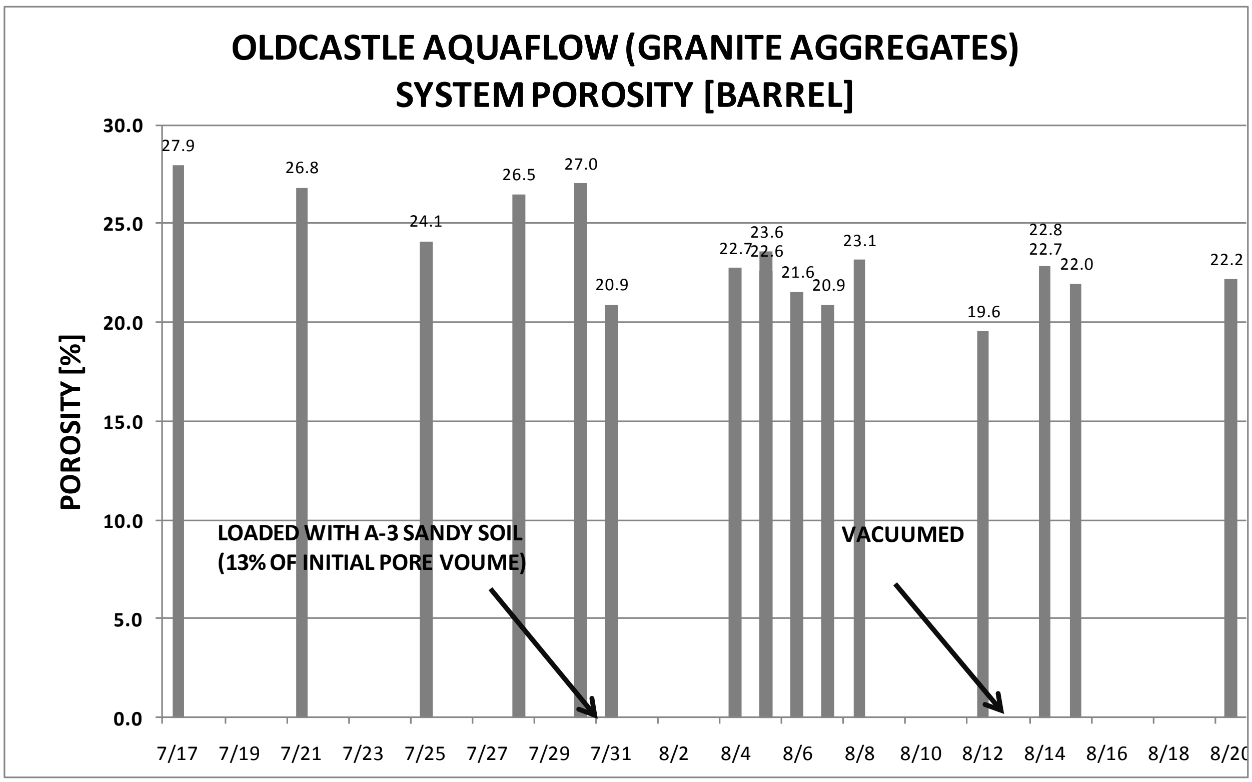


Figure 38: System porosity results using 55 gallon barrels (#4 limerock)

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™ 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

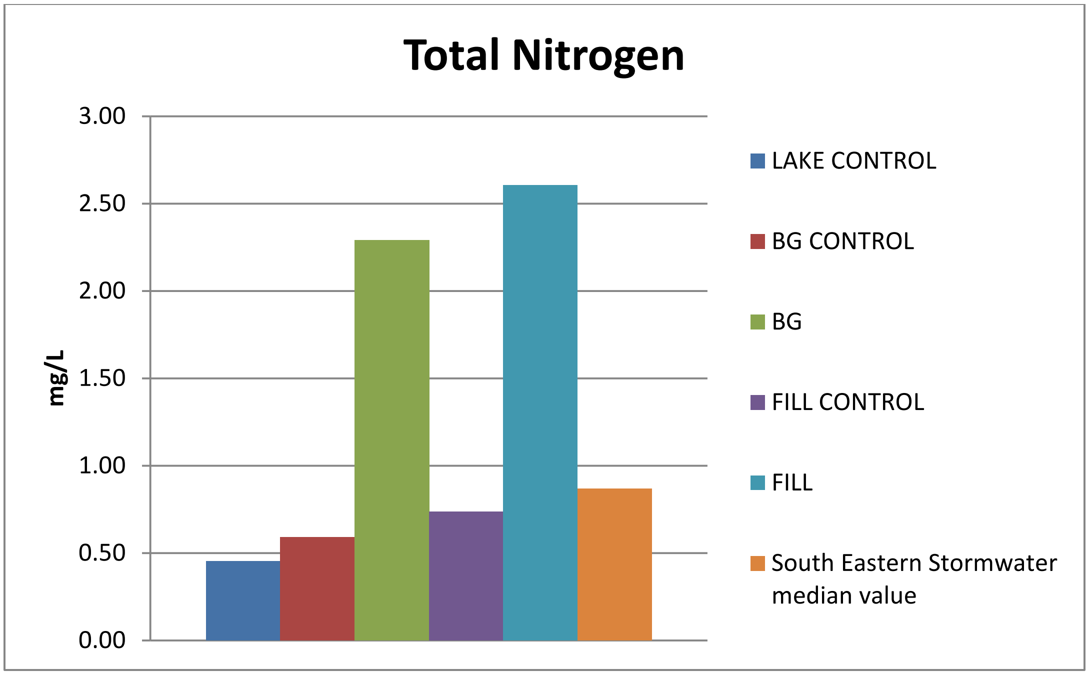


Figure 39: Total Nitrogen Results

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.

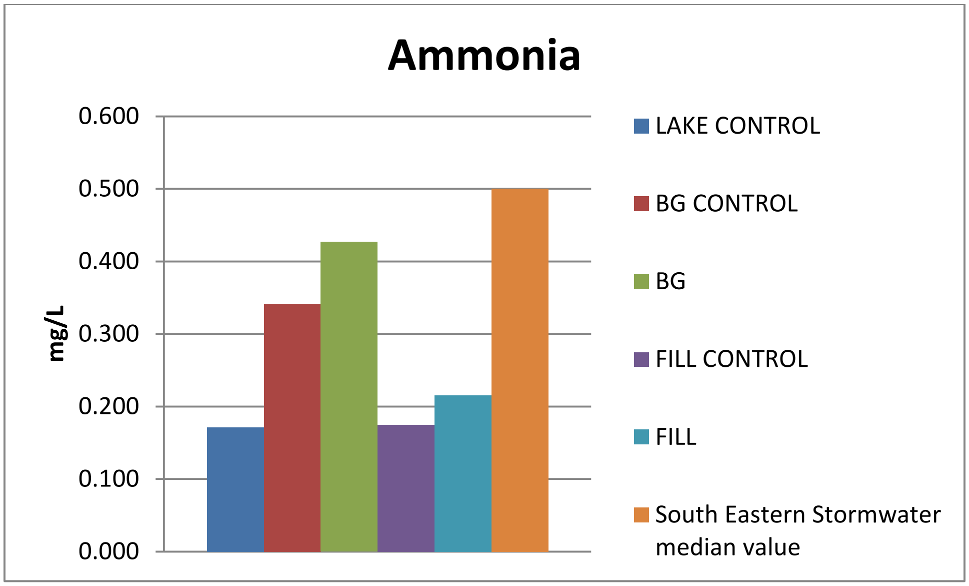


Figure 40: Ammonia Results

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™ 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.

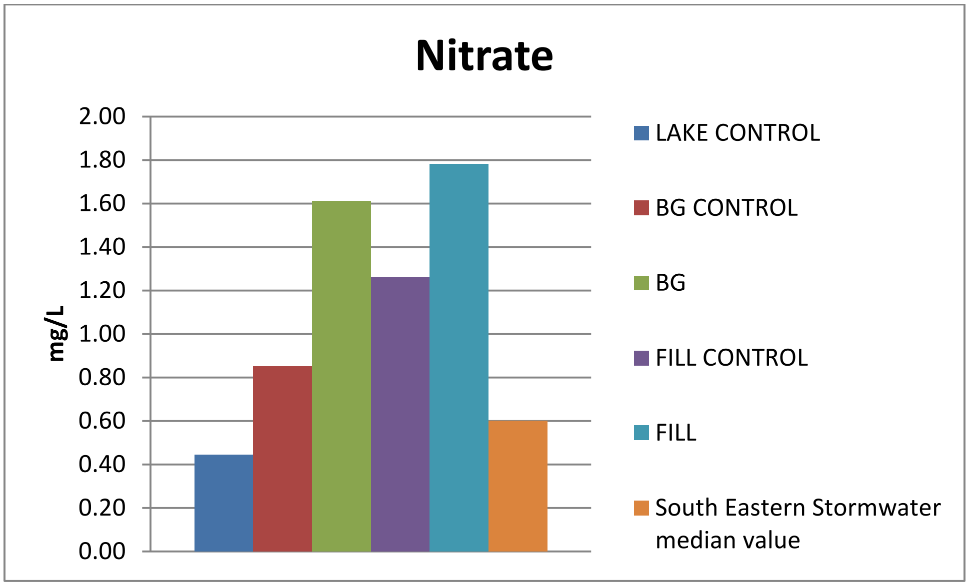


Figure 41: Nitrate Results

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.

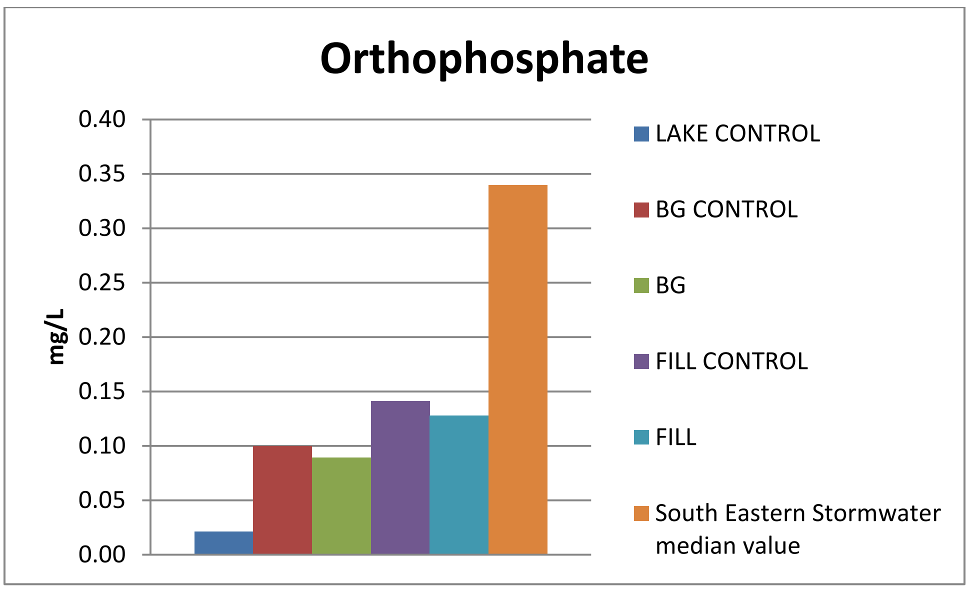


Figure 42: Ortho-Phosphate Results

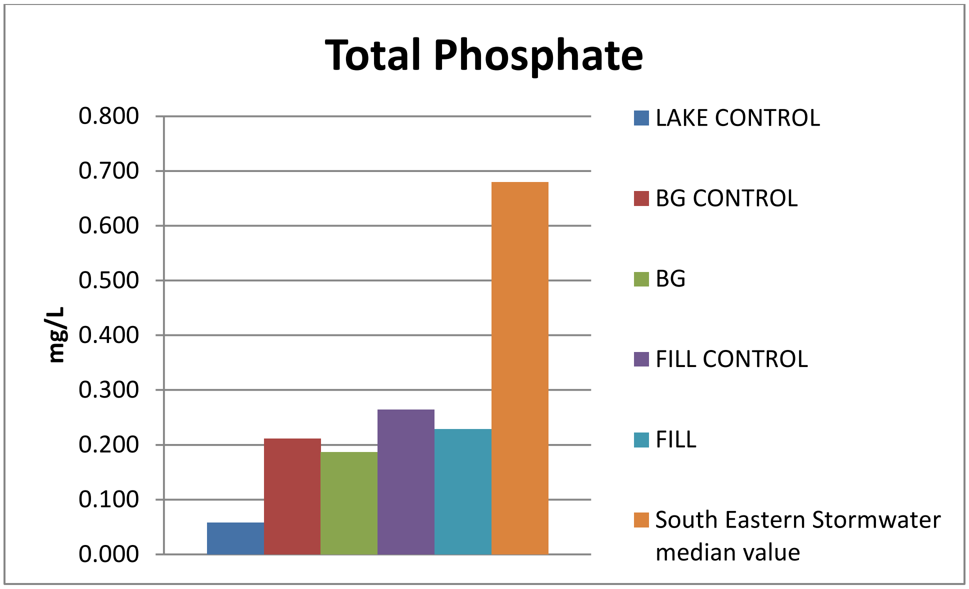


Figure 43: Total Phosphate Results

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.

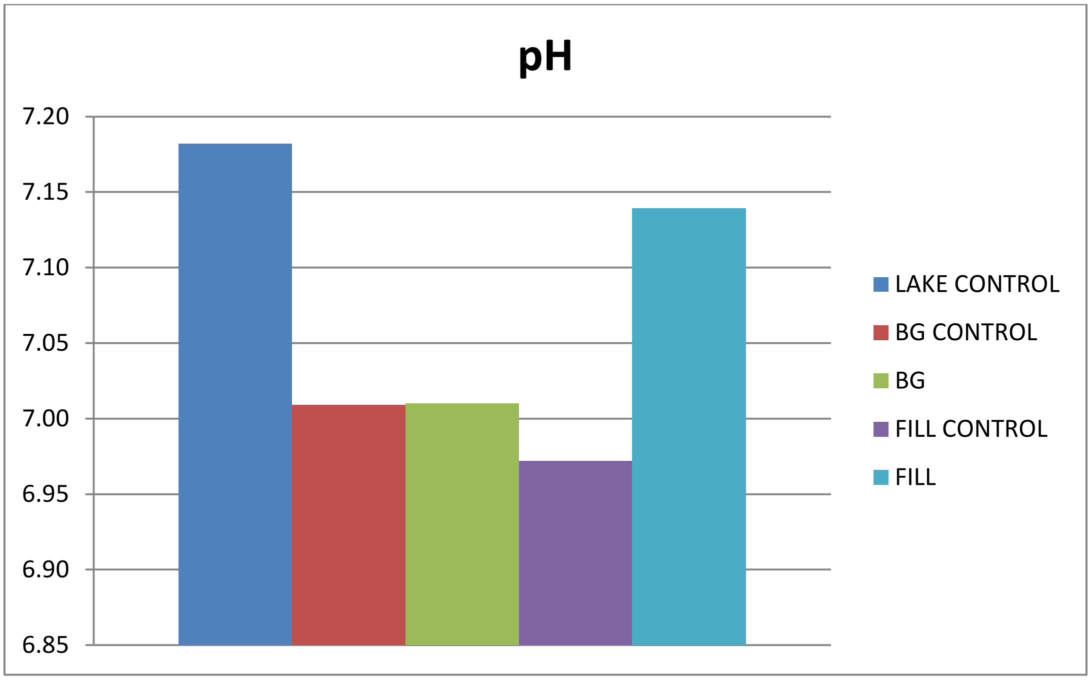


Figure 44: pH Results

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 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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Final Report

Pervious Pavements - Installation, Operations and Strength
Part 4: Flexipave® (Recycled Rubber Tires) Systems

Work Performed for the Florida Department of Transportation

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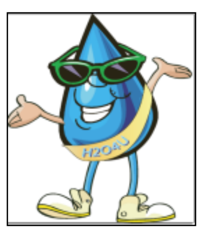

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16. Abstract

Pervious pavement systems are now being recognized as a best management practice by the Environmental Protection Agency and the state of Florida. The pervious concrete system 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 Flexipave systems indicate that they perform as intended unless subjected to excessive sediment loads or high ground water table. Maintenance by the use of a vacuum sweeper truck was successful in removing surface sediments but is ineffective at removal of deep penetrating sediments. However, it is much harder to clog these in the first place due to a more open surface nature. The reduction in rates is only observed when significant amounts of sediments enter the system and migrate into deeper locations. The sustainable storage of the entire system was found to be about 10%. This pervious pavement system is recommended as an effective infiltration BMP that will perform well throughout its service life. The average compressive strength is about 115 psi and the average modulus of rupture is around 170 psi.

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INTRODUCTION

Pervious 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 pervious pavements, by using regional or recycled materials such as local recycled automobile tire chips (used in construction of the surface layer), tire crumbs (used in blending of the pollution control media), and crushed concrete aggregates, can contribute to earning LEED^{TM} points. Pervious 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. It should be noted that due to complications in the field water quality analysis was unable to be performed. 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 was contracted to conduct water quantity, water quality, and strength analysis of FlexiPave™ (referred to as FlexiPave henceforth in this report) pervious pavement 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.
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. (Due to complications in the field water quality analysis was not possible)
4. Determine parameters that represent strength performance of the flexible 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. Pervious pavement systems offer designers and planners an effective tool for managing stormwater. These systems manage 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 minimize non-point source pollution.

The FlexiPave system is designed to have very large pore sizes in the surface layer compared to other existing pervious/permeable pavement types, which are intended to encourage maximum flow of water through the material, see Figure 1 below.

Figure 1: FlexiPave surface layer with quarter as scale reference

With such large pore sizes there exists the potential for some of the sediments to also flow freely through the material possibly reducing the storage volume in the rock reservoir layer below. The performance of pervious pavement 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 performed.

This report investigates the change in infiltration rates due to high levels of sediment 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 FlexiPave pervious 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 pervious pavement design criteria of 85% removal.

The ERIK infiltrometer is embedded into the entire pavement system section that is the pavement layer, stone support/reservoir layer, pollution control layer, and finally the parent earth below the system to measure the vertical infiltration rate. For the purpose of the study, the pavement surfaces are intentionally loaded with large amounts of AASHTO types A-3 soil, A-2-4 soil, and limerock fines to simulate long term worst case scenario clogging. This is done to test the effectiveness of vacuum cleaning as a rejuvenation method for FlexiPave pervious pavement 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 these pervious pavement systems perform, as per infiltration of water, and the effectiveness of the proposed maintenance method of vacuum truck sweeping 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 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, the practice of “out of sight, out of mind” is adhered to once the stormwater was off the pavement surface and into the drainage structure. 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 this increased velocity is the increase in stormwater‘s capability of erosion, channel widening, sedimentation, flooding, and spreading of pollutants downstream. 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, weathering, and freeze thaw cycles 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. This develops pore water pressures that result in piping and pumping effects that erode away sub soils and cause 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. This 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 level 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 pervious pavement systems can function as parking areas as well as on-site stormwater control (Dreelin, et. al., 2003). Smith (2005) compares permeable interlocking concrete pavements to infiltration 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 pervious pavement systems, trees have 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 natural solar pumps and cooling systems by using the sun's energy to pump water back to the atmosphere resulting in evaporative cooling. The pervious 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 stone reservoir/sub-base of the pervious pavement system is designed to store rainwater and allow it to percolate into sub-soils helping to restore the natural groundwater table levels. This ensures that sufficient groundwater exists to supply water wells for irrigation and drinking. It is important to allow the natural hydrologic 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. Alterations 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. Structures should be built 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, lack of sufficient 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 pavement 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 generated from pavement surfaces. Most of what has been researched before on pervious/permeable pavement 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 in 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 having 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 greatly influence 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 reveals any sub-layer clogging. A pavement systems 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 the 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 that the volume of water is measured upstream of the sample instead of downstream due to 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.

Recycled or shredded tire chips are used in civil engineering applications as replacements for some construction materials such as crushed rock or gravel (RubberPavementAssociation, 2005). Currently, the largest market for recycled rubber tires is the molded products sector, where it is combined with urethane binders. Recycled rubber tire pavements are used for low load applications. This advancement in pavement technology is ideal for driveways, parking lots, walkways, sidewalks, golf cart paths, courtyards, nature trails etc.

Due to the porous nature, recycled rubber tire pavement is being used to decrease the amount of runoff water and also to improve and control stormwater quality and quantity. This pavement is made from recycled, ground up automobile tires, coarse aggregates and some additives. These materials are bound together by means of a binding agent known as XFP75 (urethane). Recently the manufacturers introduced a new improved product. The binding agent urethane was improved so as to hold recycled passenger tires and aggregates more effectively. The new binder is called XFP95 (polyurethane). According to the manufacturers, it is easily installed over a minimum of 4 inches (100 mm) of well compacted single-sized aggregates or crushed concrete. In addition, it could be installed over concrete or asphalt pavements. It could be installed in temperatures ranges of 45°F – 95°F. But it is clearly advised that when curing this pavement the temperature should not fall below 35°F. After installation, it is ready for use after 24 hours. It comes in various colors as requested by the customer. Porosity ranges from 50% - 60% (Flexi-Pave, 2005).

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 the soil and liquid, 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 applications 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 in 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).

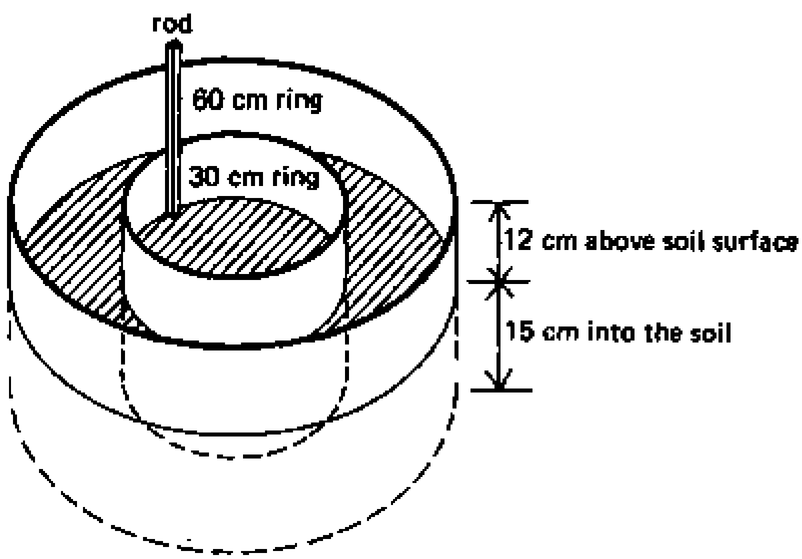
Field Infiltration Methods

Exfiltration field studies have been completed on pervious/permeable pavement 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 which drained the 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 measuring the water depths in monitor wells, 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 subsoil 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 tests at the same site are not likely to give identical results. The results are recommended primarily for comparative use (ASTM D3385 2009). The testing procedure is as described by the ASTM standard test method for infiltration rate of soils in field using a double-ring infiltrometer ASTM D3385. A typical double-ring infiltrometer set-up for field testing is presented in Figure 2 (Brouwer, et al. 1988).



(Courtesy: Brouwer, et al. 1988)

Figure 2: Double Ring Infiltrometer used for measuring infiltration into soils

The limitation of using the DRIT on pervious systems is that the rings cannot be driven into the pavement 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 the DRIT, Bean et. al., (2007) reported instances of water back up and upward flows out of the surface near the outside of the outer ring. It was determined that this upward flow was due to lower permeability of the underlying layer (Bean et. al., 2007).

More limitations encountered when using the surface infiltration rate tests on highly permeable surfaces are 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 a 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 fast enough 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 resulted in over predicted the actual surface rates. However, the 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 tests 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, pumped 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 test for infiltration measurement of soil/vegetated surfaces using a Double Ring Infiltrometer Test (DRIT) (ASTM D3385, 2009). The ERIK device was designed to overcome any difficulties in obtaining infiltration measurements of pervious pavement systems 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 at the 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 the short-ring and the 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. The long-ring ERIK 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, giving 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. Figure 33 below, presents the plan and section views of the ERIK embedded ring as installed in a permeable pavement system while not conducting a test.

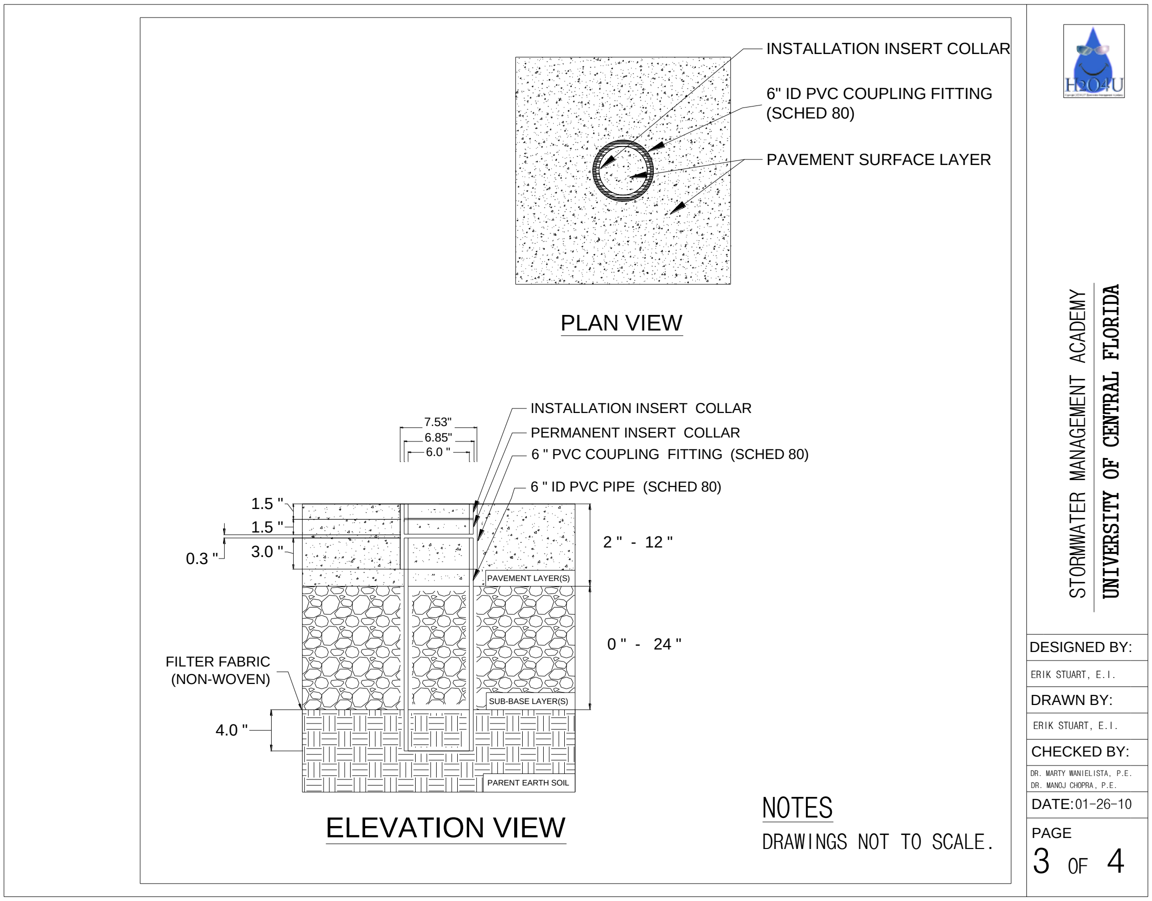


Figure 3: ERIK monitoring tube

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. 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.

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. This is illustrated in Figure 4 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 a minimum 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.

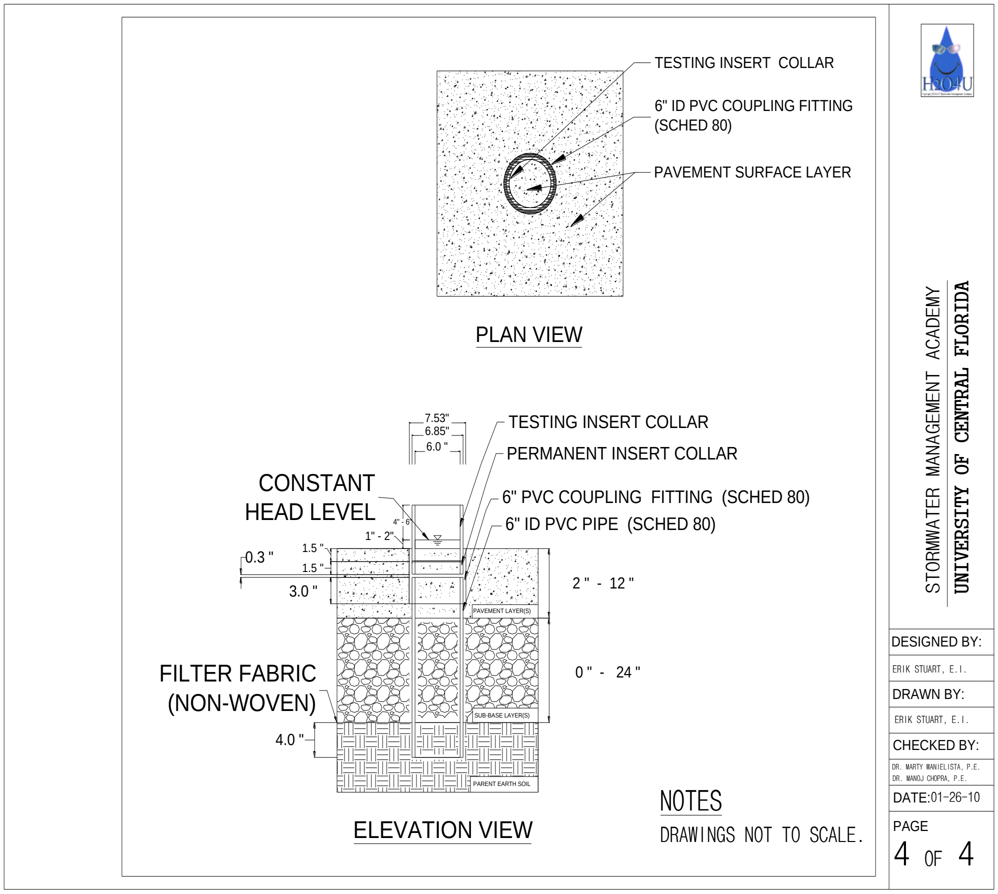


Figure 4: ERIK embedded ring installed with test collar

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 Figure 5 5 below.

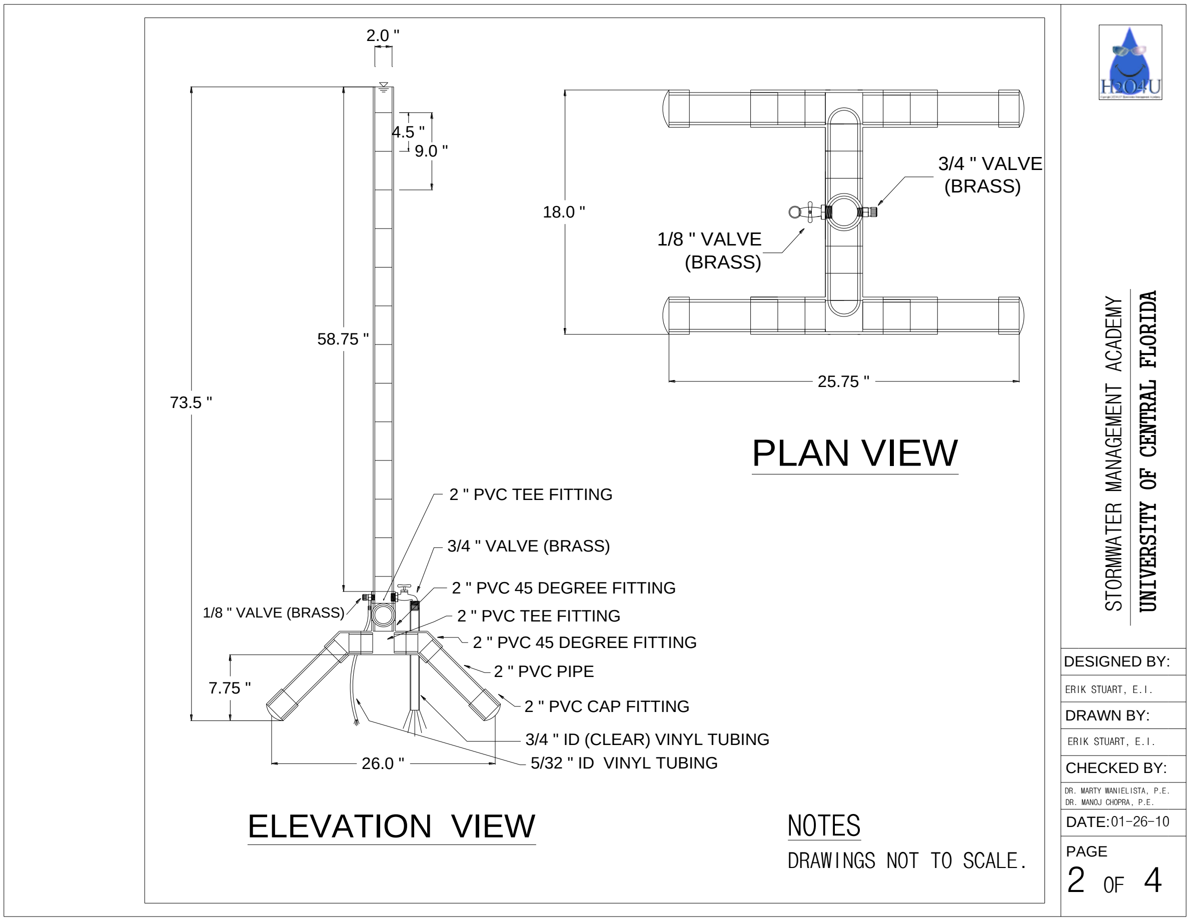


Figure 5: ERIK monitoring cylinder reservoir

PAVEMENT INSTALLATION AND SETUP

FlexiPave pavement systems were constructed at the University of Central Florida's Stormwater Management Academy laboratory over an area totaling 1500 sq ft. This system was divided into 3 different sections, one designated as the intentional sediment loading and rejuvenation pad, and the other two intended for sub-base comparison while maintaining a more natural sediment accumulation from natural wind erosion and tire tracking of sediments onto the pavements surface. The FP rejuvenation section has dimensions of 20' x 35' or 700 ft^2 with a cross section consisting of 2 inches of Flexipave pavement layer with 4 inches of #57 recycled crushed concrete as a support base/stone reservoir layer which lies on 10 more inches of sandy A-3 fill soil (parent earth). The other two sections 20' x 20' or 400 ft^2 (not portioning between the two sections) are installed with the 2 inches of Flexipave pavement layer on 4 inches of recycled crushed concrete. Impervious concrete flush perimeter curbing is recommended and used for edge restraint extending the total 16 inches of the system to prevent washout of the sub-layers. The section designated as fill consists of 10 inches of sandy A-3 soil for the sub-base and the Bold&Gold™ section uses the pollution control media, Bold&Gold™ which is made with the same sandy A-3 (parent earth) soil as the sand mixed with crumb rubber from recycled automobile tires. The pavement and sub-base layers are placed on top of the parent earth A-3 soils compacted by vibratory plate compactor prior to subsequent layer construction and separated by a non-woven filter fabric.

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. 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 shown below in Figures 6 and 7. Aggregates are brought in by trucks and dumped into piles where the loaders could then place them in their final positions before leveling and compacting.

Embedded ring infiltrometers are placed flush with the final surface elevation and extends down 4 inches for the “shallow”, and 14 inches for the “deep” infiltrometers. The inside of the embedded rings are constructed with the same layers and thicknesses as the rest of the section.

Figure 6: Site and Formwork layout

Figure 7: Filter fabric installed

Once preparations are complete the final step is to install the FlexiPave surface material. The tire chips, granite aggregates, and flexible binder are combined and mixed in a typical concrete mixer. Once the materials are thoroughly mixed wheel barrels are used to transport the material to its final destination. The mix is dumped into position and flattened using typical concrete bull floats and hand floats shown below in Figure 8. These steps were all done according to the manufacturer's recommended specifications. Figure 9 depicts the final pavement system with the sections delineated by the curbing.

Figure 8: Surface layer installation

Figure 9: Final layout of FlexiPave sections

The surface layer can be maintained by periodic application of an over coat in which the same binder used to construct the pavement layer can be re-applied by spraying a thin layer over the entire surface (Figure 10). Care should be taken to not over apply the binder in a way that may cause the binder to fill surface voids and reduce infiltration as well as the binder should be applied after vacuum sweeping when the surface is relatively free of sediments.

Figure 10: Overcoat application

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 11 below). The sediments were then washed into the pores using a garden hose (Figures 12 and 13) to simulate accelerated rain events that would eventually wash this sediment into the surface pores by transport processes. While washing the sediments into the pores it was noted that due the large sized pores, the FlexiPave surface allowed much of the sediments to easily pass through the surface layer when compared to some of the smaller pore sized pervious pavements tested. 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 11: Spreading of A-3 sediments over the entire Rejuvenation section

Figure 12: Washing sediments in with garden hose

Figure 13: Sediments on surface after being washed in

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, see Figures 14 and 15 below.

Figure 14: Post sediment loading ERIK testing

Figure 15: Post vacuumed ERIK testing

Finally, a standard street sweeping vacuum truck cleaned the pavement surfaces to simulate typical, real life maintenance, and then the infiltrometers were retested (Figures 16 and 17 below).

Figure 16: ERIK test after sediment loading

Figure 17: Standard vacuum truck performing maintenance

It was noticed that the vacuum force was unsatisfactory at detaching and removing the fine grained soils in a dry and hardened state. 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. Once the surfaces were vacuumed, post-rejuvenation ERIK measurements were continued on the FlexiPave systems, see Figure 18 below.

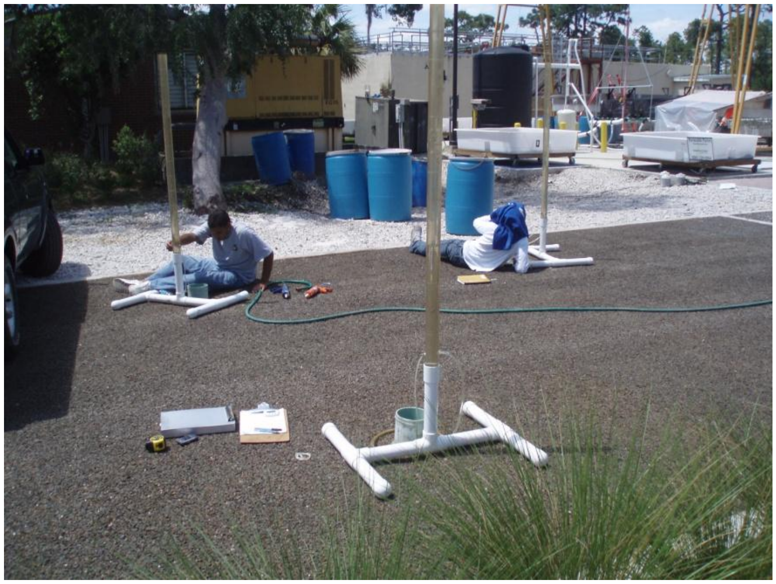


Figure 18: Successful vacuuming of Sediments

These observations lead to the recommendation of coordinating the vacuum truck maintenance 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 water could occupy 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 to see how sediments would reduce the amount of storage due to 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 19 - 21.

Figure 19: FlexiPave material in half gallon containers

Figure 20: Number 57 stone aggregates in half gallon containers

Figure 21: Bold&Gold™ materials in half gallon containers

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 non-woven 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 conducted on the samples without disturbing or changing the structure of the materials. Also, washing and compacting of sediments into the materials and later vacuuming was done while testing the storage values at the different levels of clogging and rejuvenation as shown in Figure 22 below.

Figure 22: Surface materials in ½ gallon containers being loaded and draining in sink

Component (Lab) Porosity

In accordance with this understanding, a variety of substrates were tested including: the FlexiPave surface layer material, crushed concrete (#57 stone), and Bold&Gold^{TM} pollution control layer media. 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)) 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, a digital camera, and a data sheet for the purpose of documentation.

The set up procedure included wrapping the threaded end 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 half gallon jar to the specified "Fill Line", as illustrated in Figure 23.

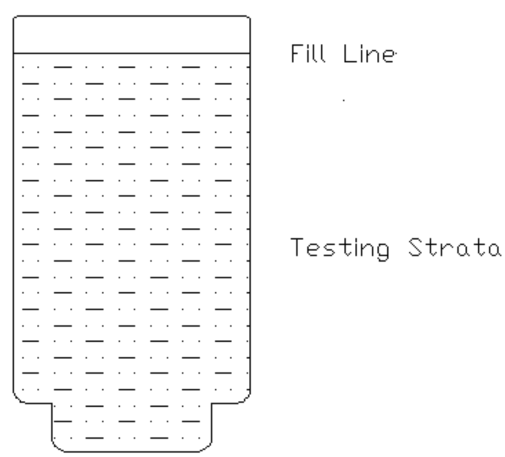


Figure 23: Half gallon container cross sectional drawing

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 and allow gravity to drain samples (see Figure 24).
- 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 24: Half gallon containers 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:

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

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

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

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

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

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

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 a full scale installation. Figure 25 below shows a cross sectional view drawing of the barrel porosity testing setup.

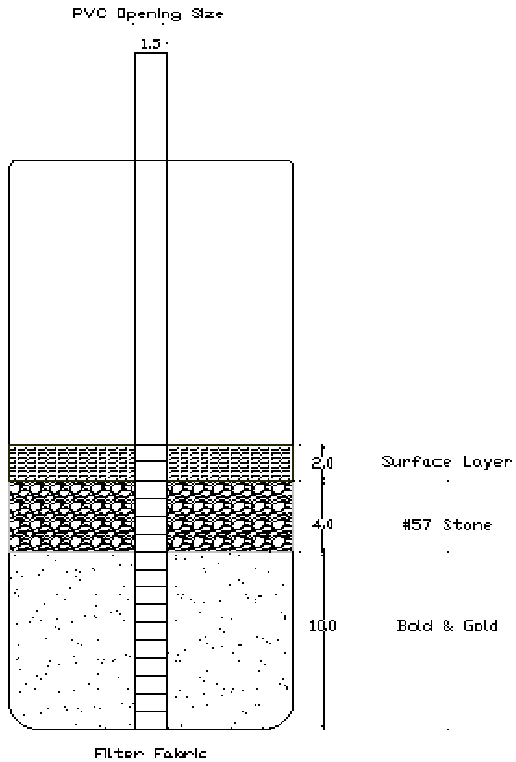


Figure 25: System 55 gallon barrel cross sectional drawing

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)) bucket, a 1-½ inch PVC pipe, nonwoven geotextile (Marifi 160N), rubber bands, epoxy glue, a funnel, measuring tape, a level, a 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 is 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 and then installed. The use of a straight edge is employed to ensure that the uppermost surface of the test surface 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 the funnel was placed in the top opening of the 1-½ inch PVC pipe. The amount of water added 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.

The porosity of the complete system was determined by extrapolating the total volume of the specimen based on its height within the 55 gallon barrel, which was 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 was calculated utilizing the aforementioned method.

While similar, the primary difference between the component (laboratory) porosity testing method and system (barrel) porosity testing 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 as opposed to weight measurements used in component porosity. 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 in cubic feet. This can then be used to calculate V_{Barrel}:

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

Therefore:

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

This procedure was replicated after sediments were loaded and washed into the pores (see Figures 26 and 27 below), and then re-tested after the sediments were vacuumed from the surface.

Figure 26: Sediments being washed in

Figure 27: System barrel being loaded with sediments

Strength Testing Setup

Laboratory Testing

Compressive strength and modulus of rupture can easily be evaluated by subjecting test samples to loadings until failure occurs. A comparison between cast in place pervious concrete and cored samples from existing parking lots is shown. Cylinders and beams used for compressive and flexural strength testing are made for one time use only. FlexiPave samples with the old proprietary mix design were prepared and tested. Four (4) cylinders with two different aggregate gradations were tested. Two (2) samples were made of the mix HD 2000 with #89 granite and XFP75 urethane and two (2) samples of the mix HD 2000 with #7 granite and XFP75 urethane. The dimension of the cylinders is 2" depth and 6" diameter. The 2 inch thickness is not a standard size for cylinders used in compressive strength test but it was used to replicate the actual thickness of the pavement on site.

Six (6) beams, with three each for the different aggregate size, were tested but the results of the test carried out on these samples were not reported in this research. Subsequent to the initial field installation, a new FlexiPave mix was provided by the manufacturer of FlexiPave and was also tested. The difference between the old and new mix design lies in the binding agent used. For the new FlexiPave samples, the binder HDX 6000 Urethane was used. With this new mix, six (6) cylinders of eight inches depth and 4 inches diameter were tested and flexural test on six (6) beam specimens was also carried out. The results of these testing procedures for the new samples are reported later in this document.

Field Testing using the 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.

Figure 28: FWD test equipment on FlexiPave section

Figure 29: FWD conducting test on FlexiPave section

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. Figure 29 shows a FWD test underway on the FlexiPave section.

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:

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

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 79 ERIK measurements were taken for the FlexiPave systems. Three rounds of sediment loading and vacuum sweeping runs have also been completed. This section describes the results of the ERIK measurements on the three pavement types. Figure 31 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 32 and 33 below. The results shown below are for the Rejuvenation section.

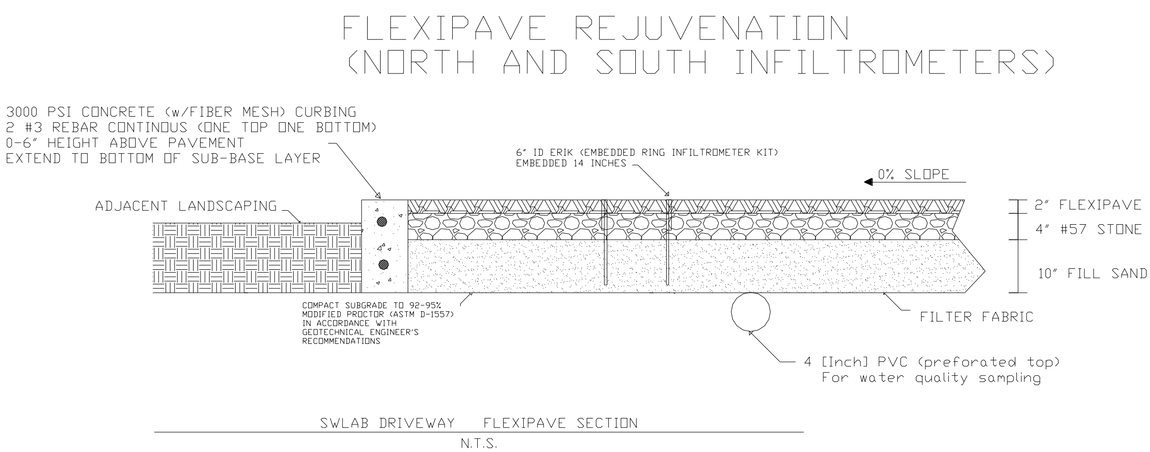


Figure 30: FlexiPave Rejuvenation cross section (north and south infiltrometers)

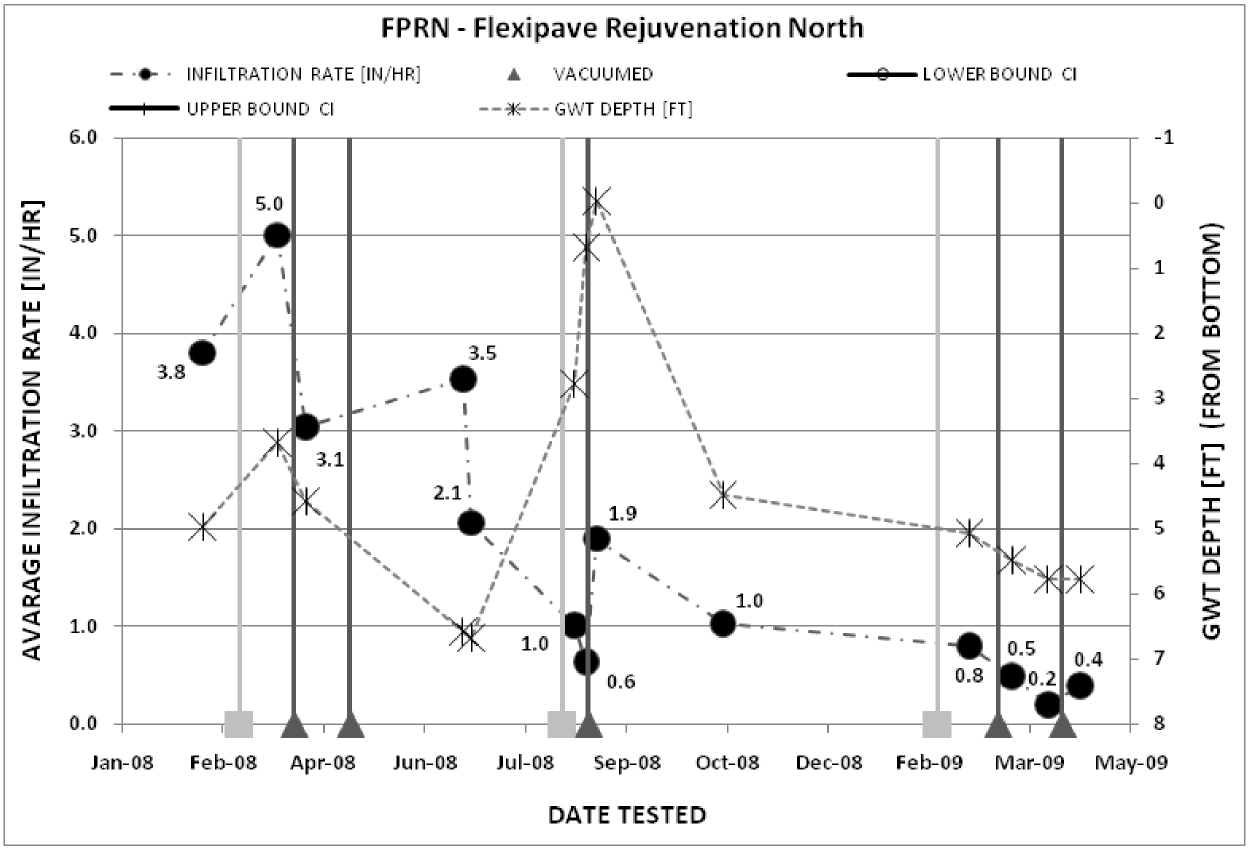


Figure 31: Infiltration Rate results (ERIK) Rejuvenation section's North infiltrometer

The initial infiltration rate measured by the north infiltrometer located in the rejuvenation pad of the flexipave systems was 3.8 in/hr. After the first sand loading event the measured rate showed no decrease and in fact increased to 5.0 in/hr. Then the pad was vacuumed and the measured rate dropped back down close to the initial rate of 3.1 in/hr. It was concluded that due to the variable nature of infiltration rates through these systems that these small differences can be expected and conclude that the first loading and vacuuming attempt did not significantly affect the infiltration rate. Similarly after a second vacuum attempt the next two tests confirmed that the rates remained close to the initial values and were 3.5, and 2.1 in/hr. The powdered limestone loading did appear to effect the pavements ability to infiltrate, causing the rate to decrease to 1.0 and 0.6 in/hr. It is noted that during the limestone loading tests, the GWT was only at a depth of less than three feet from the bottom of the system. Once vacuuming occurred on the limestone clogged pavement the subsequent test resulted in an increase back to 1.9 in/hr. A month later, the infiltrometer was retested and showed a decrease in the rate to 1.0 in/hr. Four months of natural sediment loading caused by erosion was allowed before the pavement was intentionally reloaded with sandy soils to ensure clogging of the system. The post-loaded result from the test showed that the rate of infiltration was 0.8 in/hr. The next two vacuuming attempts showed minimal success. The first two tests measured after vacuuming the sand showed infiltration rates of 0.5 and 0.2 in/hr. The surface was vacuumed again and the rate increased to 0.4 in/hr. This variation in infiltration rates is not viewed as significant and likely due to variable environmental conditions.

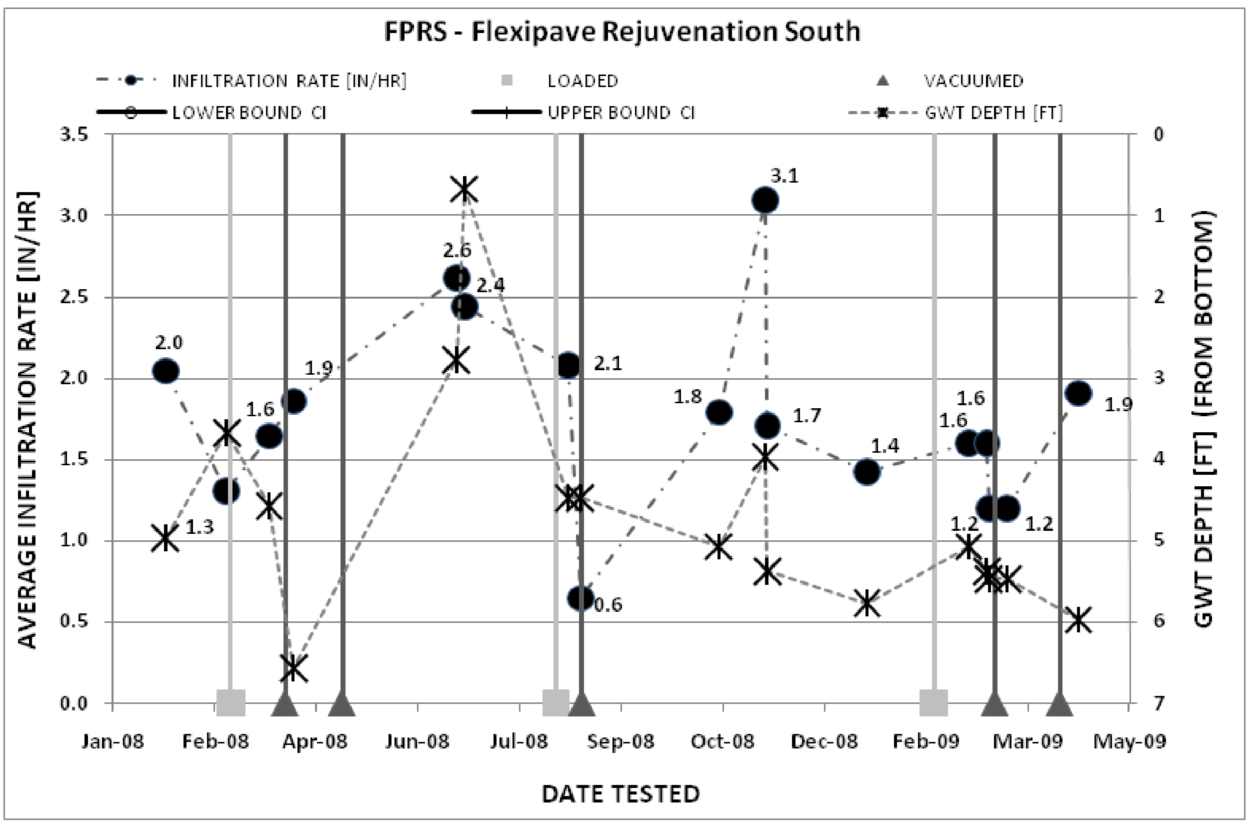


Figure 32: Infiltration Rate results (ERIK) Rejuvenation section's South infiltrometer

The southern infiltrometer on the same pad gave slightly lower initial results of 2.0 and 1.3 in/hr. Once the surface was clogged with sediments the rate measured at 1.6 in/hr, and post vacuuming rate measured 1.9 in/hr. Again the first loading and vacuuming showed little effect on the performance of the pavement and the variability shown is likely due to natural fluctuations in the soil. The surface was vacuumed again and did result in an increase of the infiltration rate up to 2.6 and 2.4 in/hr during the next two tests, which were conducted during a time of high GWT. This difference is not significant and, again, likely due to environmental conditions. The surface was then clogged with the limestone powder which also had little impact on the performance of the system. The infiltrometer was tested twice during the clogged condition and resulted in a decrease in the infiltration rate to 2.1 and 0.6 in/hr. The post vacuuming tests showed little improvement but did rejuvenate the limestone clogged system back to initial conditions. The post vacuumed rates measured were 1.8, 3.1, 1.7, and 1.4 in/hr during the next four tests respectively. Finally, the last clogging and rejuvenation attempt with A-3 fine sand had little to no effect on the systems performance, similar to the other loading events. The rate stayed at 1.6 and 1.2 in/hr after being clogged and after rejuvenation of the system the rate measured at 1.2 in/hr and the last vacuuming increased the rate up to 1.9 in/hr. Again, these differences are so small that they are not likely a result of the sediment loading and rejuvenation events but rather changes in soil moisture, GWT depth, and other environmental conditions.

Shallow (4 inches deep) infiltrometers were installed in the FlexiPave Rejuvenation sections east and west location (see Figure 34 below), and the resulting measured infiltration graphs are displayed in Figures 35 and 36.

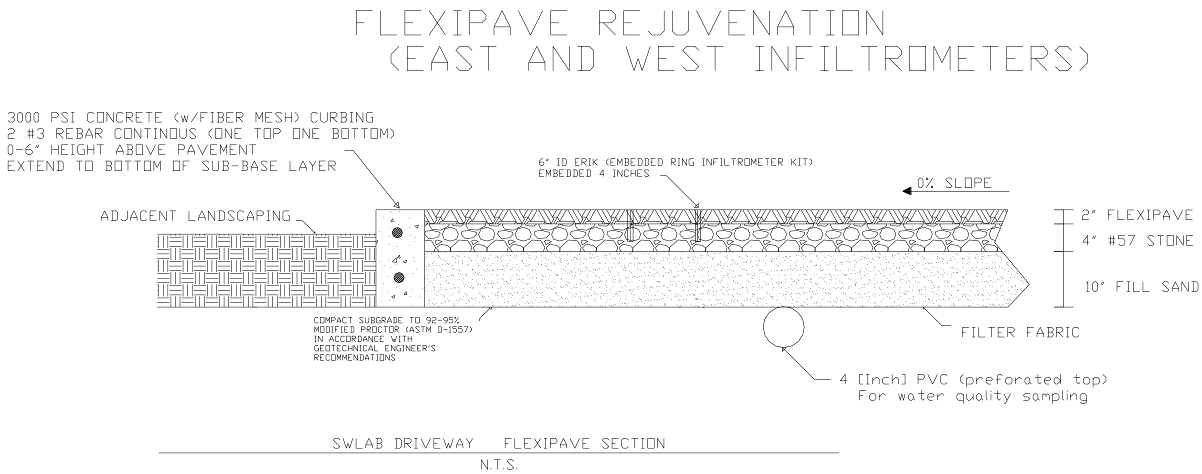


Figure 33: FlexiPave Rejuvenation cross section (East and West infiltrometers)

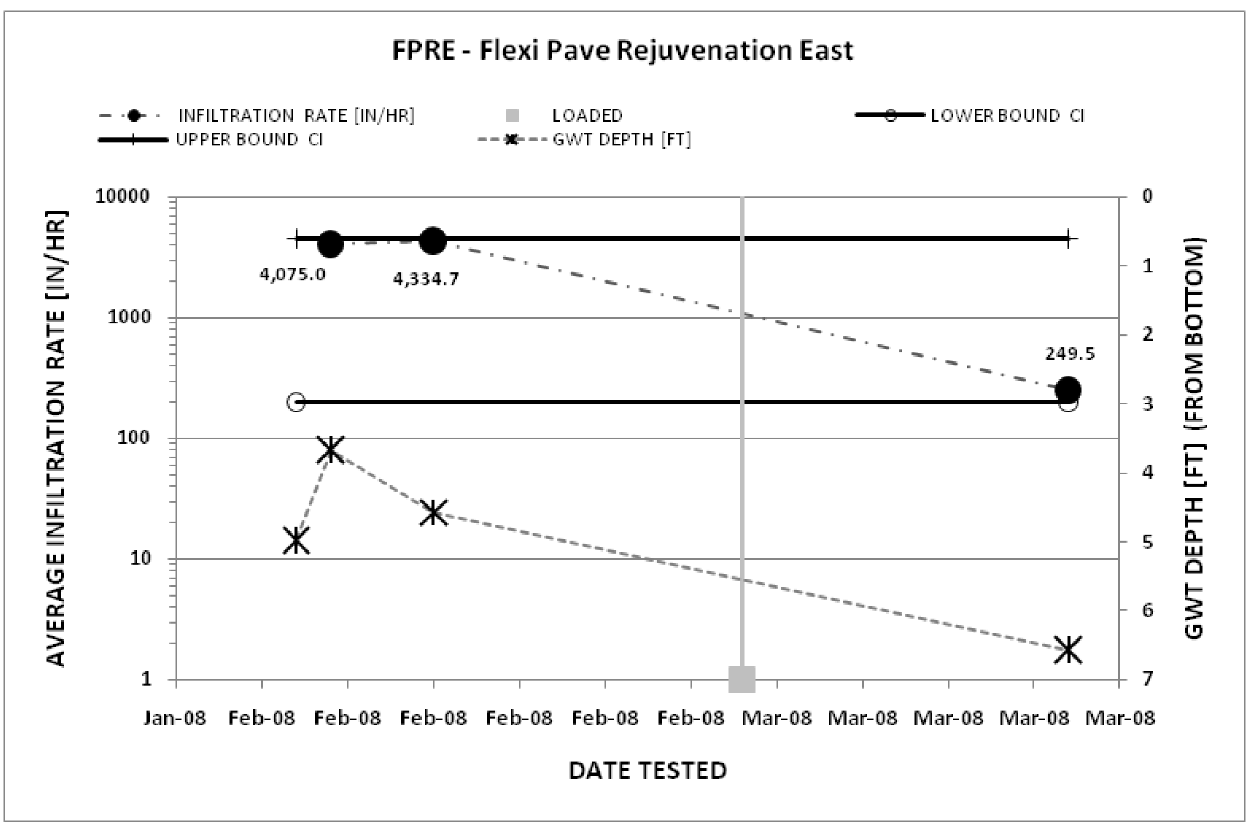


Figure 34: Infiltration Rate results (ERIK) Rejuvenation section's East infiltrometer

The first infiltrometer in the east location of the Flexipave rejuvenation pad was damaged by the skid steer's bucket while spreading the sediments over the surface, so only initial results were obtained. The initial results of the surface layer of Flexipave measured over 4000 in/hr for the first two tests. Once the sandy soils were applied, washed in, and compacted the resulting infiltration test measured 249.5 in/hr. This shows that the A-3 fine sandy soil did result in a decrease in the infiltration rates but not enough to be detected by the long ring ERIKs.

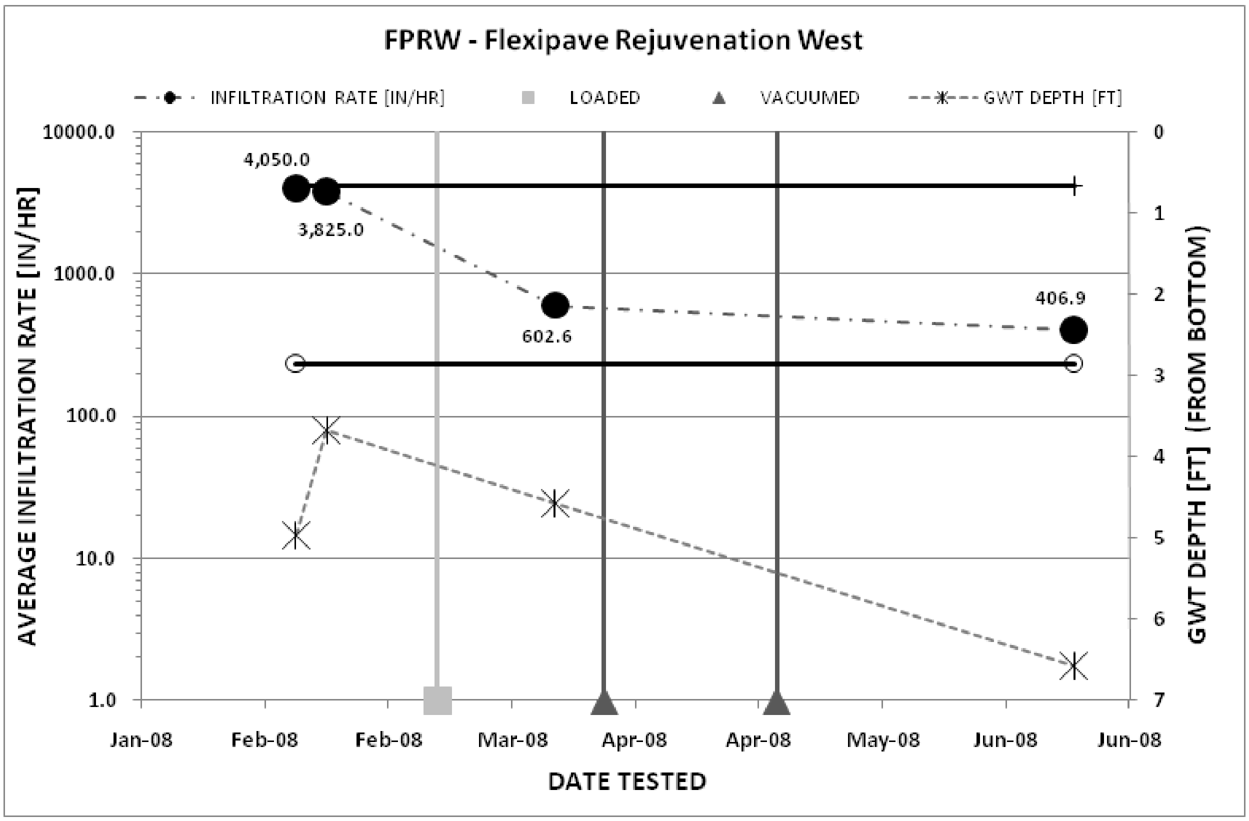


Figure 35: Infiltration Rate results (ERIK) Rejuvenation section's West infiltrometer

The west infiltrometer had similar initial results as the east with values of 4050 and 3825 in/hr. The first sand loading reduced the rate to 602.6 in/hr, and after two successive vacuums the rate measured was 406.9 in/hr. All short infiltrometers installed in the FlexiPave systems had measured rates above 100 in/hr even after intense sediment loading and high GWT. The vacuum sweeping showed no improvement in infiltration rate suggesting that sediments were allowed to penetrate to deeper layers than the effective range of the vacuum force.

The east infiltrometer was replaced with a system infiltrometer (20" in length) that extended down 4 inches into the parent earth soils is illustrated in Figure 37 below. The results for infiltration testing are displayed graphically in Figure 38 below.

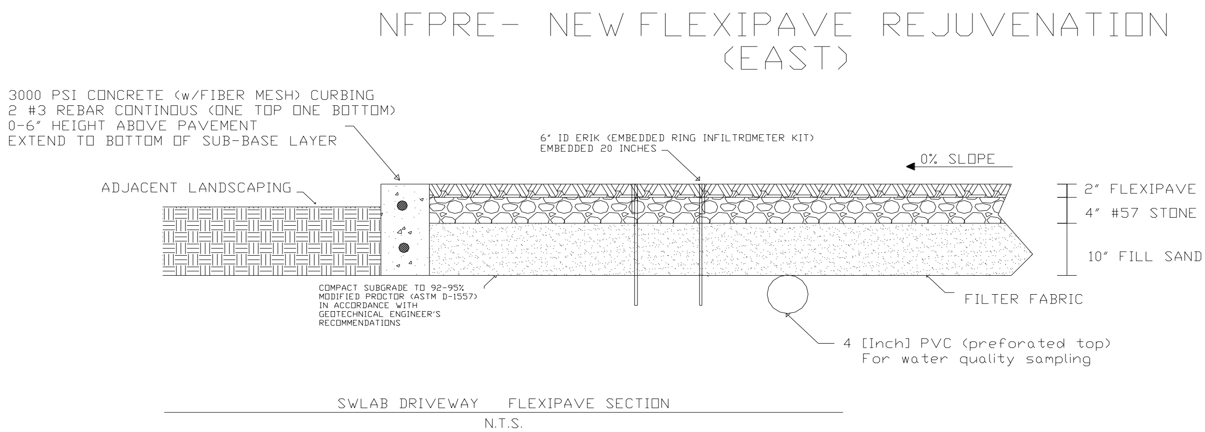


Figure 36: FlexiPave Rejuvenation cross section (New East infiltrometer)

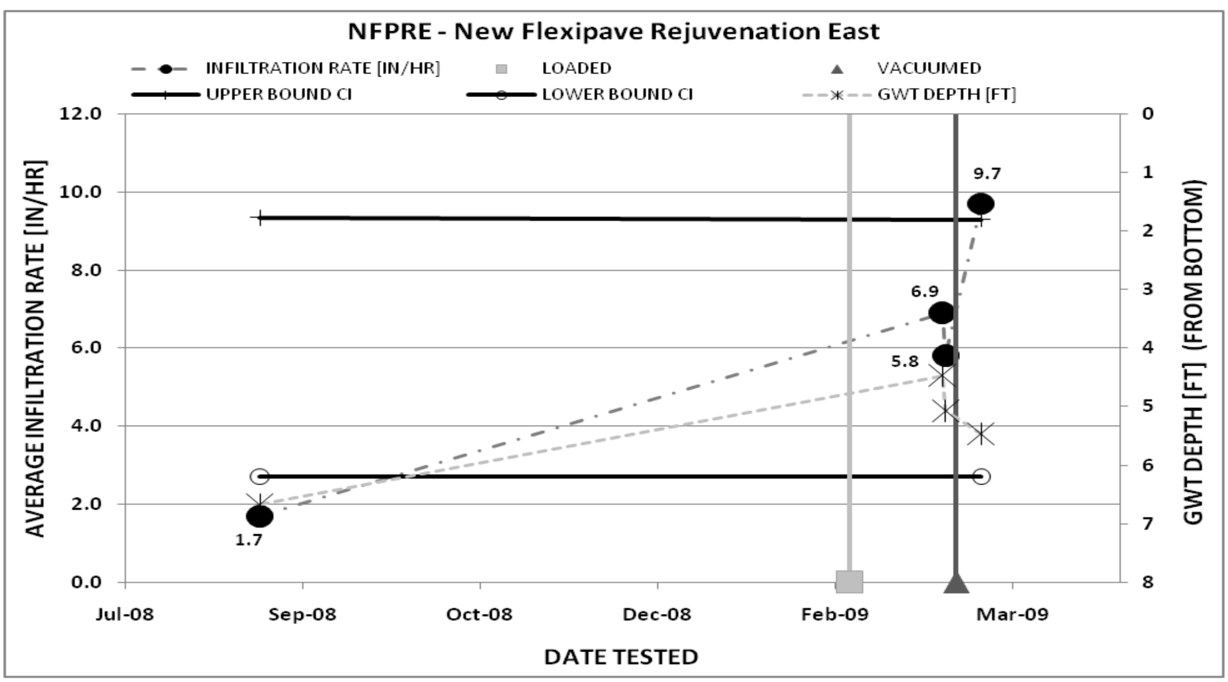


Figure 37: Infiltration Rate results (ERIK) Rejuvenation section's New East infiltrometer

An initial reading of 1.7 in/hr was measured for the deep infiltrometer. After about six months the rates measured at 6.9 and 5.8 in/hr after sediment loading. Then, after the rejuvenation attempt the measured rate increased to 9.7 in/hr. While the infiltration rate did increase after the rejuvenation event this does not indicate that the surface layer was able to be improved by the performed maintenance. This is likely due to the open structure of the pavement surface which allowed for the migration of the soil particles deeper than the vacuum force could effectively reach.

The west infiltrometer in the Rejuvenation section was replaced by a shallow (4 inch deep) infiltrometer with the cross section illustrated in Figure 39 below. The measured infiltration rate results are presented graphically in Figure 40 below.

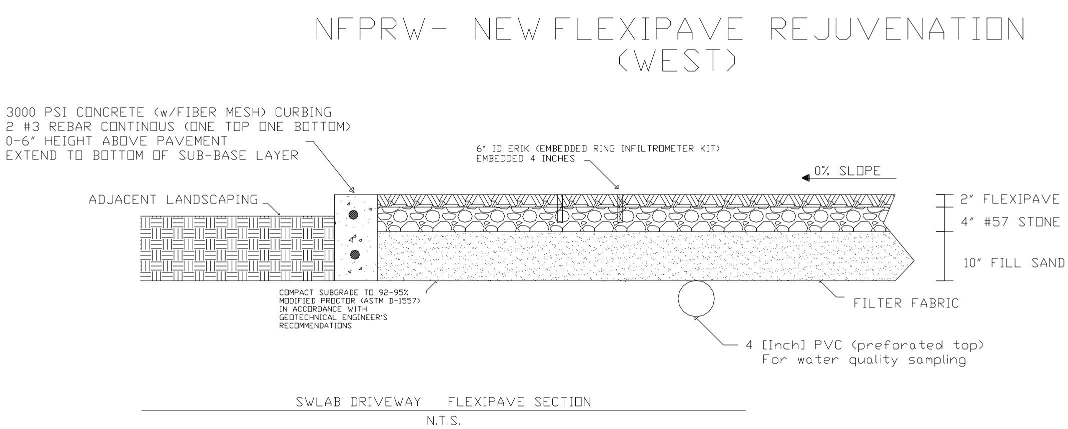


Figure 38: FlexiPave Rejuvenation cross section (New West infiltrometer)

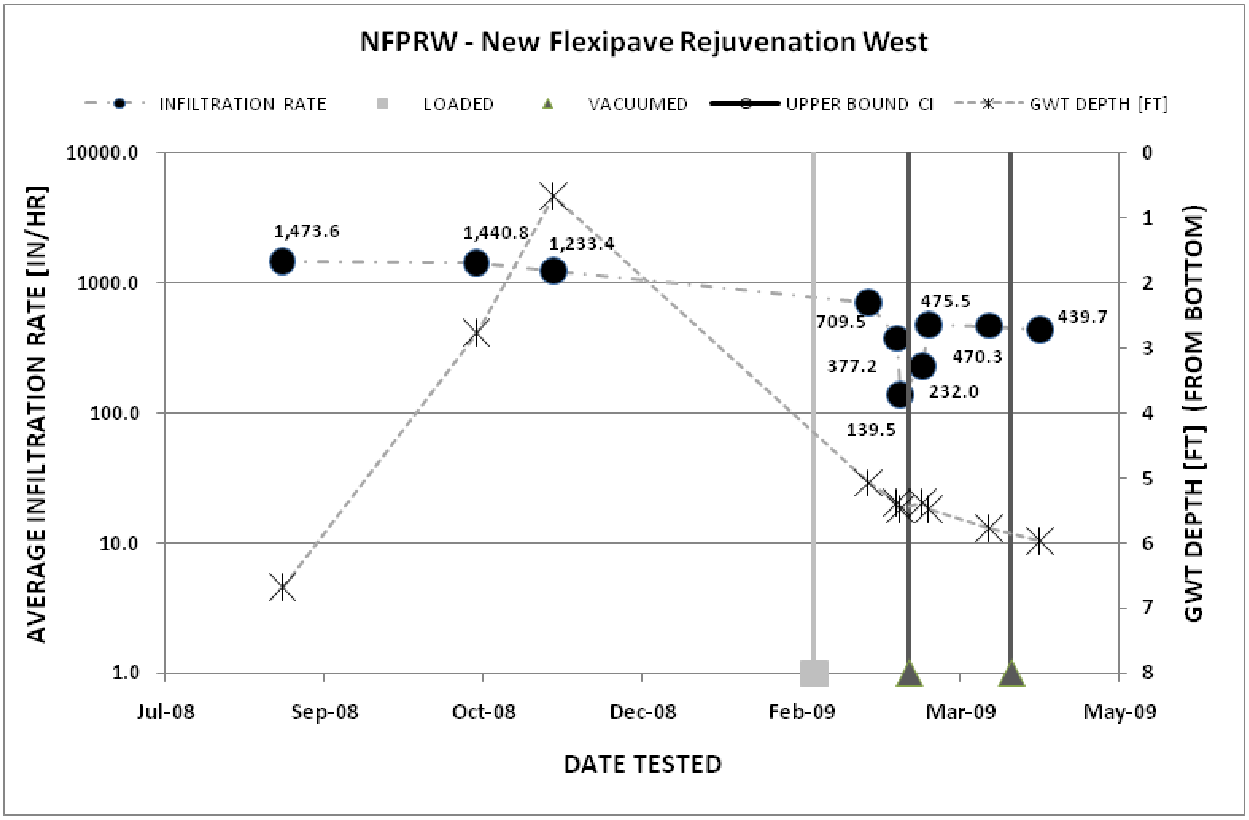


Figure 39: Infiltration Rate results (ERIK) Rejuvenation section's New West infiltrometer

The initial rate of the new FlexiPave installed in the west infiltrometer was slightly less than the previously placed FlexiPave, but the rates remained well above 2 in/hr standard throughout testing. The initial results measured remained above 1,000 in/hr even while the GWT depth was less than one foot from the bottom of the system. Once loaded with sandy soils the rates measured were reduced to 709.5, 377.2, and 139.5 in/hr. After performing maintenance with the vacuum sweeping truck the post vacuumed rates measured were 232.0, 475.5, and 470.3 in/hr. Another vacuuming took place and the resulting measured infiltration rate measured 439.7 in/hr. This indicates that vacuuming the surface will not restore the rates back to the initial values but the rate remains well above 2 in/hr on the surface of the system, even under intense sediment loading conditions.

The next system analyzed is the Bold&Gold^{TM} pollution control system with its identical East and West infiltrometers shown in the cross section illustrated in Figure 41. The resulting infiltration rates measured are presented in Figure 42 below.

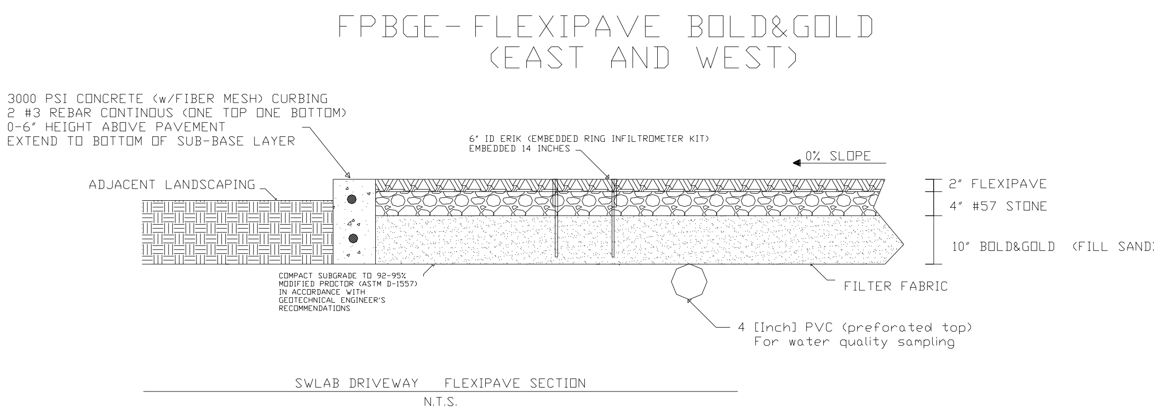


Figure 40: FlexiPave Bold&Gold^{TM} cross section (East and West infiltrometers)

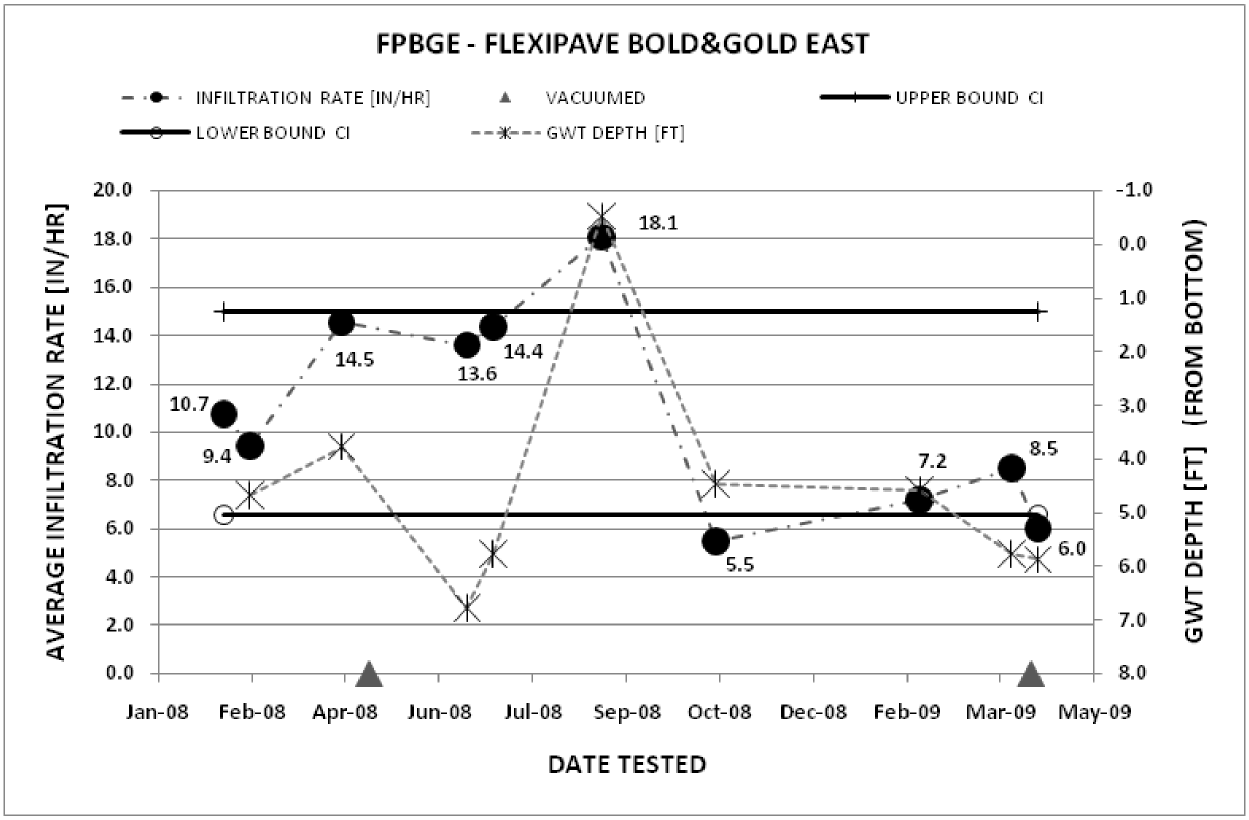


Figure 41: Infiltration rate results (ERIK) Bold&Gold™ section's East infiltrometer

The Flexipave Bold&Gold™ pad was designated as a pollution control system in which the sub-base layer was a Bold&Gold™ pollution control media mix that used local A-3 site soils as the sand component instead of the typically used washed mason sand. This system is equipped with two system infiltrometers 14 inches in length that extend down close to the bottom of the pollution control media.

The east infiltrometer measured rates of 10.7, 9.4, and 14.5 in/hr initially when the GW T was at about 4 feet below the bottom of the system. After maintenance had taken place the next three tests indicated rates of 13.6, 14.4, and 18.1 in/hr, the first two had GWT depths of greater than 5 feet, while the 18.1 in/hr took place when the GWT was actually above the bottom of the system. Over time the system naturally clogged and a system experienced a decrease in performance down to 5.5 in/hr followed by two more tests indicating rates of 7.2, and 8.5 in/hr. The pavement was vacuumed once more and the follow up test measured a rate of 6.0 in/hr for the system. It should be noted that the rate never fell below 5.5 in/hr during the study period and under natural sediment clogging conditions.

The west infiltrometer although identical to the east, resulted in slightly lower measured infiltration rates. The graphical results are presented below in Figure 43.

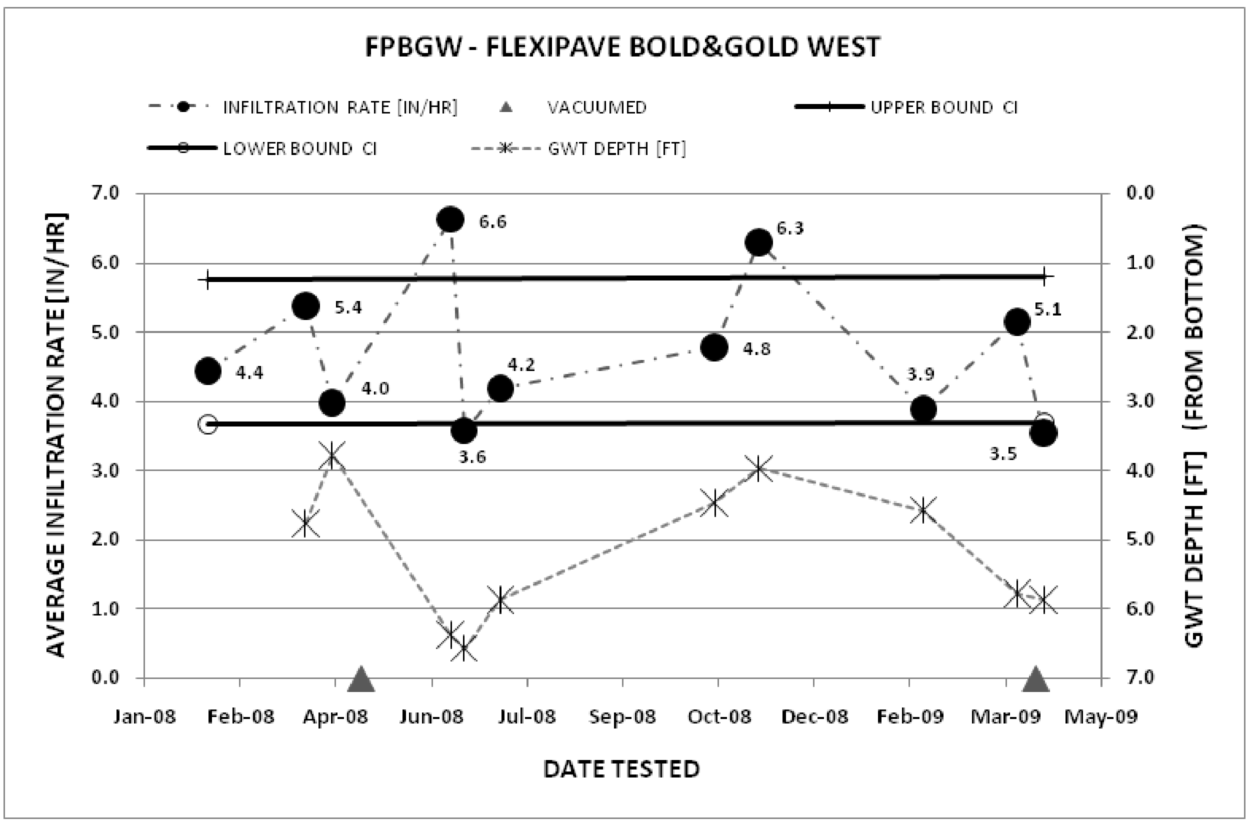


Figure 42: Infiltration rate results (ERIK) Bold&Gold^{TM} section's West infiltrometer

The west infiltrometer had very consistent measured rates throughout the study period. The initial rates measured were 4.4, 5.4, and 4.0 in/hr while the GWT was below 3 ft from the bottom of the system during this time. A vacuuming event took place on the naturally loaded pavement and the post vacuum tests resulted in rates ranging from 6.6 to 3.5 in/hr depending on the depth of the GWT. According to the results, maintenance did not need to occur on this pervious system since the rate never fell below 2.0 in/hr.

The Fill section represents the pavement layer and #57 stone reservoir layer being placed directly on parent earth soils. This could potentially save costs since excavation depth is minimal (only six inches) and additional materials would not need to be brought to the site. Figure 44 below shows the cross sectional view of the east and west infiltrometers which are identical in embedment depth. The resulting measured infiltration rates are displayed graphically in Figures 45 and 46 below.

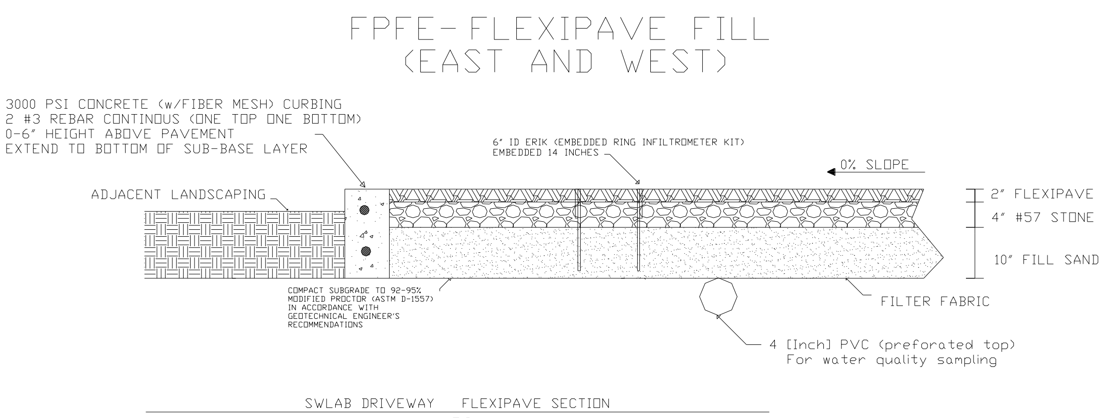


Figure 43: FlexiPave Fill cross section (East infiltrometer)

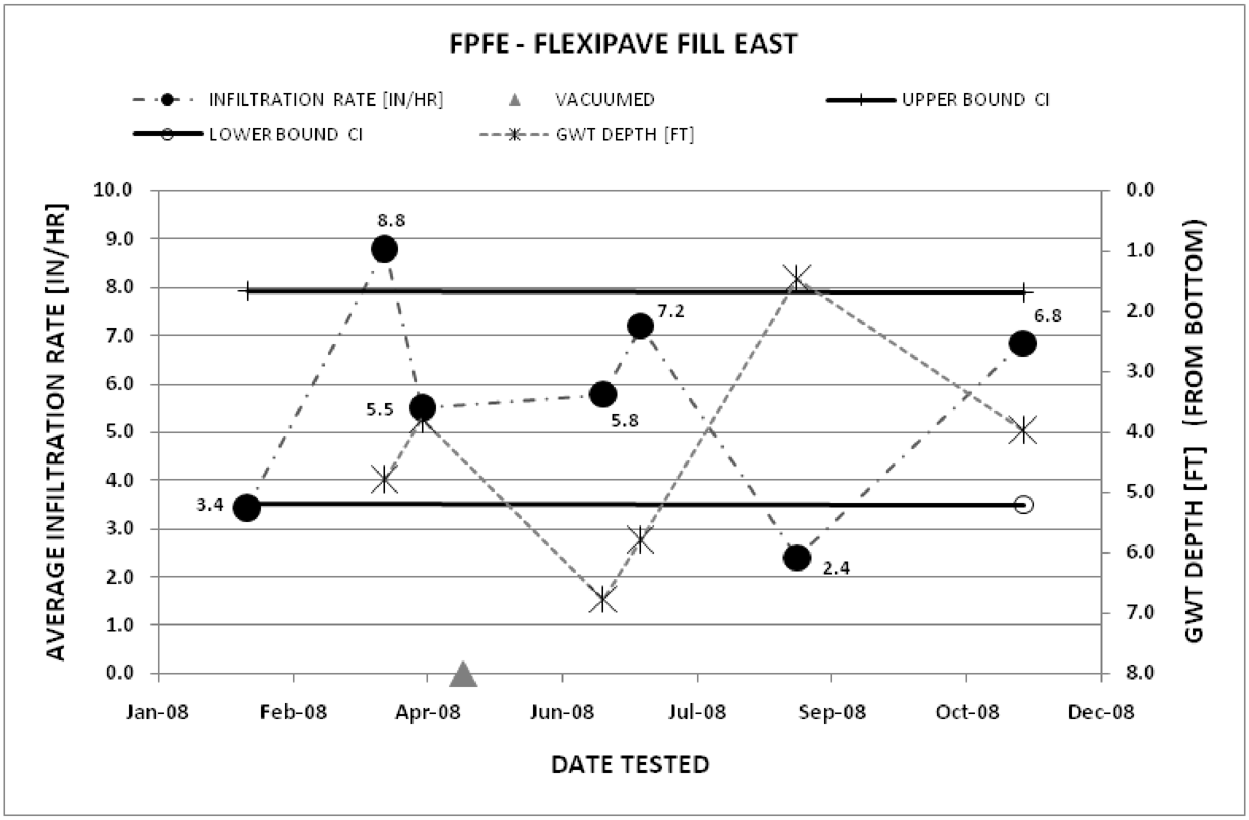


Figure 44: Infiltration Rate results (ERIK) Fill section's East infiltrometer

The east infiltrometer located in the FlexiPave section with local fill dirt as the sub-base shared similar results to that of the Bold&Gold™ sub-base which consisted of local fill dirt as the soil component of the mix. The initial measured rates were 3.4, 8.8, and 5.5 in/hr before the maintenance event took place. Once vacuumed, the measured rates were 5.8, 7.2, 2.4, and 6.8 in/hr during the period of study. The GWT depth appeared to affect the rate of infiltration reducing the rate to 2.4 in/hr while it was at a depth of about 1.5 ft beneath the bottom of the system.

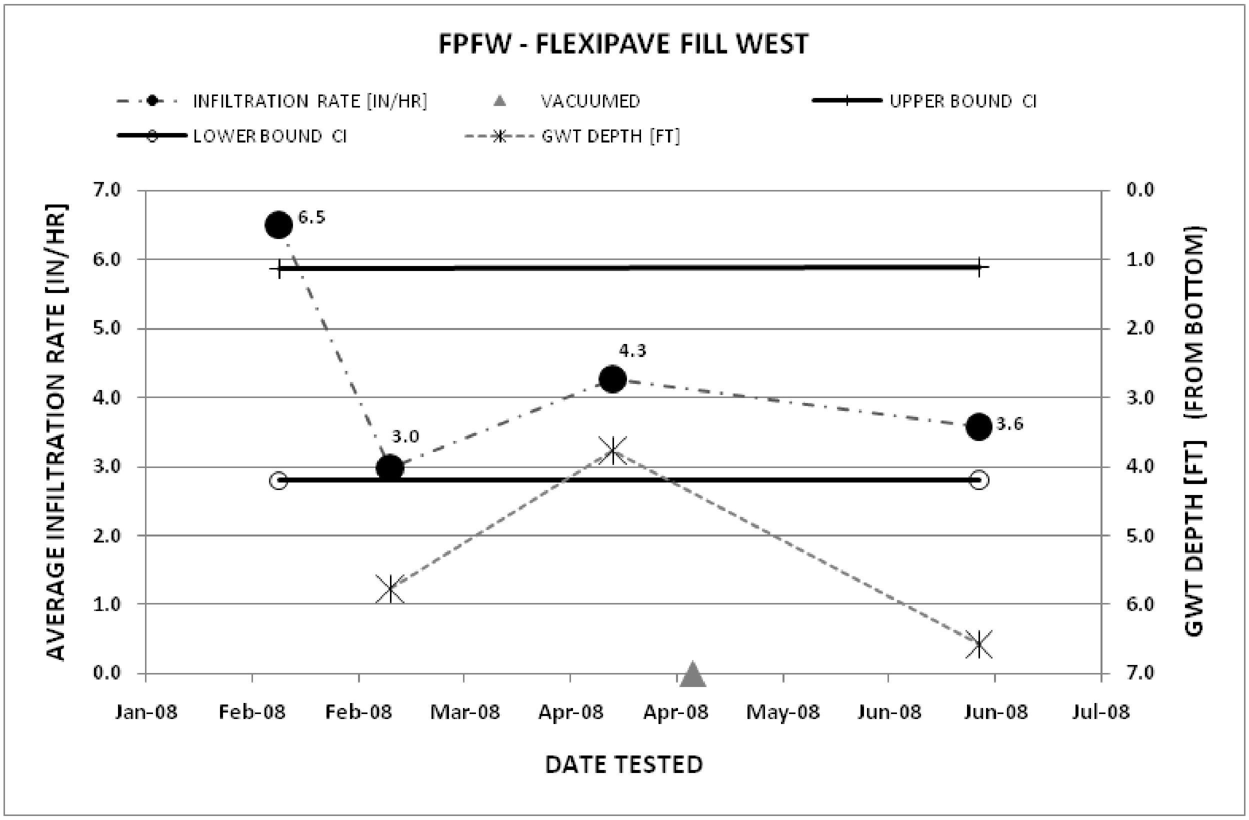


Figure 45: Infiltration Rate results (ERIK) Fill section's West infiltrometer

The west infiltrometer was damaged after four months of testing, so only results from four ERIK tests are presented. The initial rates are consistent with the east infiltrometer, and similarly, the rate never dropped much below 3.0 in/hr. The first test resulted in a rate of 6.5 in/hr, followed by rates of 3.0, and 4.3 in/hr. After vacuuming of the naturally clogged FlexiPave, the rate was measured at 3.6 in/hr, showing no significant benefit.

Sustainable Storage Evaluation Results

Sustainable Storage Strength Evaluation

The porosity testing results of the individual component materials are tabulated in Table 1 below. The total porosity of the FlexiPave surface layer measured in the ½ gallon containers is 37.3%. 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 and thus can be considered the effective porosity. As seen in Table 1, the effective porosity is 31.1% showing a slight decrease in comparison to the total porosity (almost a 17% reduction). This indicates that the FlexiPave material, with its large pore sizes, is able to dry relatively quickly and recover its storage volume. Next, the FlexiPave material is loaded with sandy sediments to induce clogging of the surface pores. This resulted in an average effective loaded porosity of 10.4% (Table 1). It should be noted that the depth of the material samples in the ½ gallon containers is much more (about 8 inches) than in the field (about 2 inch thickness), so vacuuming may not remove the amount of sediment in the deeper test containers compared to in the field. This reduction in storage is due partially to the fact that some of the volume of sediment particles is now occupying the once empty pore spaces. This is also due to a larger number of smaller pore sizes that retain a larger volume of moisture in the once air filled pores. When the pores are large enough so gravity alone can more easily drain the water from the pore storage is recovered more quickly. It was observed during the testing that much of the sediments were able to easily pass through the surface pores of the FlexiPave material and reach the bottom of the transparent containers without much filtering. This observation agrees with the data, which shows that much of the empty pore spaces were filled with sediments. Little of the sediment was extracted from the deeper parts of the cross-section by the vacuum due to the suction force not being sufficient at those depths. However the sediments near the surface were easily removed by the vacuums' suction force, up to about 1-2 inches down from the surface. Porosity measurements were taken after vacuuming the surfaces and an average effective porosity of 13.6% was been measured. This result confirms that the clogging sediments did in fact travel to the bottom of the containers and only the top portion was effectively rejuvenated by vacuuming. This proves the surface layer is not effective at filtering sandy sediments and preventing them from entering the sub-layers, which may cause an eventual reduction in storage capacity of the deeper storage layers. The advantage is the ability of the surface layer to remain unclogged and allow the passage of sediments and water. This helps prevent water from having a chance to runoff before infiltrating into the pervious pavement system.

The sub-base layer materials were tested using the small scale ½ gallon containers and were tested for both total (over dried) and effective (gravitational drainage) porosities. The #57 crushed concrete aggregates provided average values of 47.1% total porosity and 41.4% effective porosity. The Bold&Gold™ pollution control media porosity measured 38.9% for total porosity and 15.2% for effective porosity.

Table 1: Individual component Porosity Results measured in ½ gallon containers

Flexi-pave FP	AVERAGE MEASURED POROSITY [%]			
MATERIAL TYPE	Total	Effective	LOADED	VACUUMED
Flexi-pave FP	37.3	31.1	10.4	13.6
(#57) Crushed concrete	47.1	41.4		
Bold&Gold	38.9	15.2		

Presented below in Figure 47 are the results from the FlexiPave system porosity testing using the complete cross section in the 55 gallon barrels. The barrel systems consist of all the materials used in the construction of the field scale test pads including the surface layer, stone support/reservoir layer, and pollution control sub-base layer. The initial tests were conducted prior to introducing any sediment to the systems to investigate the total or maximum storage available.

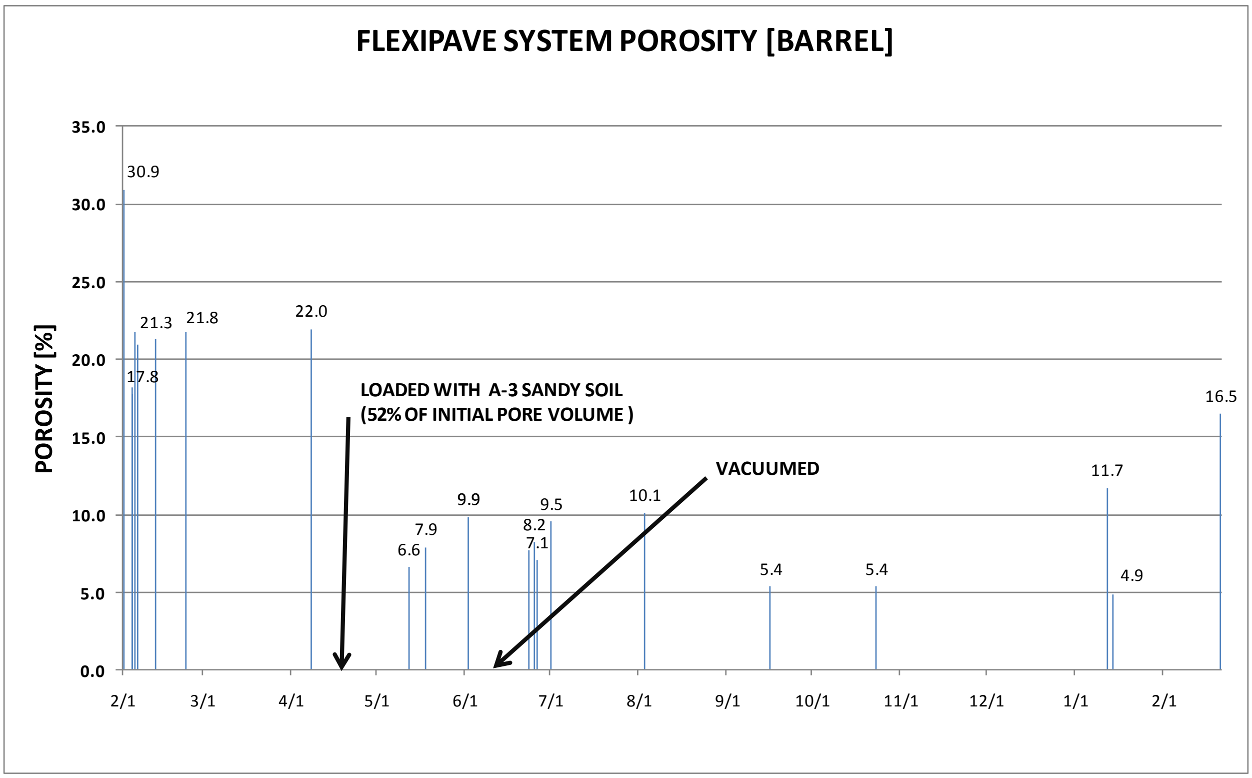


Figure 46: System porosity results using 55 gallon barrels

The first value, 30.9% 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 micro pores 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 (17.5% - 22.0%) of the system. This is the porosity which can be expected for the in-situ pavement that is not oven dried or has residual water in the micro pores. The sixth test is conducted after loading with a volume of type A-3 soil equal to 52% of the total measured pore volume. The A-3 soil loaded on the surface of the FlexiPave material was washed into the pores while simultaneously pumping the infiltrated water out of the well pipe (see Figure 48 below).

Figure 47: Washing loaded sediments into pores while pumping infiltrated water out through well pipe

After the loading takes place the effective porosity was reduced to 6.6% after only one day of drainage, while the next two tests measured rates of 7.9% and 9.9%. After the sediments were vacuumed from the surface the remainder of the tests measured values slightly greater than the loaded condition but remained almost 50% less than the total porosity measured. The range of measured porosity for the vacuumed system was from 4.9 to 16.5% depending on the number of days allowed for gravity induced drainage of the barrel system. This result indicates that the storage within the system will reduce to less than half of its original condition since the sediments are not filtered but allowed to flow freely into the deeper layers where the vacuum force cannot reach.

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 system was calculated by adding the pore volumes for each layer and then totaled to represent storage within the entire system. The theoretical calculation of the system's (total) storage was calculated at 6.6 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 4.9 inches. The same calculation using effective porosity values, the theoretical storage of 3.8 inches within the 16 inch cross section, whereas the actual barrel tests measured storage of 2.8 inches. This shows that there is some mixing of the layers which causes a slight decrease in the pore volume of the complete system.

In conducting the same analysis of the FlexiPave system after intentional sediment loading, the theoretical effective storage in the system is calculated to be 3.4 inches using the individual components with the actual barrel measurement of 1.1 inches. After vacuuming the surfaces the effective theoretical storage in this system is calculated at 3.5 inches while the actual barrel storage is measured at 1.6 inches. It can be concluded that the actual total porosity of a complete system is about, on the average 26% less than if calculated theoretically using the individual components. The actual effective porosity is, on the average, 49% less than calculated theoretically using the individual components.

Strength Results

Laboratory Test Results for Flexi-pave

As result of its flexibility and its ability to return to its previous shape after the application of load or deformation, the compressive strength may not be the most desired test on this type of pavement but was studied for comparison. The sample sizes were 8 in. x 4 in. The average porosity of the sample was found to be 0.53, while its average compressive strength was found to be 115.4 psi.

Table 2 presents the results of the laboratory test conducted on the 8 x 4 cylinders. These representative samples were prepared by the manufacturer. The compressive strength ranges from 108 – 129 psi. The porosity is 0.53 while the unit weight ranges from 57 – 59 psi.

Table 2: Porosity and void ratio data of recycled rubber tire pavement (Flexi-pave®)

Sample	Maximum Load (lbf)	Compressive strength (psi)	Unit weight (lb/ft^3)	Porosity, n	Void ratio, e
A2	1449	119.0	56.76	0.53	1.14
B2	1312	107.75	56.33	0.53	1.12
C2	1373	112.76	55.88	0.53	1.14
D2	1568	128.77	58.08	0.53	1.12
E2	1379	113.29	55.88	0.53	1.14
F2	1351	110.95	56.76	0.52	1.10

The average void ratio and porosity for these samples are 1.12 and 0.53 respectively and are shown in Table 3. The 2σ test shows that all the void ratio values fall within the specified range.

Table 3: Statistical Data for Porosity

Sample	Average Void ratio, e	Average Porosity, n	Standard deviation, σ	Range (n - 2σ,n +2σ)	Proportion within 2σ	Coefficient of variation, CV
A2 – F2	1.12	0.53	0.0033	(0.52, 0.54)	1	0.006

Table 4 shows that the average compressive strength of these 8 x 4 cylinders is 115.41 psi. All the compressive strength values are within the range in the 2σ test. The compressive strength is low but unlike other pervious pavements it can still withstand more applied load even after failure because of its high flexibility. It is important to note that the number of samples tested was low. A sample size of six is limiting the drawing a very accurate conclusion based on this test.

Table 4: Statistical Data for Compressive strength

Sample	Average Compressive strength (psi)	Standard deviation, σ	Range	Proportion within 2σ	Coefficient of variation, CV
A2 – F2	115.41	7.506	(100.40, 130.42)	1	0.065

Also at the instance of failure, from visual observations, it is seen that the crack is not very visible. The elasticity of the sample allows it to return to its initial position upon application of the load. It can however be said that the sample can still accommodate more load even after failure.

The flexural strength is the preferred strength test on this type of pavement because in compression it has the ability to return to its original position after deformation. Visible diagonal cracks were observed at the middle third of the beam under flexural behavior. For this pavement type, it appears that this test actually measures the strength of the polyurethane binder in bending. Table 5 presents the modulus of rupture for each corresponding sample. The range of Modulus of Rupture (MR) is between 164 – 186 psi.

Table 5: Flexural strength of new recycled rubber tire pavement

Sample	Maximum load at failure, P (lbf)	Modulus of Rupture, MR (psi)
G2	2153	178.94
H2	2011	184.99
I2	2074	178.26
J2	1751	163.46
K2	2026	180.14
L2	2037	178.53

The statistical analysis of the flexural strength is shown in Table 6. All the results obtained fall within acceptable range. The average modulus of rupture of these samples is 177.39 psi.

Table 6: Statistical Data for Modulus of Rupture

Sample	Average Modulus of Rupture (psi)	Standard Deviation, σ	Range	Proportion within 2σ	Coefficient of variation, CV
G2 – L2	177.39	7.26	(12.86, 191.91)	1	0.041

FWD Testing Results

Flexipave elastic modulus was between 20 – 230 ksi because of the flexibility of this pavement, the FWD deflection reading was erroneous. The deflections especially at the point of load application surpassed the maximum allowable deflection value by the FWD equipment used (129 mils). It is concluded that FWD should NOT be used for determining the modulus of Flexipave pervious pavements.

CONCLUSIONS AND OBSERVATIONS

General Observations

Observations made during the installation of the pavement sections are included below. By using recycled #57 stone crushed concrete, the materials were readily available and were regional materials providing ease of acquiring the material to the site. This material was noticed to have a small amount of metals and other debris mixed in with the aggregates. The surface layer materials, including the tire chips, granite aggregates, and binder were trucked in by bags and 5 gallon buckets and stored near the site.

Shortly after installation and throughout the study period it was notice that there was a moderate amount of minor surface raveling throughout the sections that was caused by turning movements of the heavy vehicles (semi-trucks, dump trucks, heavy construction equipment, etc.) that drove on the sections. New developments in the strength of the binder were made by the manufacturer since the installation of the pavement, so application of an overcoat was applied to the surface which re-bonded the aggregates to the pavement slab. After application of the overcoat spray, the degree of raveling was greatly reduced.

Infiltration Rates

The determination of the FlexiPave system 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 74.7% of the runs provided values above the minimum of 2.0 in/hr for all three sections measured by the infiltrometers. For the Rejuvenation section, 58.8% of the results, for Bold&Gold™ section 100% of the results, 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. In conclusion, infiltration rates did not drop below 2 inches per hour unless excessive amounts of sediments were spread over, washed in, and compacted into the surface pores. 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 FlexiPave pervious pavement systems will perform as intended, unless a worst case scenario excessive sediment loading condition and high ground water table levels exist. Maintenance by the use of a vacuum sweeper truck will remove surface sediments but is ineffective at removal of deep penetrating sediments. However, throughout the study period, there was never ponding observed on the surface during rainfall events in which ponding was observed on many of the other smaller pore sized pervious/permeable pavement types.

Under normal sediment loading conditions it is expected that the FlexiPave systems will perform well above 2 in/hr. The amount of sediment loading depends on the site location and its exposer to sediments being brought onto the pavement's surface by natural (wind and water laid sediments) or un-natural sources (ie. Tire tracking of sediments, spills, etc.).

This pervious 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 lower layer pores, a standard vacuum truck may be unsuccessful at improving its capability to infiltrate, but the surface layer remains unclogged to allow the initial precipitation that falls on its surface to be infiltrated. The ability to readily infiltrate water was noticed as an important factor in preventing runoff despite allowing sediments to pass through the surface layer so the rainfall has a change to enter the system through the surface before it forced to become runoff due to surface clogging.

Sustainable Storage

After multiple porosity tests were conducted on all the individual components that make up the entire pavement cross section and the actual constructed system that mimicked ideal conditions as well as those in the field such as oven dried samples, gravity drained samples, samples loaded with sediments, and samples 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 is less than the calculated theoretical storage of 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 FlexiPave pervious pavement system is about 10%.

Water Quality

One of the objectives of this study was to examine the quality of water that infiltrates through two FlexiPave pervious pavement systems but due to unforeseen circumstances this analysis was unable to be performed. The ongoing testing of fertilizer runoff from fertilized slopes using the test beds and rainfall simulator next to the Flexipave sections caused very high levels of nutrients to be detected in the water samples collected from the below the pavements. Testing of the quality of water through these sections was shifted to the laboratory using barrels.

However, examination of other pervious pavements showed that the quality of water that infiltrates through these systems is typical of concentrations measured in stormwater in the Orlando Florida area. 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 FlexiPave as the specified product. The cross section for this system consists of a 4 inch deep layer of # 57 recycled concrete with 2 inches of FlexiPave on top. There is a non-woven filter fabric separating the parent earth soil from the limerock 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 0.79 mg/L as N and 0.68 mg/L as PO_4^{3-}, respectively.

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 0.88. 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 7.39 cfs and multiplying that by the 10 minute duration gives a runoff volume of 4,435 cubic feet, or 125,585 liters. Therefore, the TN mass leaving the system is 99.2 grams and the TP mass leaving the system is 85.4 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 FlexiPave system would have a TN mass reduction of 8.8 grams (8%) and a TP mass reduction of 7.5 grams (8%) for a one acre parking lot.

The above analysis and example problem shows that there is a water quality benefit to using a FlexiPave 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

The average porosity of the sample was found to be 0.53, while its average compressive strength was found to be 115.4 psi. The compressive strength ranges from 108 – 129 psi while the unit weight ranges from 57 – 59 psi. The average void ratio and porosity for these samples are 1.12 and 0.53 respectively.

The compressive strength is low but unlike other pervious pavements it can still withstand additional applied load even after failure because of its high flexibility. The elasticity of the sample allows it to return to its initial position upon application of the load. The flexural test is more suited but primarily measures the strength of the polyurethane binder in bending. The range of Modulus of Rupture (MR) is between 164 – 186 psi.

Flexipave elastic modulus was between 20 – 230 ksi because of the flexibility of this pavement, the FWD deflection reading was erroneous. It is concluded that FWD should NOT be used for Flexipave pavements.

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