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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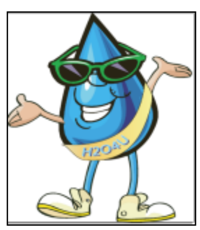

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation. Furthermore, the authors are not responsible for the actual effectiveness 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).

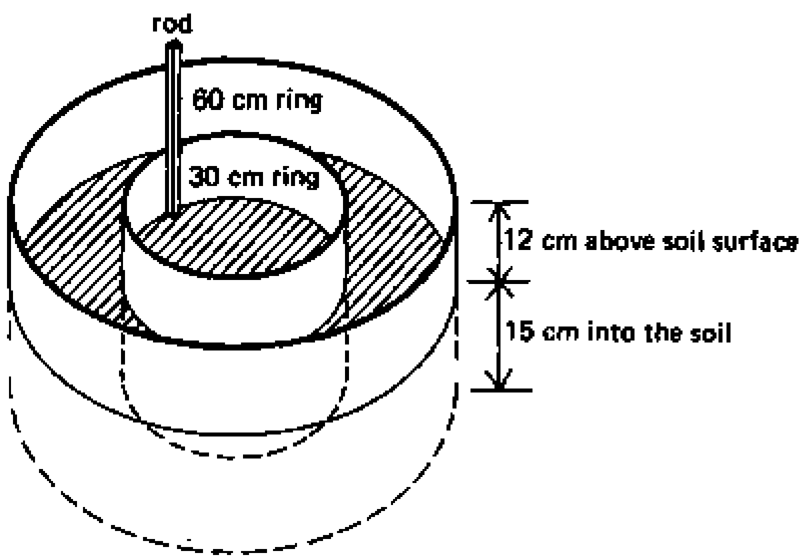
Field Infiltration Methods

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.

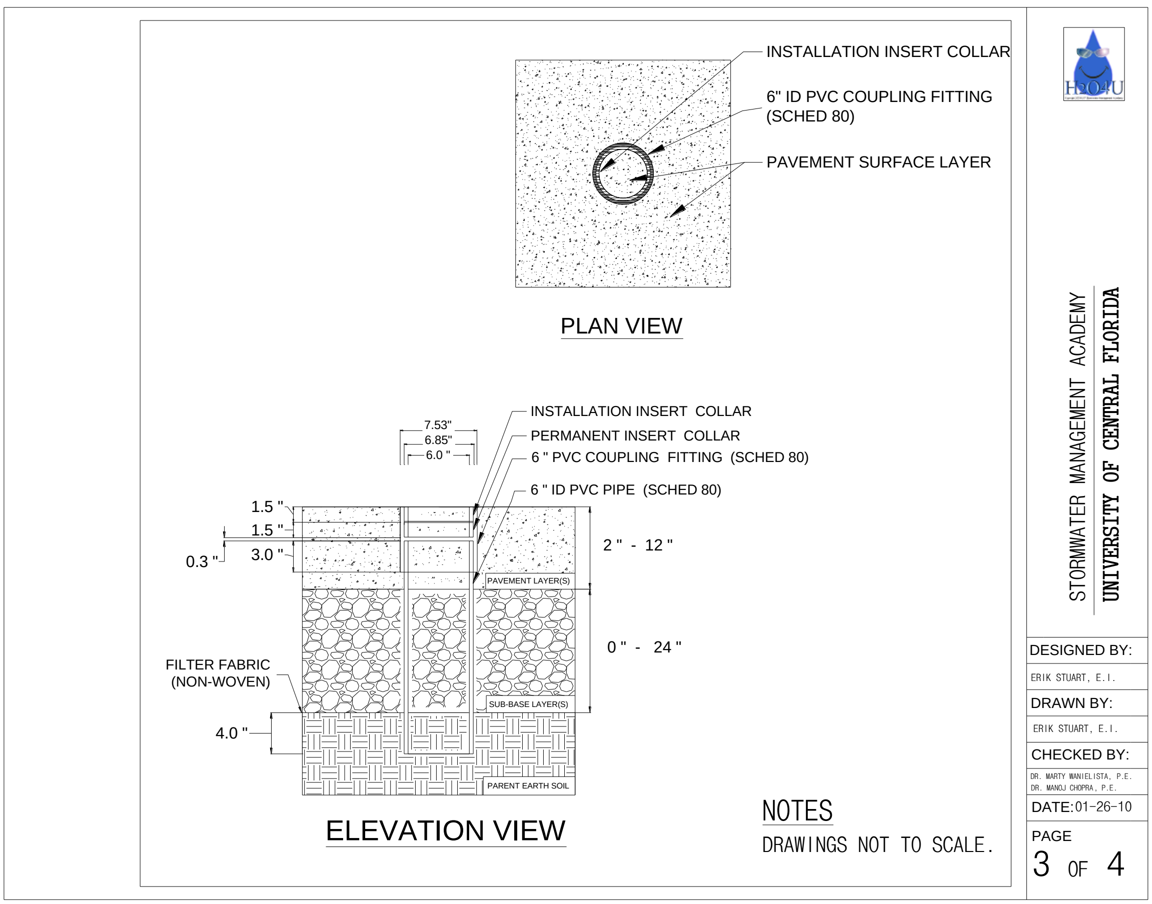


Figure 2: ERIK monitoring tube

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.

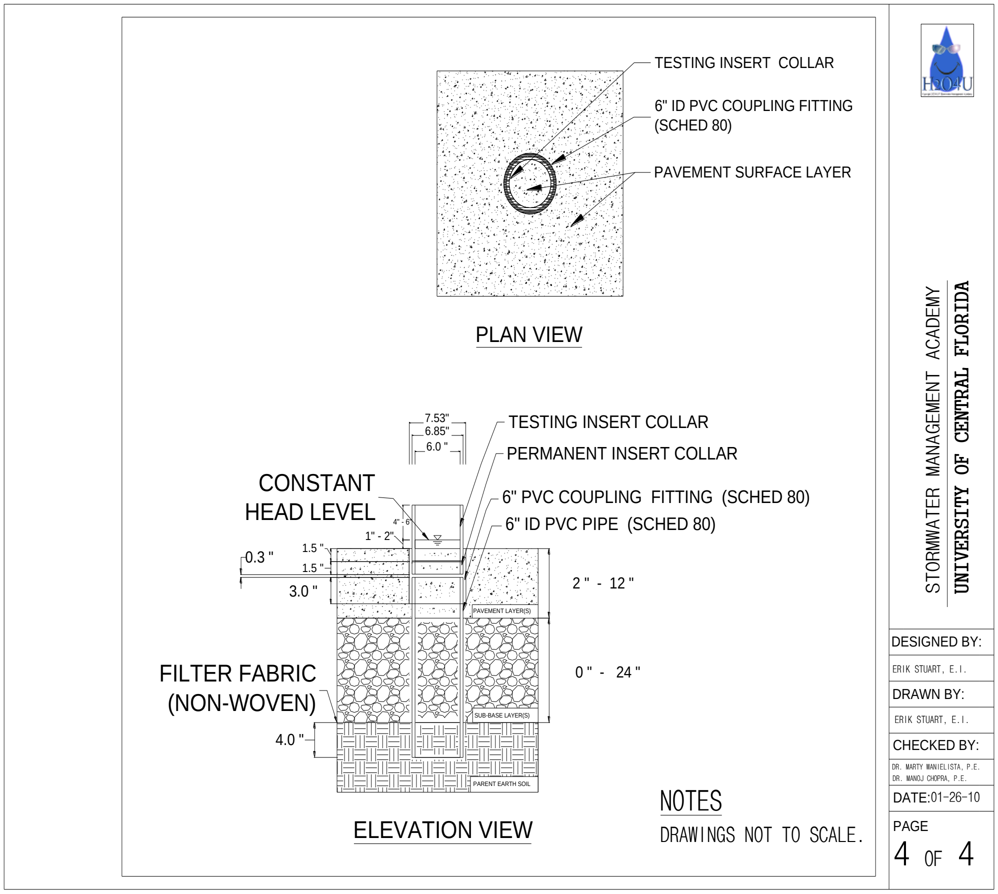


Figure 3: ERIK embedded ring installed

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.

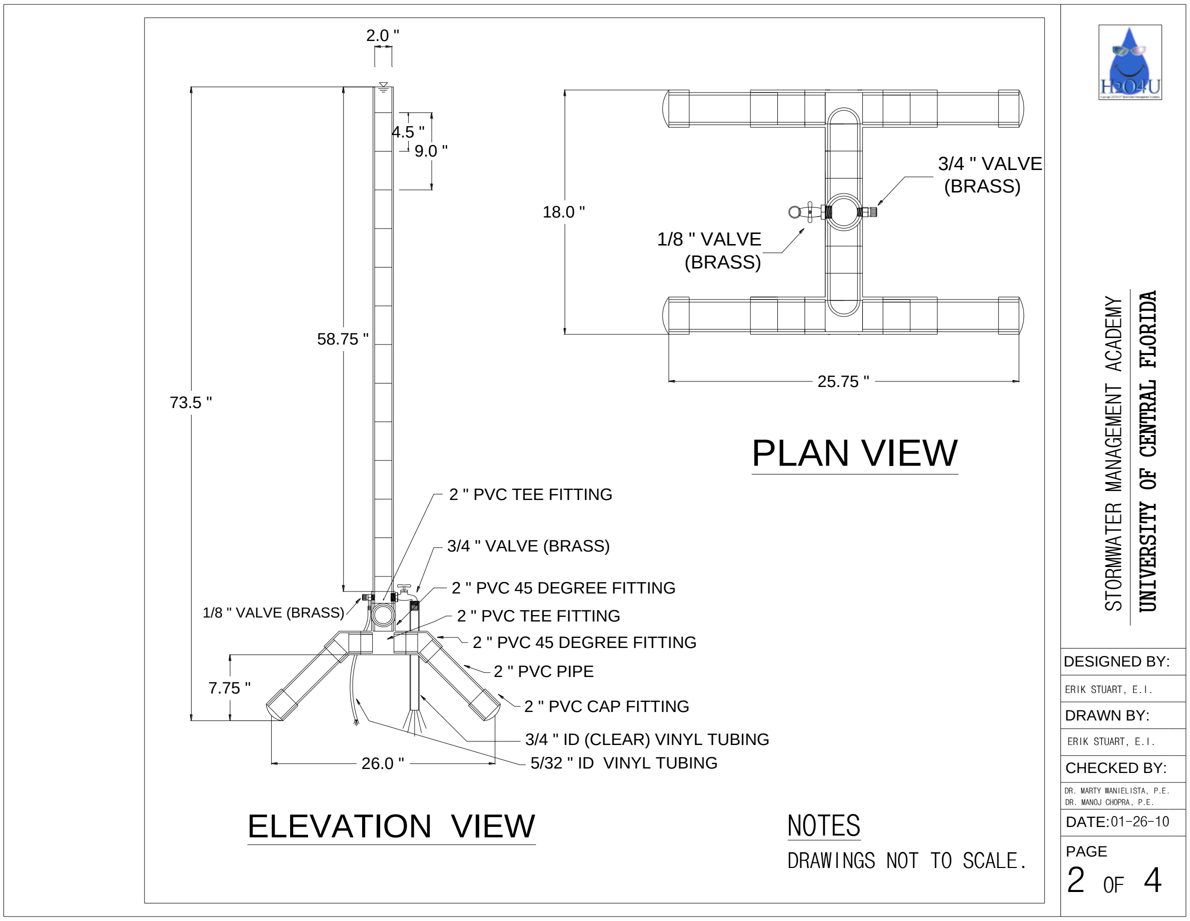


Figure 4: ERIK monitoring cylinder reservoir

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

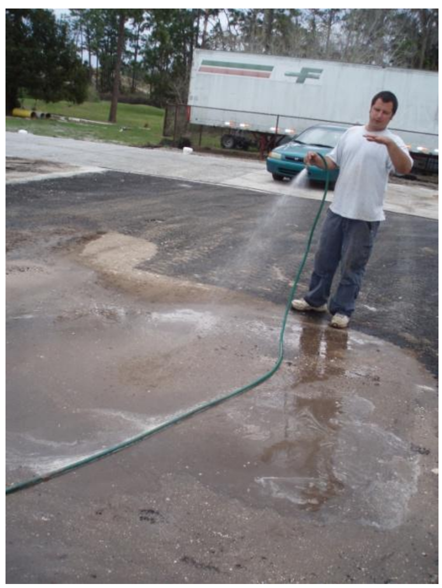


Figure 11: Washing in sediments using garden hose

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.

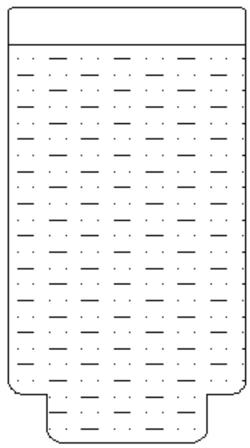


Figure 24: Half Gallon plastic jar cross section for component testing

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.

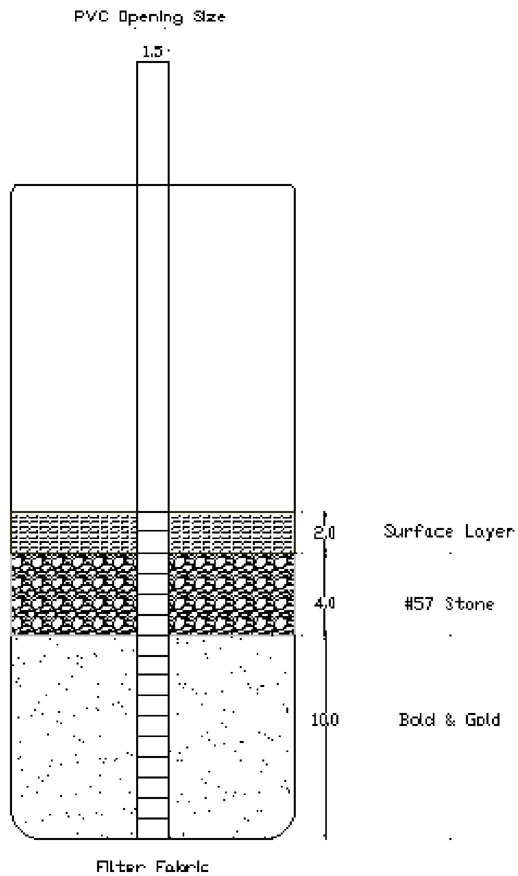


Figure 26: 55 Gallon Barrel for System testing

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.

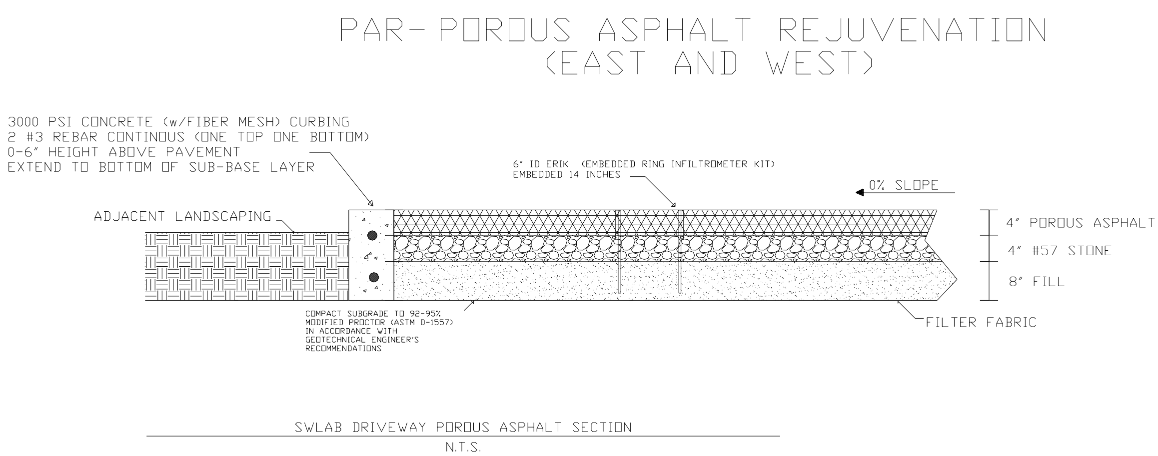


Figure 31: Porous Asphalt Rejuvenation Cross Section (East and West infiltrometers)

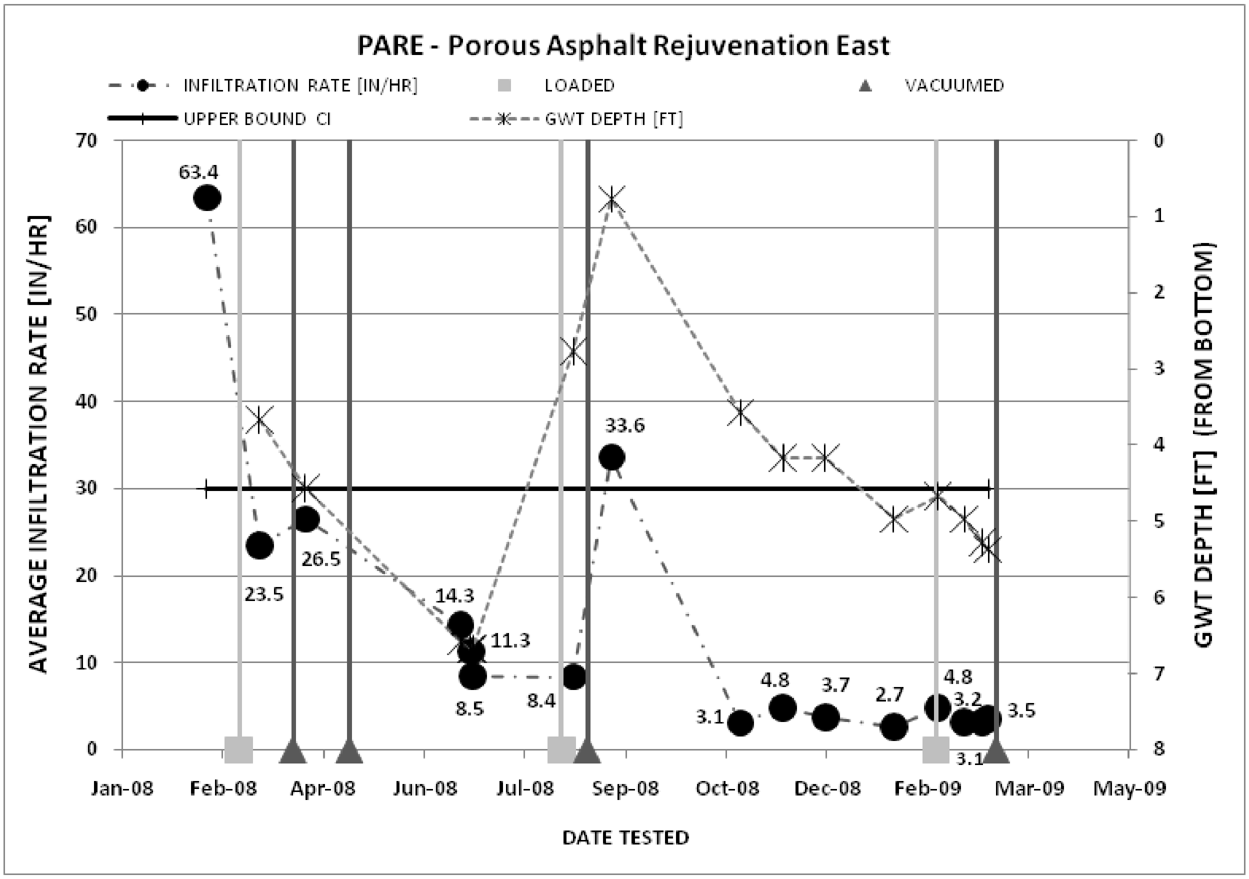


Figure 32: Infiltration Rate (ERIK) Results for the Rejuvenation Section East Infiltrometer

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.

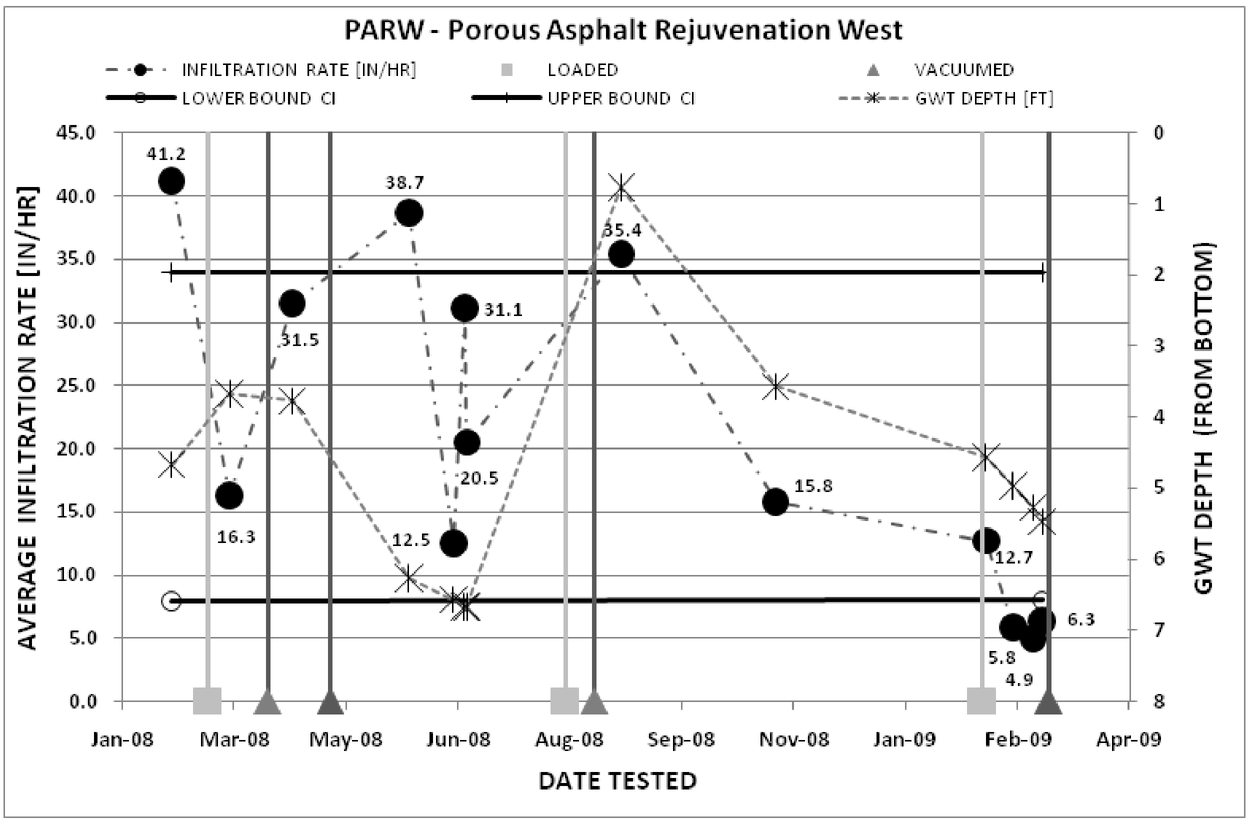


Figure 33: Infiltration Rate (ERIK) Results for the Rejuvenation Section West Infiltrometer

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.

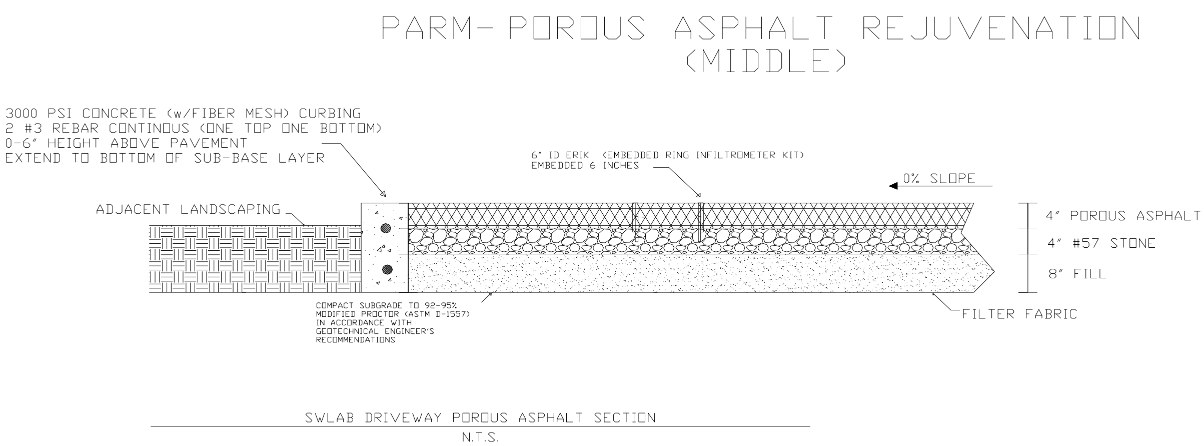


Figure 34: Porous Asphalt Rejuvenation Cross Section (Middle infiltrometer)

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

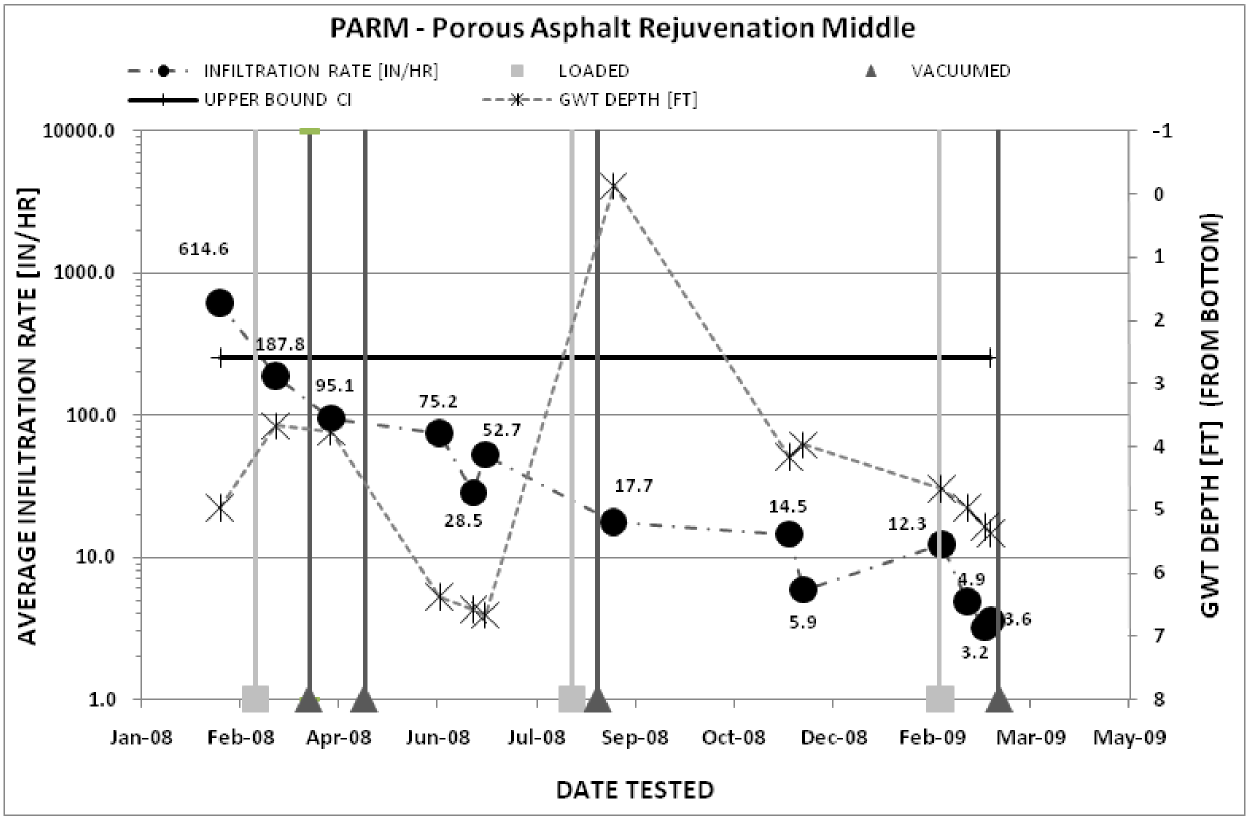


Figure 35: Infiltration Rate (ERIK) Results for the Rejuvenation Section Middle Infiltrometer

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.

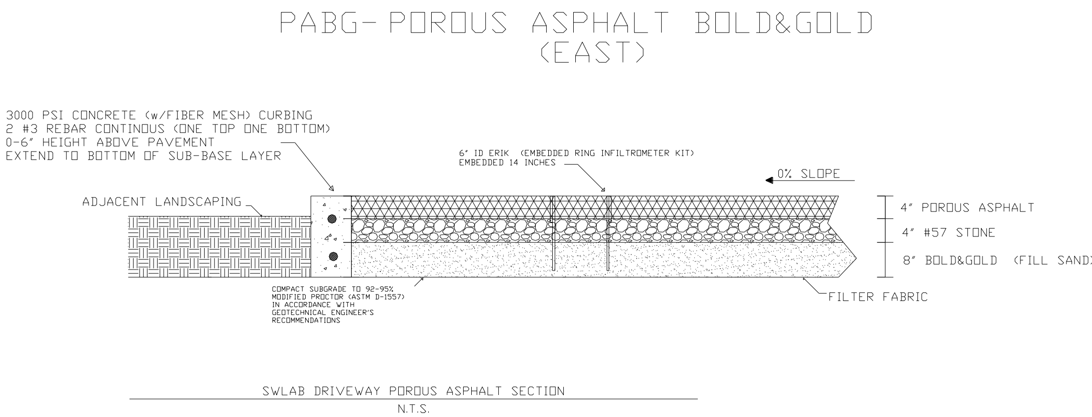


Figure 36: Porous Asphalt Bold&Gold^{TM} Cross Section (East infiltrometer)

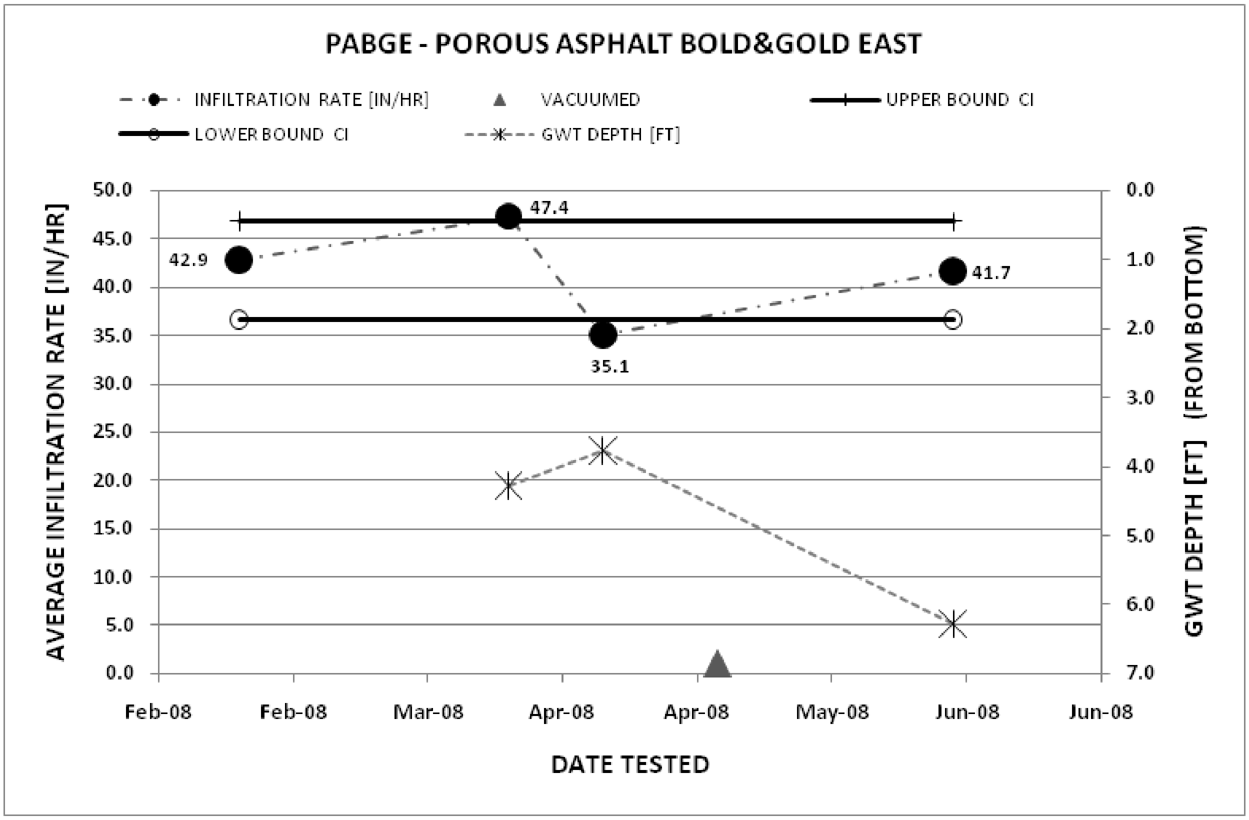


Figure 37: Infiltration Rate (ERIK) Results for the Bold&Gold™ Section East Infiltrometer

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™ 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.

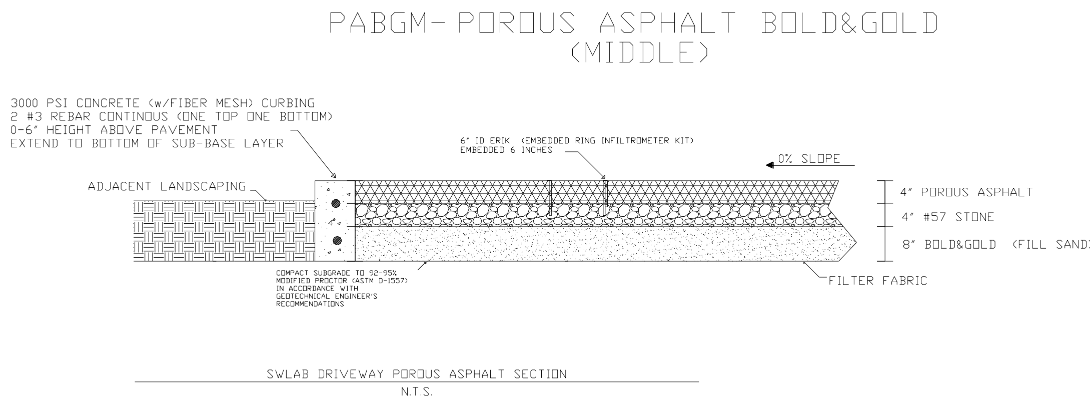


Figure 38: Porous Asphalt Bold&Gold™ Cross Section (middle infiltrometer)

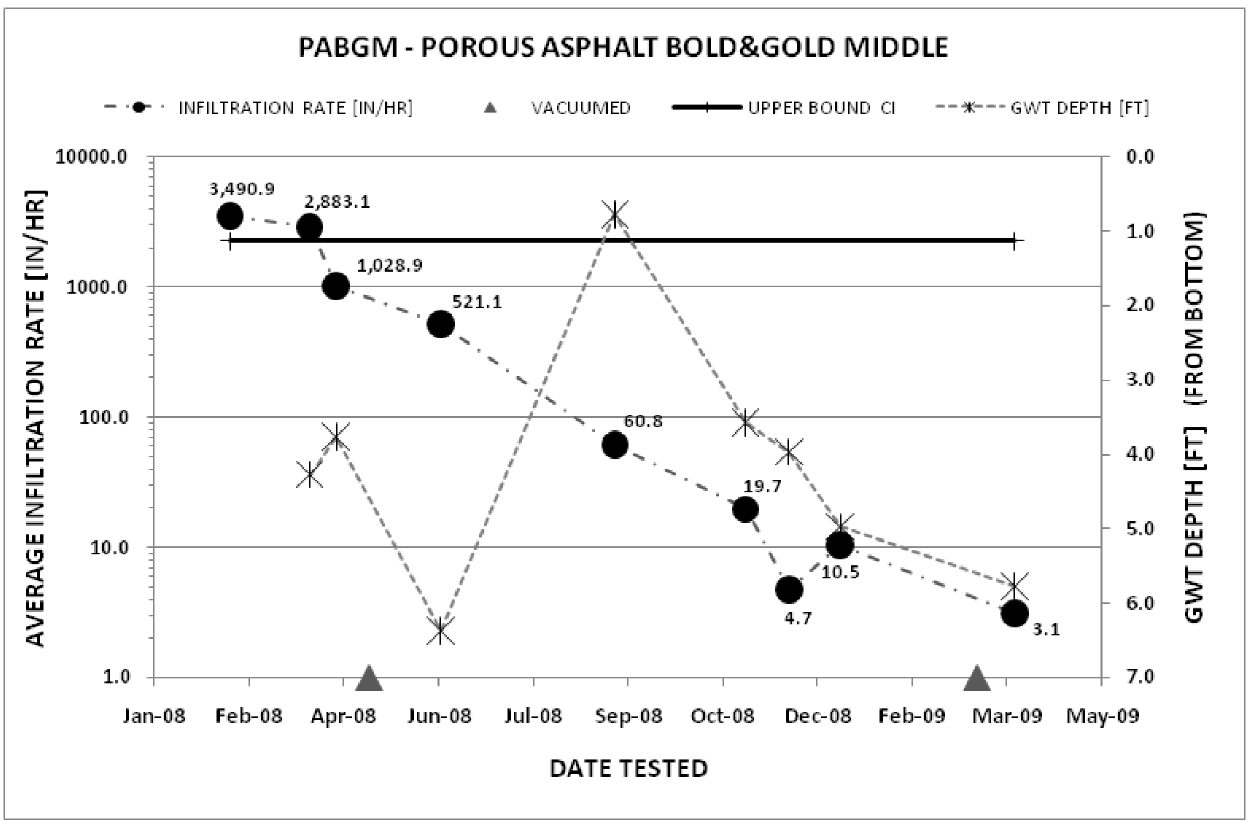


Figure 39: Infiltration Rate (ERIK) Results for the Bold&Gold™ Section Middle Infiltrometer

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.

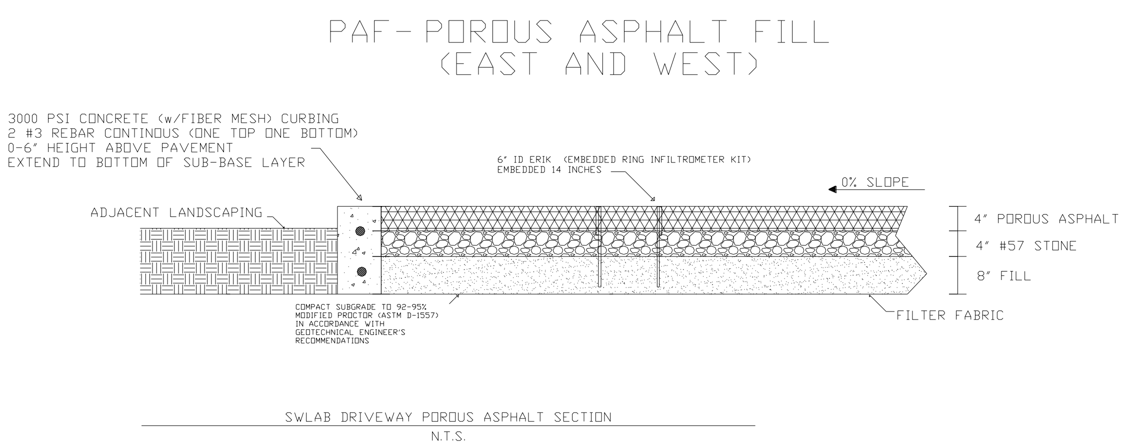


Figure 40: Porous Asphalt Fill Cross Section (West infiltrometer)

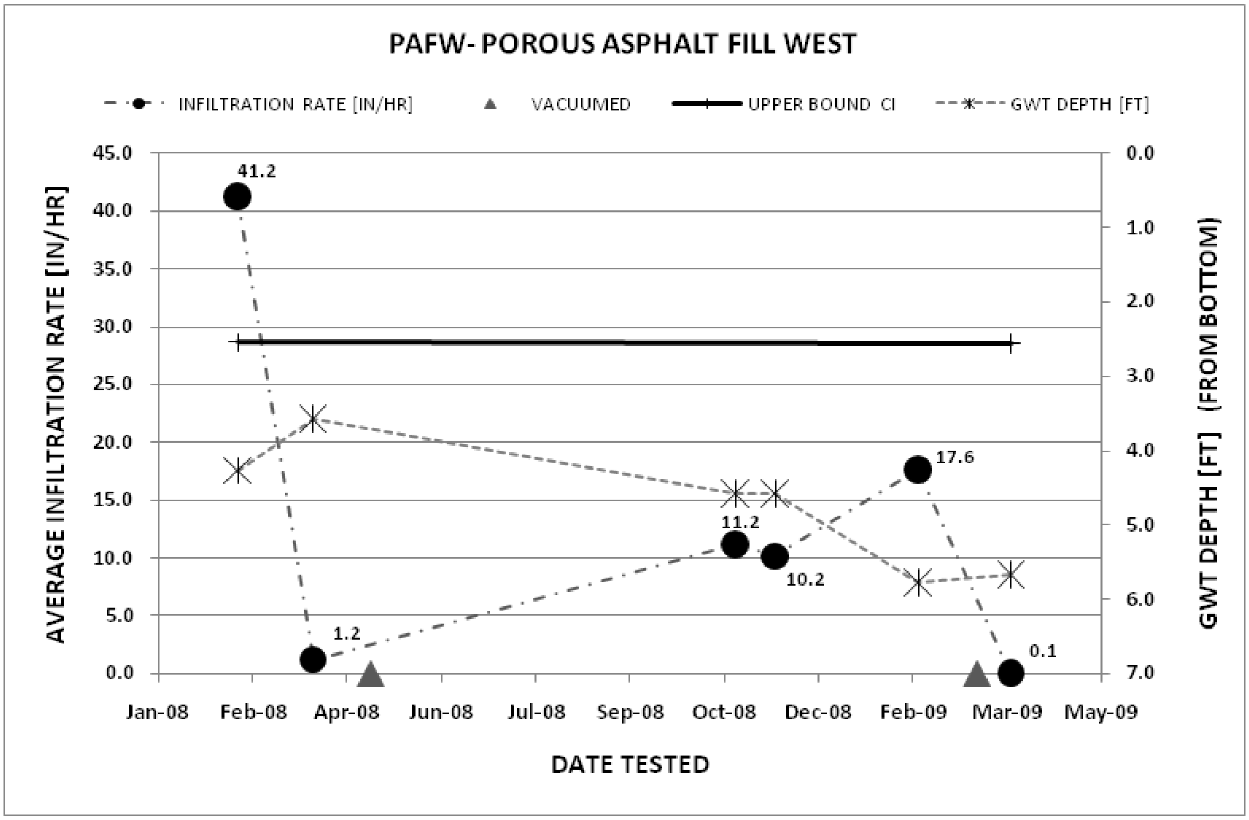


Figure 41: Infiltration Rate (ERIK) Results for the Fill Section West Infiltrometer

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.

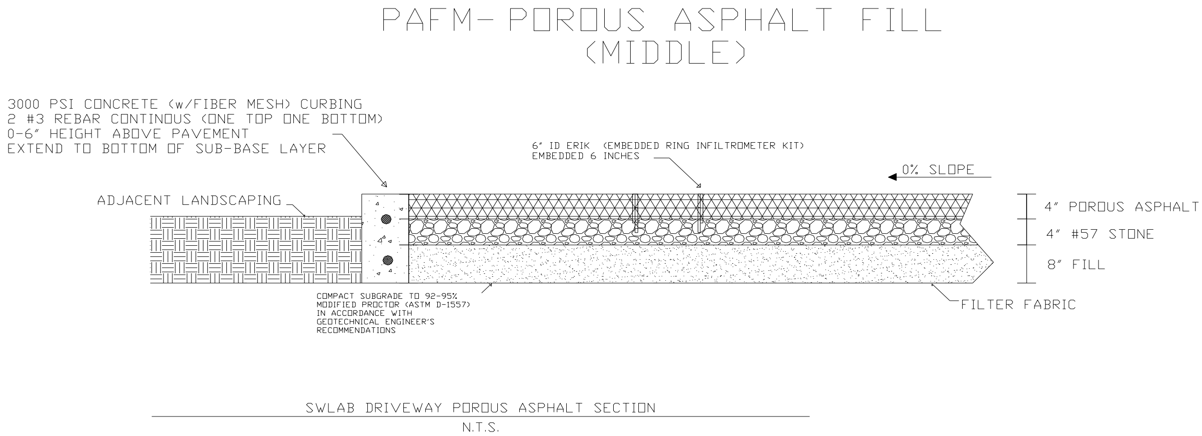


Figure 42: Porous Asphalt Fill Cross Section (Middle infiltrometer)

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

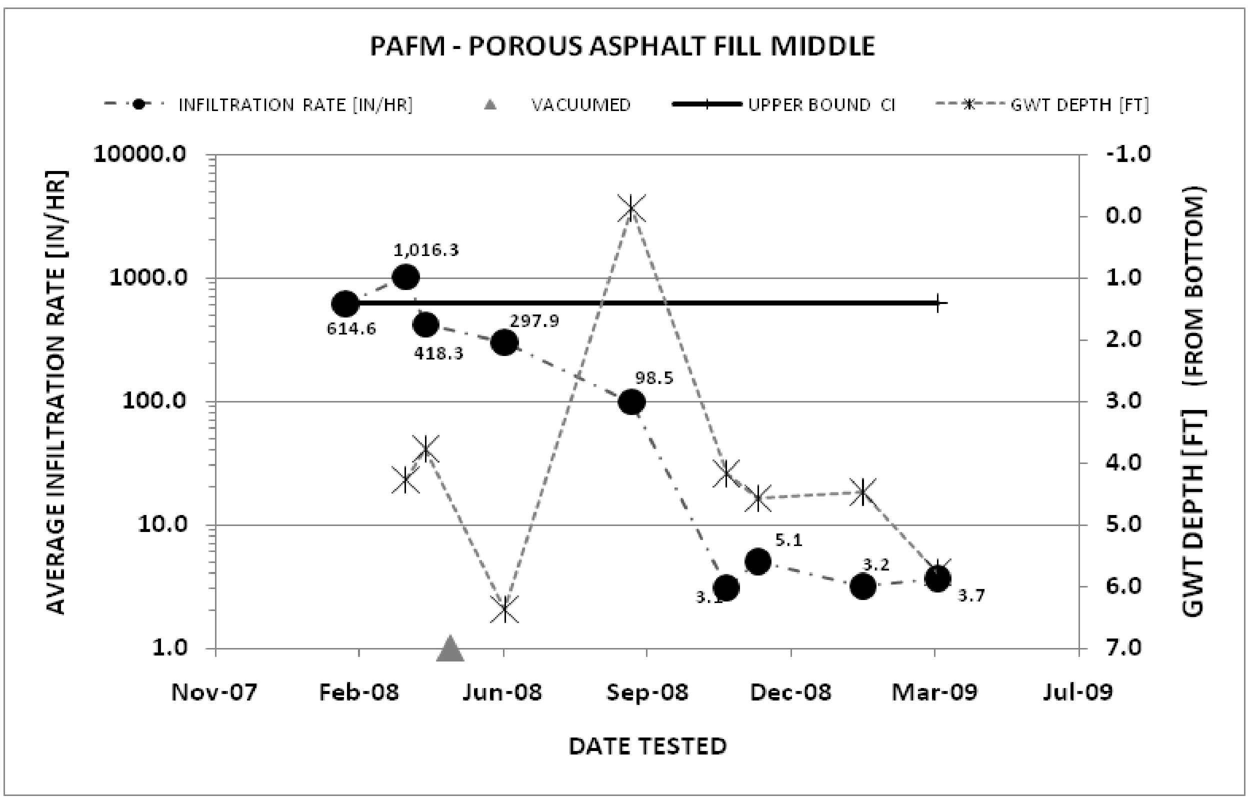


Figure 43: Infiltration Rate (ERIK) Results for the Fill Section Middle Infiltrometer

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.

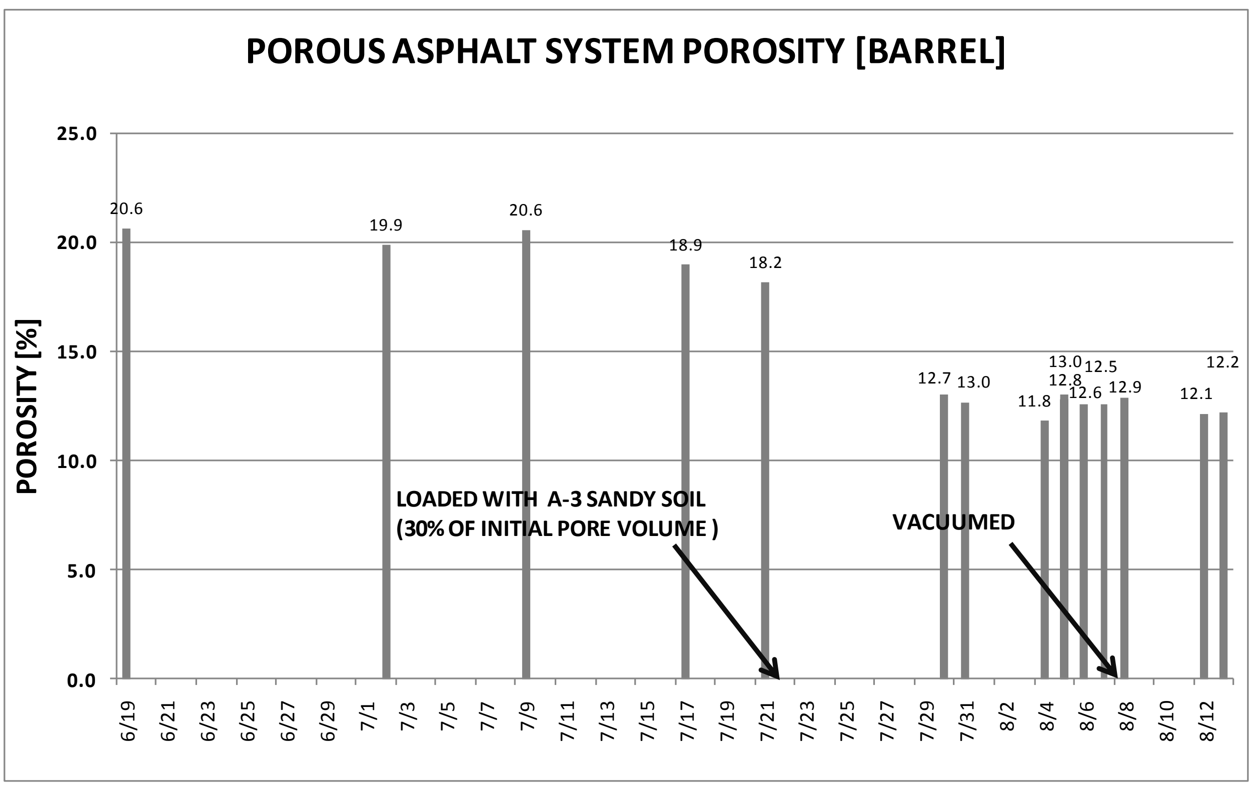


Figure 44: Porous Asphalt System Porosity Results

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.

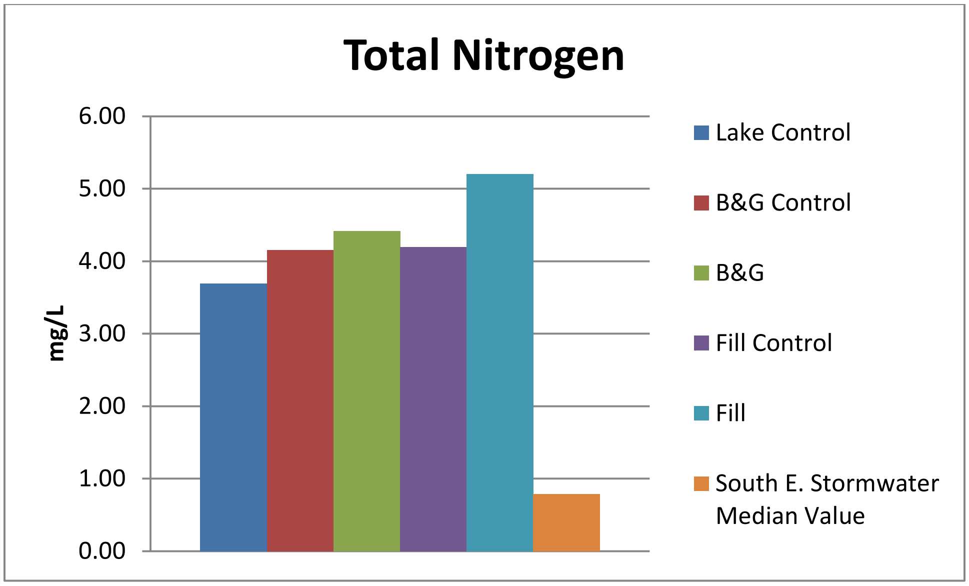


Figure 46: Total Nitrogen Results

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.

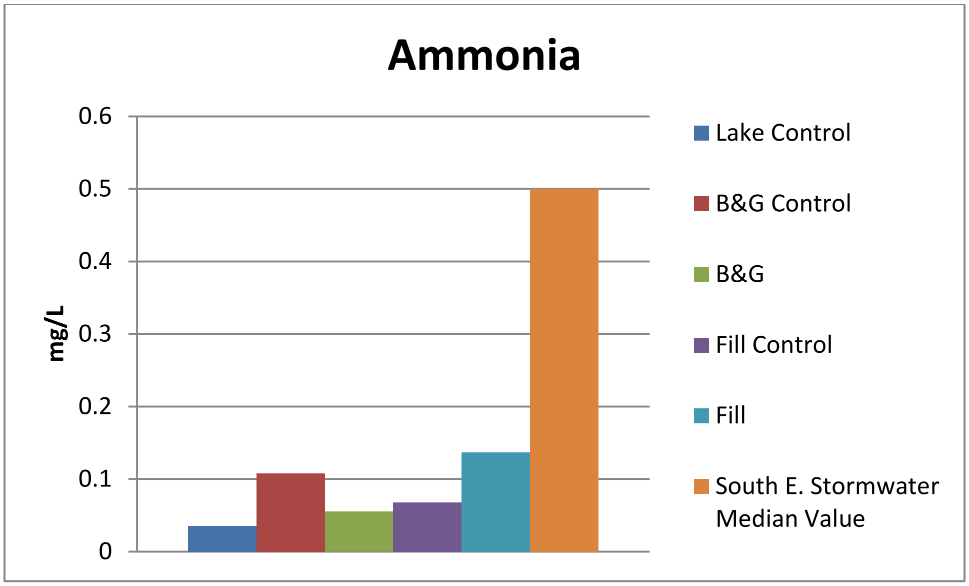


Figure 47: Ammonia Results

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.

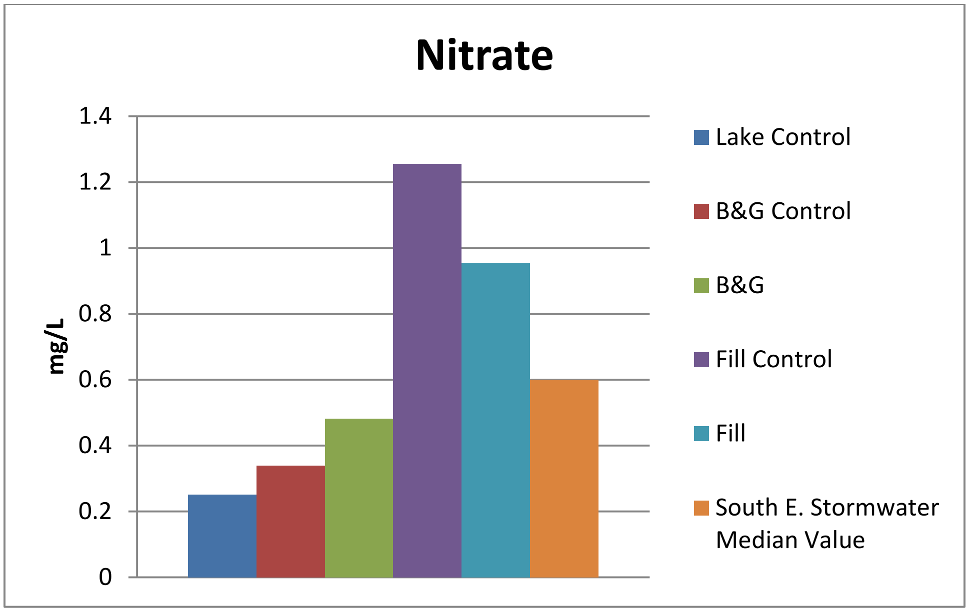


Figure 48: Nitrate Results

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 ($\alpha=0.05$) 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.

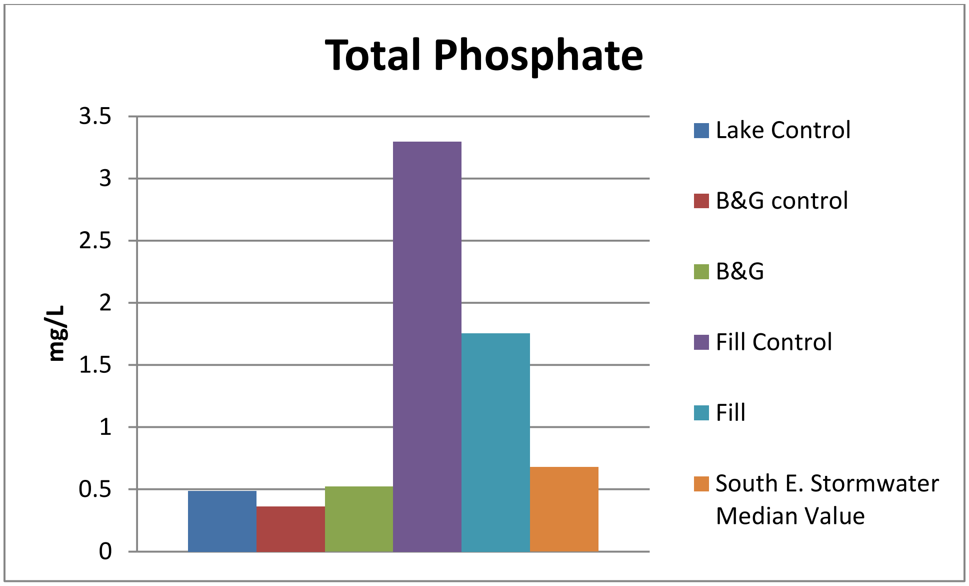


Figure 49: Total Phosphate Results

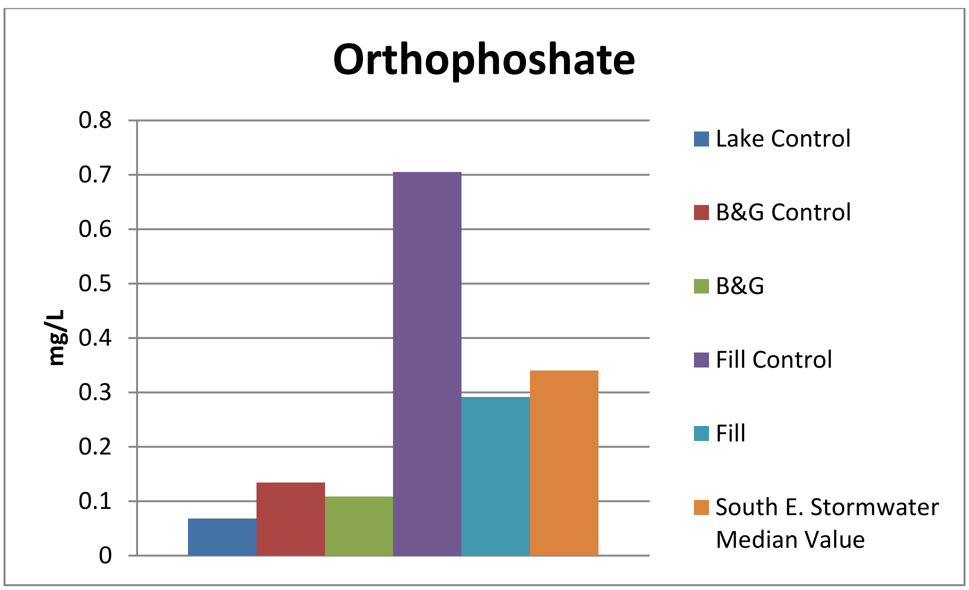


Figure 50: Orthophosphate Results

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.

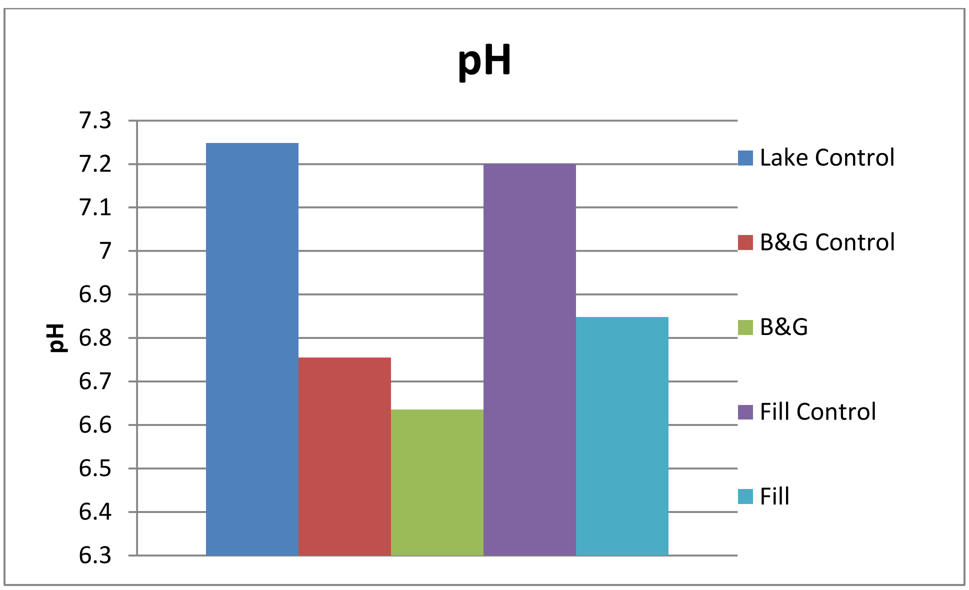


Figure 51: pH Results

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.

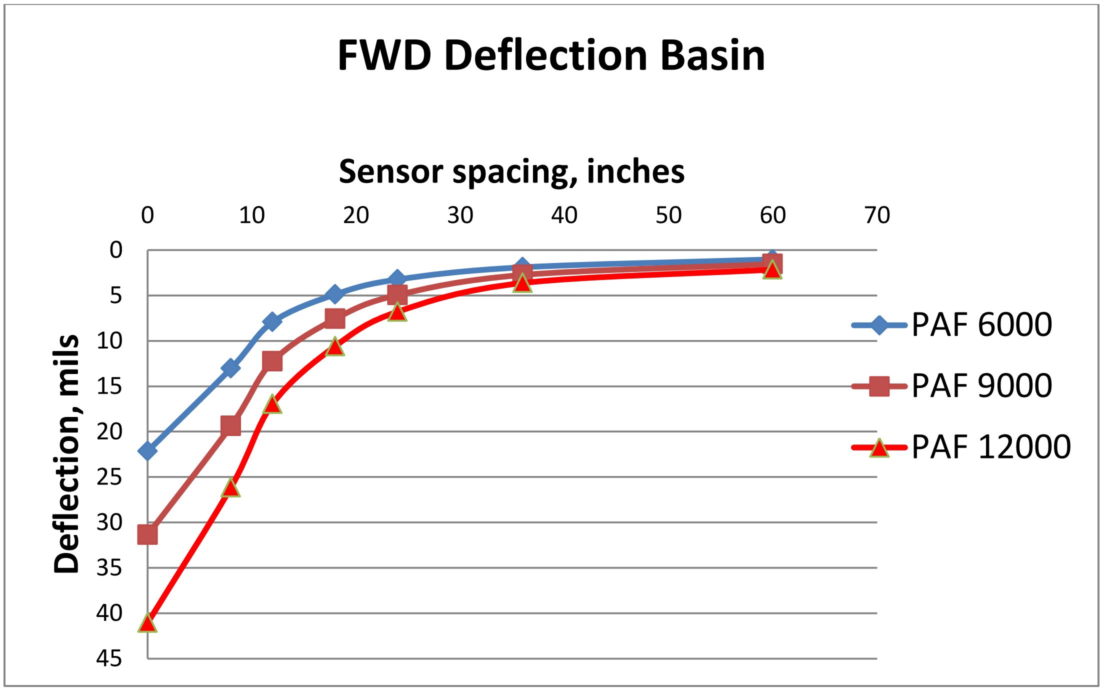


Figure 52: FWD Deflection basins for porous asphalt

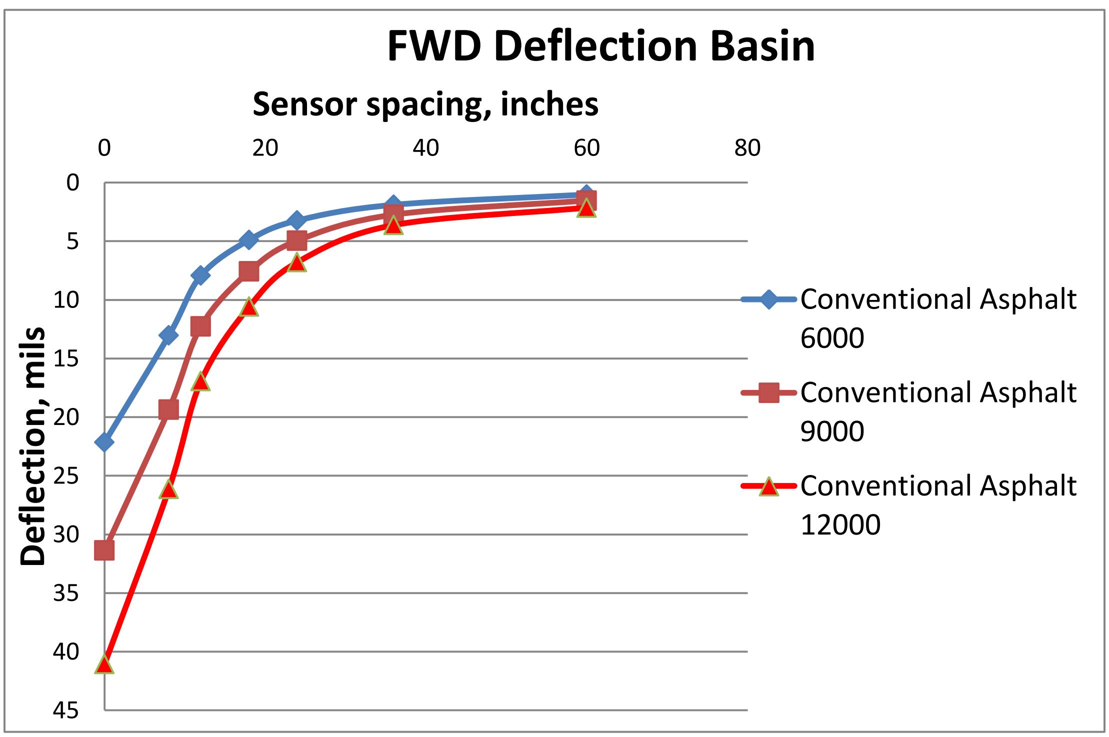


Figure 53: FWD deflection basins for conventional asphalt

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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