Villanova University
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Water Quantity Comparison of Pervious Concrete and Porous Asphalt Products for Infiltration Best Management Practices

A Thesis in
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Porous Asphalt Products for Infiltration Best Management Practices

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Abstract

The research objectives of this study are to compare the design, construction, maintenance, and water quantity performance of pervious concrete and porous asphalt in Southeastern Pennsylvania. A companion thesis by James Barbis will address the water quality comparison of the products.

For this project, a parking area located behind Mendel Hall at Villanova University was retrofitted to provide 279 square meters (3000 square feet) of porous pavement parking. Half of this area was paved with pervious concrete and half with porous asphalt. Because the pavements are located directly adjacent to one another, they experience the same vehicle loads, precipitation, and pollution loads.

In one year of operation, several conclusions have been made with respect to the porous pavements used in this study. These conclusions show that the design of both pavements, with respect to water quantity, follow largely the same procedure. Proper construction is a critical component of installing porous pavements, with qualified professionals being necessary for proper installation. Also, pervious concrete is more time intensive to pour than porous asphalt. Maintenance of both pavements is easily accomplished with a few preventative measures, such as proper design and placement of the pavements, and occasional vacuum sweeping. With proper maintenance, both pavements used in this study have performed well structurally and hydraulically over the first year, with only minor problems occurring.

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Chapter 1 Project Overview

Stormwater runoff results in a number of problems in developed watersheds. Impervious cover within watersheds prevents infiltration of precipitation and results in additional runoff that carries pollutants and high flows into receiving streams during storm events. Additionally, the reduced infiltration reduces base flow in receiving streams during dry times. A number of measures, commonly known as Best Management Practices (BMPs) have been developed over the years to combat the problems associated with stormwater runoff. Included in these BMPs are porous pavements. Porous pavements allow precipitation to infiltrate into the soil, reducing the quantity of runoff and associated pollutants as well as maintaining base flows during dry times. This project focuses on two types of porous pavements, pervious concrete and porous asphalt, and their benefits related to the quantity of stormwater runoff within a watershed. For the project, a parking lot was retrofitted to contain 10 parking bays paved with pervious concrete directly adjacent to 10 parking bays paved with porous asphalt. The site was monitored and modeled for a water quantity comparison of the two products. The research objectives of this thesis are to compare the design, construction, maintenance, and water quantity performance of pervious concrete and porous asphalt. A companion thesis by James Barbis will address the water quality comparison of the products.

1.1 The Stormwater Challenge

Stormwater runoff is generated when precipitation exceeds the infiltration and evapotranspiration capacity of the area it falls upon. This excess precipitation runs off of the land, and eventually flows into receiving lakes and streams, carrying with it any pollutants that it picks up along the way. In a rural setting, land cover is highly pervious, consisting of forests, meadows, and occasionally impervious areas such as houses and roads. This results in high amounts of infiltration and evapotranspiration and low amounts of stormwater runoff. However, urbanized areas are largely covered with impervious land uses such as roadways, parking lots and buildings, resulting in significant amounts of runoff and low infiltration and reduced evapotranspiration. The result of increased runoff and decreased infiltration is a disturbed hydrologic cycle, as illustrated in Figure 1-1 (Maryland Department of the Environment 2008). Increased runoff creates high flows entering streams during storm events that cause stream erosion and flooding problems. Furthermore, this runoff carries pollution such as excess nutrients, heavy metals, hydrocarbons, trash, and high temperature runoff into receiving waters. Decreased infiltration contributes to lower water table elevations, a major source of water for most rivers and lakes during dry times. Thus, at dry times, the base flow of a river is reduced and the lack of water can take a toll on the quality of life for aquatic species as well as our society.

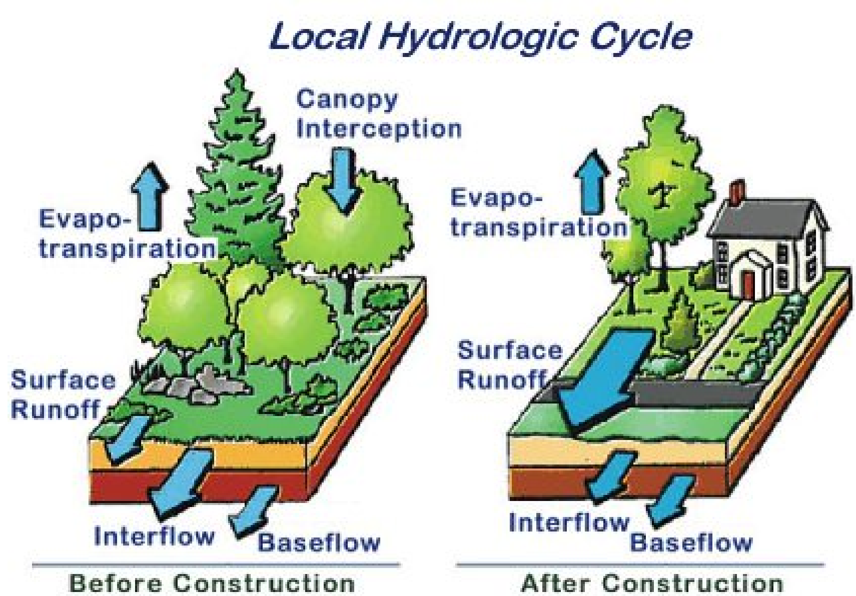

Figure 1-1 Local Hydrologic Cycle Disturbance (Maryland Department of the Environment 2008)

Early attempts at correcting the disturbed hydrologic cycle caused by impervious cover relied primarily on widespread use of detention basins. Detention basins are manmade basins constructed to capture runoff from impervious developments and store the excess water to be released slowly to receiving streams. These are effective at reducing peak flow rates to streams, thus reducing some erosion and flooding problems. The problem, however, is that they do nothing to restore the infiltration of stormwater and the restoration of base flows in streams. Additionally, they do very little for the removal of pollutants because they are not designed for small rain storms.

More recently, attempts to restore the disturbed hydrologic cycle caused by impervious cover have involved the use of infiltration practices. Infiltration practices are designed to capture stormwater runoff and allow it to soak into the ground. These are typically designed to allow the first 25-50 mm (1-2 inches) of precipitation to infiltrate, and the remainder overflows to receiving streams and lakes. The infiltrated water helps maintain base flows in streams and is filtered by the soil to remove pollutants. Infiltration practices can have extensive vegetation to aid in water capture and pollutant removal such as in bioinfiltration practices, or can be designed without vegetation such as in porous pavements. The remainder of this thesis will focus on the use of porous pavements to restore the hydrologic cycle.

1.2 Porous Pavements as the Solution

Porous pavements, namely porous asphalt and pervious concrete, are relatively new technologies. Porous pavements for use as a stormwater infiltration device was first developed by the Franklin Institute in Philadelphia, Pennsylvania in 1972 (Ferguson 2005). Acceptance of these technologies has grown slowly over the decades, as industries have continuously improved mix designs to provide both porosity and strength. Porous pavements are increasingly being used to manage stormwater runoff quality and quantity in development projects. These pavements are comparable to their standard concrete and asphalt counterparts; however the fine materials are removed from the mix. This reduction in fine aggregate results in greater pore space in the pavement, resulting in an ability for water to flow through the pavement. Traditionally, a stone infiltration bed is then placed beneath the pavement to store stormwater until it is able to infiltrate into the soil below (Tennis, et al. 2004). This is a tremendous benefit because it satisfies regulations requiring stormwater runoff volume mitigation, as well as providings significant water quality benefits because of the filtering capacity of the soil. The increased infiltration of stormwater reduces flooding and erosion problems in nearby streams during storm events, and increases stream base flow during drier times, providing a much healthier and safer ecosystem. Furthermore, in urban areas these pavements can provide significant cost savings as they place required stormwater storage beneath parking areas, compared to more traditional detention basins which can require large amounts of developable land (Pennsylvania Department of Envirionmental Protection 2006). Additional benefits of porous pavements are increased skid resistance, lower surface temperatures on hot days, reduced black ice formation, and noise reduction.

1.2.1 Pervious Concrete

The first documented use of pervious concrete was in 1856 when two homes and a seagroin were constructed in the United Kingdom using a form of pervious concrete (Ghafoori and Dutta 1995). Additionally, following World War II there was a massive demand for bricks that could not be met. This led to the manufacturing of pervious concrete bricks because they used less cement per volume than traditional concrete. However, the first use of pervious concrete as a pavement came around 1970 when English engineers utilized a surface coating of pervious concrete on a roadway to provide better drainage (Ghafoori and Dutta 1995). In the late 1970’s, pervious concrete was first used as a stormwater infiltration device in the United States for parking lots in Florida. The pavement was used to meet regulatory requirements of infiltrating stormwater onsite. Since then pervious concrete has spread in use from warmer, wetter climates northward with improving mix designs.

Pervious concrete can also be referred to as porous concrete, permeable concrete, no-fines concrete, gap-graded concrete, and enhanced porosity concrete (Tennis, et al. 2004). Pervious concrete, much like traditional concrete, is a mix of aggregates, cement, and water. Unlike conventional concrete, the fine particles are removed and a narrow range of aggregate sizes is used. For more information on pervious concrete mix design, refer to chapter 3 of this document. Pore space in pervious concrete is typically between 15 and 20%, resulting in infiltration rates ranging from 7 to 20 m/hr (288 to 770 in/hr) (Tennis, et al. 2004). These rates are far greater than could be produced by any storm. Compressive strengths can be achieved in excess of 20.5 MPa (3000 psi) and tensile strengths in excess of 3.5 MPa (500 psi) have been reported (Tennis, et al. 2004). The strength can be increased by reducing the voids, and thus the infiltration capacity. These strengths are generally less than that desired for roadways, but are suitable for parking lots and pedestrian paths.

1.2.2 Porous Asphalt

Porous asphalt was first developed for use as a surface coating on airport runways and as a drainage medium in horse stables in the mid 1950’s (Ferguson 2005). Its use spread to surface coatings for highways to improve drainage off of conventional asphalt primarily in California and the United Kingdom. Porous asphalt was first used as a stormwater infiltration device following research and development by the Franklin Institute in Philadelphia, Pennsylvania in 1972. Since the Franklin Institute research, further studies have been conducted to improve the mix design of porous asphalt and expand its use across the country.

Porous asphalt, much like traditional asphalt, is composed of an asphalt binder and aggregates. Unlike conventional asphalt, the fine particles are omitted and the size range of aggregates is much narrower. More information regarding mix design of porous asphalt can be found in chapter 3 of this document. Porous asphalt pore space typically ranges from 16 to 25%, resulting in infiltration rates as high as 35 m/hr (1400 in/hr) (Schaus 2007). These rates are far greater than could be produced by any storm. Although strength data is difficult to come by, one particular study reported compressive strengths up to 14 MPa (2000 psi) and tensile strengths up to 0.4 MPa (60 psi) (Schaus 2007). The strength can be increased by reducing the voids, and thus the infiltration capacity. These strengths are generally less than that desired for roadways, but are suitable for parking lots and pedestrian paths. The only known application of porous asphalt for a major roadway exists in Chandler, Arizona and was constructed in 1986 (National Asphalt Pavement Association 2007). It is still in use, but has undergone several repairs.

1.3 Project Site

Figure 1-2 Composite Photograph of Porous Pavement Section (porous asphalt in background, pervious concrete in foreground, stone bed and geotextile beneath)

The project site is located in a faculty parking lot behind Mendel Hall of Villanova University in southeastern Pennsylvania (Figure 1-2). Site construction was completed in October 2007. The primary objective of the study is to provide a side by side comparison of the water quantity (covered in this thesis) and quality (covered in a companion thesis) benefits of porous asphalt and pervious concrete, as well as the constructability and durability of the two technologies. The parking area measures 9.1 meters (30 feet) by 30.5 meters (100 feet), half of which is paved with porous asphalt and the other half with pervious concrete. The infiltration beds are located directly beneath the pavements. These beds have level bottoms and a minimum depth of 0.5 meters (1.5 feet), resulting in depths ranging from 0.5 to 1.5 meters (1.5 to 5 feet). The infiltration bed consists of clean, washed AASHTO #2 stone (approximately 102 millimeters, or 4 inches in diameter) lined with a non-woven geotextile. A section view of the bed can be seen in Figure 1-2 showing the pavement, stone bed, and geotextile. The size of the infiltration beds allow for 51 millimeters (2.0 inches) of rain to fall on the 0.07 hectare (0.18 acre) drainage area to be stored and infiltrated. This equates to approximately 80% of the annual rainfall volume for southeastern Pennsylvania (Ladd 2004). Any excess precipitation will overflow to the preexisting stormwater catch basins and make its way to the constructed stormwater wetland BMP also located on Villanova's campus. The bed is separated into two sections, one beneath the porous asphalt and one beneath the pervious concrete, by a concrete barrier lined with a 2.0 millimeter (80 mil) geomembrane such that water from each bed cannot mix with the other. A concrete box manhole is located at each end of the parking area to monitor the water depth in the beds, as well as to provide a means for overflow should a significantly large storm occur. The site is well instrumented. A tipping bucket rain gage is located on Mendel Hall, directly adjacent to the parking area. First flush samplers are located at the high end of the parking area to sample the water quality entering the site. Pressure transducers are located in the manholes at each side of the parking area to measure the depth of water in the beds as well as the overflow out of the beds. Finally lysimeters for soil pore water collection and sampling are located in each bed at depths of 152, 305, and 457 millimeters (6, 12, and 18 inches) below the bottom of the bed.

Chapter 2 Literature Review

With increasing regulatory requirements to detain and infiltrate stormwater runoff from new developments, significant research has been conducted concerning the use of best management practices (BMPs) such as porous asphalt and pervious concrete to meet these requirements. The following review represents a summary of the current state of research on porous asphalt and pervious concrete BMPs. This review includes research related to a hydrologic assessment of porous asphalt and pervious concrete. Specifically the topics of porous pavement BMP design, maintenance requirements, and infiltration BMP modeling will be addressed.

2.1 Best Management Practice Design

The design of porous pavement BMPs requires attention to both the infiltration bed and the pavement. The infiltration bed is located beneath the surface pavement, and typically consists of coarse gravel with sufficient pore space to hold runoff water until it is infiltrated into the subsoil. Overlaying the infiltration bed is the surface pavement. The surface pavement can consist of porous asphalt or pervious concrete, as is used in this study, or other surface pavements such as porous pavers. Design of the surface pavement must include a strength analysis to ensure that it can support the intended loads, and a hydrologic analysis to ensure runoff can be effectively conveyed to the infiltration bed. A typical cross section illustrating the infiltration bed and porous pavement is shown in Figure 2-1.

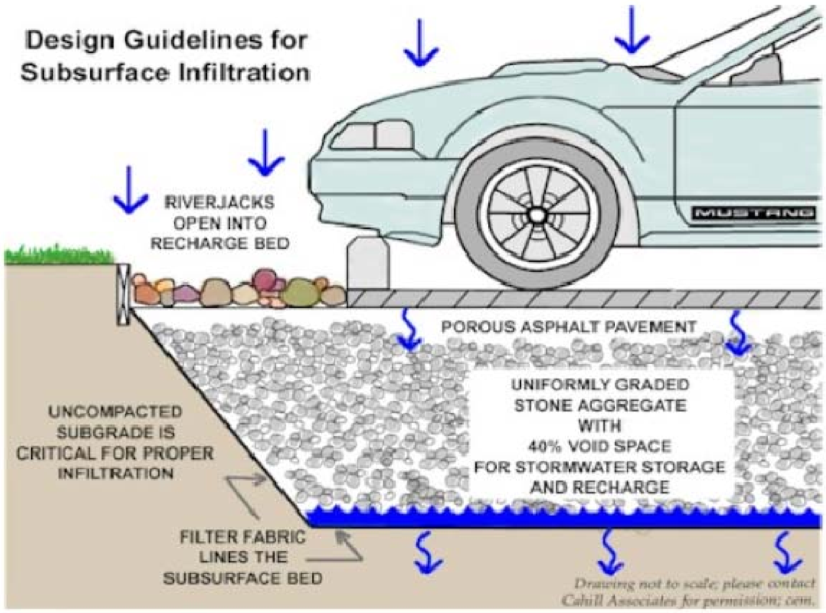

Figure 2-1 Typical Porous Pavement Cross Section (Cahill Associates 2006)

2.1.1 Infiltration Bed Design

There are two main aspects of designing an infiltration bed. The first aspect is the bed geometry, which will determine the amount of stormwater runoff that can be effectively infiltrated. The second aspect is a series of design details that can help extend the useful life of the infiltration bed. These design details include the inclusion of an overflow structure to prevent flooding, wrapping the bed in a geotextile to prevent clogging, and the construction of an edge drain around the infiltration bed to allow for use of the infiltration bed even if the porous pavement became clogged.

2.1.1.1 Bed Geometry

The primary concern when designing an infiltration bed is to ensure that there is enough storage volume to hold the desired stormwater runoff while it infiltrates into the subsoil. This requires a runoff hydrograph for the site based on a specific design storm (Akan 2002). A runoff hydrograph is simply a plot of flow into the infiltration bed with respect to time for a given design storm. An example hydrograph can be found in Figure 2-2. A design storm is simply the size of a storm that the infiltration bed will be designed to infiltrate safely, expressed in terms of a recurrence interval. A typical design storm is the 2 year storm, meaning that there is a 1 in 2 chance of a larger storm occurring in any given year. Similarly, a 100 year storm would indicate a 1 in 100 chance of a larger storm occurring in any given year. The choice of a design storm will often be guided by local stormwater regulations.

Several computer programs exist to aid in the development of a runoff hydrograph, including TR-20, HEC-1, SWMM and HEC-HMS (Akan 2002). These programs have various methods of determining the excess runoff from a site, the shape of the hydrograph, the peak flow achieved, and the time it takes to achieve this peak flow.

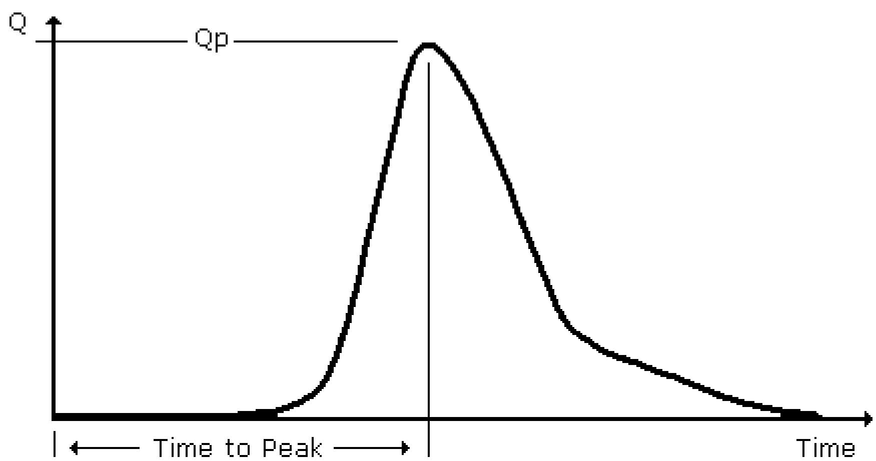

Figure 2-2 Runoff Unit Hydrograph (National Resources Conservation Service 1997)

The dimensions of an infiltration bed are controlled by a number of factors. The bed should drain within a given period of time, usually 72 hours, and must be a certain distance, usually around 1 meter, from the groundwater table (Akan 2002). These factors can be addressed by choosing an infiltration bed depth using the following equation:

$$d_{max} = \min\left(\frac{f\,T_s}{n}, GW - h_{req}\right) \qquad \text{Eq. 2-1}$$

Where d_{max} is the maximum allowable bed depth, f is the subsoil infiltration rate, T_s is the required time to drain, n is the bed material porosity, GW is the depth to the groundwater table, and h_{req} is the required distance between the infiltration bed and the groundwater table. The porosity of the bed material can be assumed to be 0.40 for uniformly graded crushed stone (Ferguson and Debo 1987). It should also be noted that the bottom of the infiltration bed should be kept level to ensure even infiltration of runoff (Pennsylvania Department of Envirionmental Protection 2006) as well as to prevent water from running down the slope and out of the infiltration bed. The length and width of the infiltration bed can then be chosen based on the required storage volume, the maximum depth, and the porosity of the bed material.

2.1.1.2 Overflow Structure

An overflow structure should be incorporated into infiltration bed designs to prevent flooding of the bed and potential damage to the bed and surrounding property. This overflow structure should prevent water from reaching the pavement surface and should be sized to convey more intense storms than the infiltration bed is sized for, possibly the 100 year storm (Pennsylvania Department of Envirionmental Protection 2006). The required overflow structure can be cost-effectively constructed by using a typical inlet box or outlet pipes with outlets near the top of the infiltration bed.

2.1.1.3 Geotextile Selection

A geotextile can be placed at the bottom of the infiltration bed to prevent the migration of fine subsoil particles into the course gravel infiltration bed. This will help prevent clogging and decreased storage volume of the infiltration bed over time. Choosing a geotextile is often accomplished through a design by function approach (Koerner 2006). This means that the primary function of the geotextile is identified first and then required properties and a factor of safety are determined. Using this information, ultimate geotextile properties can be calculated and an appropriate geotextile can be chosen.

The primary function of a geotextile used in an infiltration bed is separation (Koerner 2006). The geotextile must separate the stone infiltration bed from the subsoil to prevent clogging. Therefore, geotextile permittivity and opening size values should be calculated. Guidance on calculating these values can be found in “Designing with Geosynthetics” (Koerner 2006). However, for most infiltration bed applications, any non-woven geotextile will perform sufficiently.

2.1.1.4 Edge Drain

An inflow trench should be constructed around the perimeter of the porous pavement to allow for a backup method for water to be conveyed to the infiltration bed (Pennsylvania Department of Envirionmental Protection 2006). This can be constructed by leaving a 60 mm (2 foot) wide unpaved stone trench that is open to the infiltration bed. Allowing for the edge drain in an infiltration bed design will ensure proper performance of the infiltration bed in the event that the porous pavement should become clogged. An example of an edge drain design can be found in Figure 2-1.

2.1.2 Porous Asphalt Design

Design of porous asphalt pavement requires consideration of both the pavement thickness and the pavement mix design. Infiltration capabilities of the asphalt are generally not considered because the infiltration rate of the asphalt is much greater than that of the subsoil. Schaus (2007) cites porous asphalt permeability values on the order of 35 m/hr (1400 in/hr). However more permeability can be achieved by sacrificing strength, and vice versa.

Comparatively, typical soil permeability values range from 0 to 0.8 m/hr (32 in/hr) (Pitt, et al. 2002).

2.1.2.1 Porous Asphalt Thickness

Structural design of porous asphalt follows the same methods employed for structural design of standard asphalt. The required thickness of the pavement will depend on the subsoil properties, porous asphalt mix characteristics, and loading. Typically, porous asphalt thickness ranges from 50 to 100 mm (2 to 4 inches) (Schaus 2007). For guidance on specifying a proper asphalt pavement thickness the American Association of State Highway and Transportation Officials (AASHTO) offers a "Guide for Design of Pavement Structures" document (1993).

2.1.2.2 Porous Asphalt Mix

Porous asphalt is comprised of a mix essentially the same as standard asphalt with a few notable exceptions: the fine aggregates are removed and a narrower size distribution is utilized. The effect of these changes is an asphalt mix that has significant pore space, allowing for infiltration of stormwater.

One common method of specifying porous asphalt mixes is ASTM Standard D7064 - Standard Practice for Open-Graded Friction Course (OGFC) Mix Design (Hansen 2006). This system requires specification of three values: the aggregate gradation, asphalt binder content, and binder grade. Additionally, fibers can be added to the design mix. The National Asphalt Pavement Association (NAPA) also has a similar method of specifying porous asphalt mixes (Roberts 1996).

The size of aggregates used in porous asphalt mixes can vary depending on who is preparing the mix design and what the desired properties of the asphalt are. Coarser aggregates and a narrower range of aggregate sizes ensures proper pore space and permeability are achieved in the mix (Schaus 2007). Figure 2-3 shows typical gradation curves for typical porous asphalt mix designs.

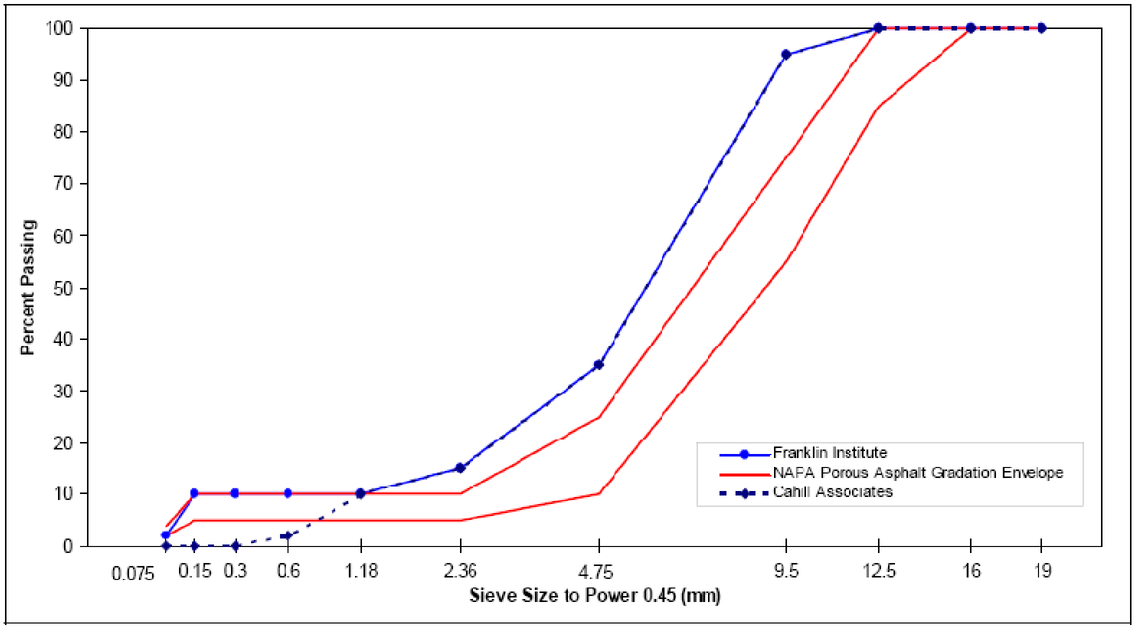

Figure 2-3 Typical Porous Asphalt Aggregate Gradation (Schaus 2007)

The asphalt binder content of a porous asphalt mix is a main factor in controlling the durability of the pavement (Hansen 2006). The asphalt binder is what holds the aggregates together. If insufficient asphalt is included in the mix, the aggregates will begin to separate from the asphalt and significant wear will be observed. On the other hand, too much asphalt will decrease the pore space of the pavement and affect its permeability. Typical asphalt binder contents range from 5.5 to 6.5% of the mix.

The grade of the asphalt binder is important to the longevity of the asphalt pavement (Schaus 2007). Binder grade determines the working temperatures that the asphalt pavement can endure. For example, a PG 58-28 binder can sustain 7-day average temperatures up to 58 degrees C and as low as 28 degrees C.

Finally, fibers can be added to porous asphalt mixes to improve longevity (Hassan and Al-Jabri 2005). The fibers are used to reduce the potential for draindown in porous asphalt pavement. Draindown is when the binder separates from the aggregate and drains out of the pavement.

2.1.3 Pervious Concrete Design

Just as when designing a porous asphalt pavement, pervious concrete pavements require consideration of both the pavement thickness and the pavement mix design. Infiltration capabilities of the concrete are generally not considered because the infiltration rate of the concrete is much greater than that of the subsoil. Typical pervious concrete permeability values range from 7 to 20 m/hr (288 to 770 in/hr) (Tennis, et al. 2004). However more permeability can be achieved by sacrificing strength, and vice versa. Comparatively, typical soil permeability values range from 0 to 0.8 m/hr (32 in/hr) (Pitt, et al. 2002).

2.1.3.1 Pervious Concrete Thickness

Structural design of pervious concrete follows the same methods employed for structural design of standard concrete (Tennis, et al. 2004). The required thickness of the pavement will depend on the subsoil properties, pervious concrete mix characteristics, and loading. Typical pervious concrete thicknesses range from 100 to 300 mm (4 to 12 inches). For guidance on specifying a proper concrete pavement thickness the American Association of State Highway and Transportation Officials (AASHTO) offers a "Guide for Design of Pavement Structures" document (1993).

2.1.3.2 Pervious Concrete Mix

Pervious concrete is comprised of a mix essentially the same as standard concrete with a few notable exceptions: the fine aggregates are removed and a narrower size distribution is utilized (Tennis, et al. 2004). The effect of these changes is a concrete mix that has significant pore space, allowing for infiltration of stormwater. The quality control of the mix must be more strictly followed and proper installation techniques must be utilized with this pervious mix to ensure expected results.

Typical Ranges of Materials Proportions in Pervious Concrete***

	Proportions, lb/yd³	Proportions, kg/m³
Cementitious materials	450 to 700	270 to 415
Aggregate	2000 to 2500	1190 to 1480
Water:cement ratio*** (by mass)	0.27 to 0.34	
Aggregate:cement ratio*** (by mass)	4 to 4.5:1	
Fine:coarse aggregate ratio**** (by mass)	0 to 1:1	

* These proportions are given for information only. Successful mixture design will depend on properties of the particular materials used and must be tested in trial batches to establish proper proportions and determine expected behavior. Concrete producers may have mixture proportions for pervious concrete optimized for performance with local materials. In such instances those proportions are preferable.

** Chemical admixtures, particularly retarders and hydration stabilizers, are also used commonly, at dosages recommended by the manufacturer. Use of supplementary cementitious materials, such as fly ash and slag, is common as well.

*** Higher ratios have been used, but significant reductions in strength and durability may result.

**** Addition of fine aggregate will decrease the void content and increase strength.

Table 2-1 Typical Pervious Concrete Mix Proportions (Tennis, et al. 2004)

Mix designs are arrived upon by batch testing of different mixtures of aggregates, cement, water, and admixtures (Tennis, et al. 2004). Although typical mix designs can be found, such as that shown in Table 2-1, a local concrete producer would be the best source to gather information on a proper mix design that has performed well in a particular region.

A number of cementitious materials can be used in pervious concrete mixes, including Portland cements, fly ash, and blast furnace slag (Tennis, et al. 2004). The cementitious materials react with water to form the hard surface in concrete. A number of aggregate sizes and grading can be utilized as well. The most common is probably a mix containing crushed stone or gravel with sizes ranging from 0.3 to 9.5 mm. Larger aggregate sizes will result in a coarser surface finish. The water content should be tightly controlled and may need to be adjusted on-site to establish a suitable mix. The concrete should be able to be formed into a ball without crumbling or losing structure.

A number of admixtures can also be added to pervious concrete to achieve desired properties. Hydration-stabilizing admixtures are often used because of the quick setting properties of pervious concrete and can provide up to 1.5 hours of additional working time (Delatte, et al. 2007). High range water reducers can be added to improve the workability of the concrete mix. Viscosity modifiers can be used to make the pervious concrete mix flow easier as well as to increase strength. Harder surface finishing techniques can be utilized when latex modifiers are added to the mix. Also, air entraining admixtures can be used to improve freeze-thaw durability of pervious concrete in cold regions. Freeze-thaw durability can also be influenced by the addition of sand or latex into the concrete mix (Kevern, et al. 2005). With all of these variables on the mix designs of pervious concrete one can see why it is extremely important to conduct batch testing to ensure that desirable qualities are achieved.

2.2 Maintenance Requirements

As with any stormwater BMP, maintenance is an important issue for both porous asphalt and pervious concrete. Because these are relatively new technologies, maintenance guidelines are still being developed to maximize the useful life of porous pavements. The majority of properly designed porous pavement installations have functioned for many years with little to no maintenance; however it has been shown that significant performance improvements can be achieved through relatively simple maintenance procedures (Tennis, et al. 2004). The most common methods for maintaining porous pavements include following proper landscaping guidelines, vacuum sweeping, pressure washing, and proper snow removal practices. This section will also discuss repair of porous pavements and estimated design lives.

2.2.1 Landscaping

Following proper landscaping guidelines for areas surrounding porous pavements is possibly one of the most important maintenance activities for porous pavements. Tennis, et al. (2004) suggests that no landscaped areas should drain onto porous pavements. The Pennsylvania Department of Environmental Protection (2006) however does allow for drainage from landscaped areas, so long as the areas are well maintained with plant cover. Landscaped areas that drain to porous pavements should be inspected several times per year and any bare areas should be replanted immediately. This is important because stormwater runoff from landscaped areas, particularly areas without plant cover, often contain high levels of sediments. These sediments can clog the void space of porous pavements, decreasing their permeability and effectiveness. In addition to proper maintenance of landscaped areas, landscaping materials should not be loaded on porous pavements (Tennis, et al. 2004), nor should construction vehicles be permitted to track excess dirt across the surface (Pennsylvania Department of Envirionmental Protection 2006).

2.2.2 Vacuum Sweeping

The most common methods of restoring infiltration capacity of porous pavements are vacuum sweeping and pressure washing. Vacuum sweeping is often performed using a truck similar to a conventional street sweeping truck. The vacuum truck removes sediments from the porous pavement void space for disposal. One study found effective results using a 4.8 kW (6.5 horsepower) wet/dry vacuum for sediment removal (Chopra, et al. 2007). This study reported that vacuum sweeping provides a 90% increase in infiltration rates, and a 200% increase when combined with pressure washing. Recommendations for vacuum sweeping frequency range from annually (Tennis, et al. 2004), to semi-annually (Pennsylvania Department of Envirionmental Protection 2006), to quarterly (US Environmental Protection Agency 1999).

2.2.3 Pressure Washing

Pressure washing, along with vacuum sweeping, is among the most commonly employed methods of restoring porous pavement infiltration capacity. Pressure washing utilizes a high power spray nozzle to wash sediments out of the porous pavement pore space and down into the infiltration bed. Reported pressures used range from 103,400 mbar (1,500 psi) (Delatte, et al. 2007) to 206,800 mbar (3,000 psi) (Chopra, et al. 2007). Care should be taken not to use excess pressure, as surface deterioration may occur. The pressure can be tested on a small patch of pavement prior to complete washing. Effectiveness has been reported from as low as 35% restoration of infiltration capacity (Delatte, et al. 2007), to 80-90% (Mississippi Concrete Industries Association 2002), to 100% (Chopra, et al. 2007). Chopra, et al. (2007) also reported 200% increases in infiltration capacity when pressure washing was combined with vacuum sweeping. The Environmental Protection Agency (1999) recommends pressure washing four times per year. However, the Pennsylvania Department of Environmental Protection (2006) does not recommend the use of pressure washing on porous pavements due to the potential for washing contaminants through to receiving streams.

2.2.4 Snow Removal

Snow removal is an important aspect of safety for any roadway, parking lot, or sidewalk. Porous pavement infiltration beds can store heat in winter and cause snow to melt more quickly on porous pavements than on traditional pavements (Pennsylvania Department of Envirionmental Protection 2006). Furthermore, properly functioning porous pavements will immediately drain any melting snow, preventing the formation of ice on the pavement. However, some form of snow removal is usually still required to ensure vehicular and pedestrian safety. Porous pavements require special attention when it comes to choosing a method of snow removal. For example, de-icing sand and gravel should be avoided on and around porous pavements because it can clog pore spaces and reduce infiltration capacity (Adams 2003). Also, snowplows can potentially cause surface raveling of the pavement (Tennis, et al. 2004). Snowplows can still be used, as long as the plow is raised approximately 25 mm (1 inch) above the pavement (Pennsylvania Department of Envirionmental Protection 2006). Salt is also an acceptable means of snow removal; however it should be noted that porous pavements do not filter chlorides and they will pass through to receiving bodies of water (Potier 2008). The University of New Hampshire has reported that due to the quick melting and draining properties of porous pavements, they have been able to reduce salt usage on porous pavements by as much as 70%. However, it should be noted that salt can be corrosive to concrete. Most concrete installers, traditional and pervious, recommend that concrete should not be salted for the first year to 18 months.

2.2.5 Repair

Should damage to porous pavements occur proper repair techniques should be followed to ensure vehicular and pedestrian safety, as well as to maintain proper drainage through the pavement. The Environmental Protection Agency (1999) states that surface damage to less than 10% of the pavement area can be repaired using a non porous mix. The Pennsylvania Department of Environmental Protection (2006) puts the limit at 4.6 square meters (50 square feet) of surface damage for non porous repairs. A design professional should be contacted for repairs greater than these limits to ensure proper functionality of the pavement as a stormwater BMP. Additionally, clogged pavement can be repaired by drilling 13 mm (½ inch) holes approximately every meter to allow for drainage into the infiltration bed (US Environmental Protection Agency 1999).

2.2.6 Design Life

The design life for porous pavements is difficult to determine because of the young age of the technology. One of the oldest installations of porous asphalt was done by Cahill Associates in West Chester, Pennsylvania (Adams 2003). They constructed a porous asphalt parking lot for Siemans World Headquarters in an area prone to sinkholes in 1983. 25 years later the pavement has received very little maintenance and is still functioning. Additionally, because of the spreading out of infiltration over the large infiltration beds, sinkhole formation has been less frequent in areas with porous asphalt than with standard asphalt. The porous asphalt has also proven more durable than the nearby sections of standard asphalt. Cahill Associates attributes this increased durability to the strength provided by the solid subbase of the infiltration bed. A study done by Transfund New Zealand, however claims that the design life of porous asphalt in New Zealand is only 10.5 years, compared to 16.2 years for conventional asphalt (Herrington, et al. 2005). They claim that the durability is limited by the oxidization of the asphalt binder. Oxidation causes the pavement to become brittle and leads to surface chipping.

Pervious concrete has similar design life ranges expressed in the literature. A Stormwater Management Academy reports pervious concrete installations as old as 20 years (Chopra, et al. 2007), while a University of Rhode Island study suggests design lives of 15-20 years (McNally, et al. 2005).

2.3 Infiltration BMP Modeling

There are a number of ways to model stormwater projects such as infiltration basins. Modeling can be accomplished using physical models (constructing and observing a smaller scale version of the project), analog models (utilizing the flow of electricity in a circuit to simulate the flow of water in a watershed), or the more commonly used mathematical models (a set of equations that are chosen to govern the flow of water throughout a system) (US Army Corps of Engineers 2000). Mathematical models are the most commonly used method of modeling stormwater BMPs due to their relative ease of use and accuracy.

Computer software makes mathematical models much easier to use and visualize. Hydrologic Engineering Center – Hydrologic Modeling System, more commonly known as HEC-HMS, is the most extensively used computer software package that models stormwater processes. HEC-HMS was developed by the US Army Corps of Engineers to model precipitation-runoff processes within a watershed (US Army Corps of Engineers 2000). The software allows users to provide hydrologic characteristics of their site and analyze the performance under a variety of conditions. There are four steps to creating an infiltration basin HEC-HMS model; runoff volume calculations, runoff modeling, reservoir modeling, and calibration.

2.3.1 Runoff Volume Calculations

HEC-HMS begins modeling by computing runoff volumes for the watershed (US Army Corps of Engineers 2000). This requires that the user provide various watershed characteristics, which vary based on the modeling method chosen by the user, as well as precipitation information. Precipitation data can be entered as a design storm to analyze performance under hypothetical conditions, or can be actual data to analyze performance under real conditions.

Runoff volumes are calculated by watershed characteristics. All watershed areas are either classified as directly-connected impervious area, or pervious area (US Army Corps of Engineers 2000). Directly-connected impervious area is land that experiences no infiltration or evaporation and all precipitation becomes runoff. Pervious areas experience some loss of volume. This loss can be quantified based on several methods, including an initial and constant-rate loss method, deficit and constant-rate method, SCS curve number loss method, and Green and Ampt loss method. Each method utilizes different mathematical equations and assumptions to determine the precipitation loss. This paper will focus on the SCS curve number method because it is a well established and widely used method in the field of stormwater modeling.

The SCS curve number method for runoff volume calculation is a simple method developed by the Soil Conservation Service (SCS) that relies on only one parameter (US Army Corps of Engineers 2000). The following equation was developed by the SCS to model excess precipitation:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \qquad \text{Eq. 2-2}$$

Where P_e is the excess precipitation at time t, P is the accumulated rainfall at time t, I_a is the initial precipitation loss, and S is the potential maximum retention. However, data from the SCS relates I_a and S, producing the following simplified equation:

$$P_e = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} \qquad \text{Eq. 2-3}$$

Finally, S is determined through the use of a curve number (CN) that represents the watershed characteristics. S is computed from the CN in the following manner:

$$S = \begin{Bmatrix} \frac{1000-10\,CN}{CN} \; foot-pound\ system \\ \frac{25400-254\,CN}{CN} \; SI\ system \end{Bmatrix} \qquad \text{Eq. 2-4}$$

The CN varies between 100 (for water bodies) to 30 (for highly permeable soils). Guidance on the selection of curve numbers can be found in the National Engineering Handbook – Part 630 Hydrology (National Resources Conservation Service 1997).

It should be noted that the SCS curve number method has been highly criticized for poor performance in modeling small storms, which are often the main focus of infiltration beds designed to improve water quality (Pitt 1999). The NRCS curve number method specifies that the method should not be used for storms less than 25 mm (1 inch) (National Resources Conservation Service 1997). As a result, the small storm method developed by Robert Pitt (1999) is preferred when small storms are being modeled. The same method of calculating excess precipitation as the SCS method can be followed, with the only exception being the choice of a curve number. Instead of utilizing NRCS curve numbers for determining curve numbers, curve numbers can be obtained from Pitt (1999). The curve numbers obtained from Pitt are less than those provided by the SCS and vary with precipitation depth. Smaller rainfalls will yield smaller curve numbers, and vice versa. Pitt provides curve numbers for a variety of land covers for precipitation depths ranging from 1 mm (0.04 inches) to 125 mm (4.9 inches).

2.3.2 Runoff Modeling

After computing the amount of excess precipitation within a watershed, HEC-HMS uses a runoff model to demonstrate the effects of excess precipitation (US Army Corps of Engineers 2000). HEC-HMS has two methods to quantify these effects: empirical models or conceptual models. HEC-HMS contains several empirical models which develop unit hydrographs to model the runoff of a watershed. They establish a relationship between the excess precipitation and runoff without analyzing all of the processes that contribute to this relationship. On the other hand, the conceptual model used by HEC-HMS attempts to analyze all of the mechanisms that control the flow of excess precipitation throughout the watershed. The choice of a runoff model method should take into account the assumptions of the models and their applicability to the studied watershed. This paper will focus on the SCS Unit Hydrograph method due to its popularity and applicability to watersheds that have sufficient data to perform calibration measures.

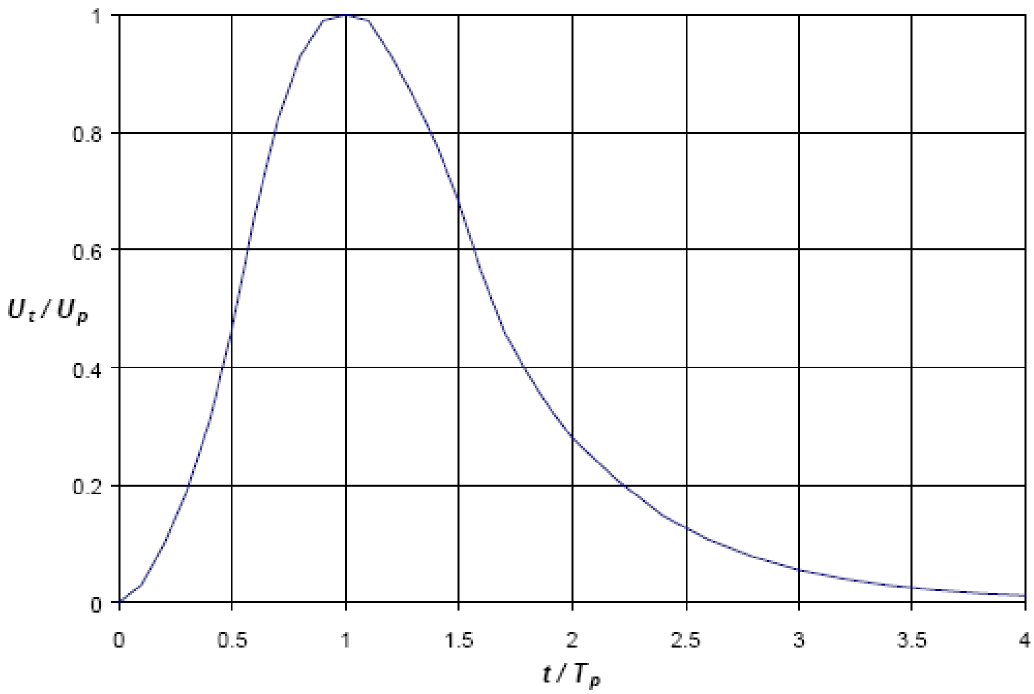

Figure 2-4 SCS Unit Hydrograph (US Army Corps of Engineers 2000)

The SCS Unit Hydrograph method of runoff modeling assumes that the runoff hydrograph can be constructed by scaling a single peaked dimensionless hydrograph to the desired watershed (US Army Corps of Engineers 2000). Figure 2-4 illustrates this dimensionless unit hydrograph. On the y-axis, the discharge at a given time, U_t, is expressed as a fraction of the peak discharge, U_p. On the x-axis, the time, t, is expressed as a fraction of the time to peak, T_p. The peak discharge and time to peak are found by SCS to be related according to the following equation:

$$U_p = C\frac{A}{T_p} \qquad \text{Eq. 2-5}$$

Where *C* is a conversion constant equal to 2.08 in SI units and 484 in the foot-pound system. *A* is the watershed area. Additionally, the time to peak is calculated as follows:

$$T_p = \frac{\Delta t}{2} + t_{lag} \qquad \text{Eq. 2-6}$$

Where Δt is the incremental duration of excess precipitation, and t_{lag} is the basin lag. The basin lag is considered to be time difference between the center of mass of rainfall excess and the hydrograph peak. The basin lag is best determined through calibration of the model; however it can be estimated as 0.6 times the time of concentration for the watershed. The time of concentration is a commonly used parameter in watershed modeling and represents the time for a particle of water at the furthest point in the watershed to reach the watershed outlet.

2.3.3 Reservoir Modeling

A reservoir stores flow from the watershed and releases it at a slower rate based on the method of outflow. For a porous pavement infiltration bed, the inflow is the runoff from the drainage area and the outflow is the infiltration into the subsoil as well as any overflow. Reservoirs are modeled in HEC-HMS using the Modified Puls routing model (US Army Corps of Engineers 2000). This model discretizes time into time steps of Δt and solves a one dimensional approximation of the continuity equation as follows:

$$I_{avg} - O_{avg} = \frac{\Delta S}{\Delta t} \qquad \text{Eq. 2-7}$$

Where I_{avg} and O_{avg} are the average inflow and outflow, respectively, during the time interval Δt. ΔS is the change in reservoir storage during the given time interval. The inflow is known from the runoff hydrograph already calculated in HEC-HMS, and the time step is defined by the user. The remaining two variables, the outflow and the storage, can both be expressed in terms of the height of water in the reservoir. This leaves one unknown, the depth of water in the reservoir, to be solved for using the above equation. HEC-HMS requires that the user specify both a depth-storage and depth-outflow curve for the reservoir so that the outflow and storage is known for any reservoir depth. The depth-storage curve will simply be a function of the geometry and the porosity of the media used to fill the infiltration bed. The depth-outflow curve will depend on the infiltration rate of the subsoil and the method of overflow utilized. The outflow will simply be the infiltration rate until large depths cause an overflow from the reservoir. If a weir is used, an outflow equation can be developed based on the weir geometry and incorporated into the depth-outflow curve.

If the user desires to know how much runoff has been infiltrated and how much runoff has overflowed the infiltration bed for a given model run, the infiltration can be modeled in HEC-HMS as a diversion (Ladd 2004). HEC-HMS will divert a certain flow from the reservoir to be considered infiltration, and any remaining flow will be passed along as overflow.

2.3.4 Calibration

Because many of the parameters used in HEC-HMS models are estimations of what is occurring in the physical watershed, calibration of HEC-HMS models are very important. Calibration requires the user to obtain observed rainfall and runoff values from the modeled watershed (US Army Corps of Engineers 2000). For an infiltration basin, this can include precipitation and bed depths for a series of storms. When creating a HEC-HMS model, the user should select estimates of the required parameters to create an initial simulation of runoff in the watershed. HEC-HMS will then compare the simulation to the actual data, and iterate on the input parameters until a simulation that most accurately reflects the actual data is obtained. This process is illustrated in Figure 2-5.

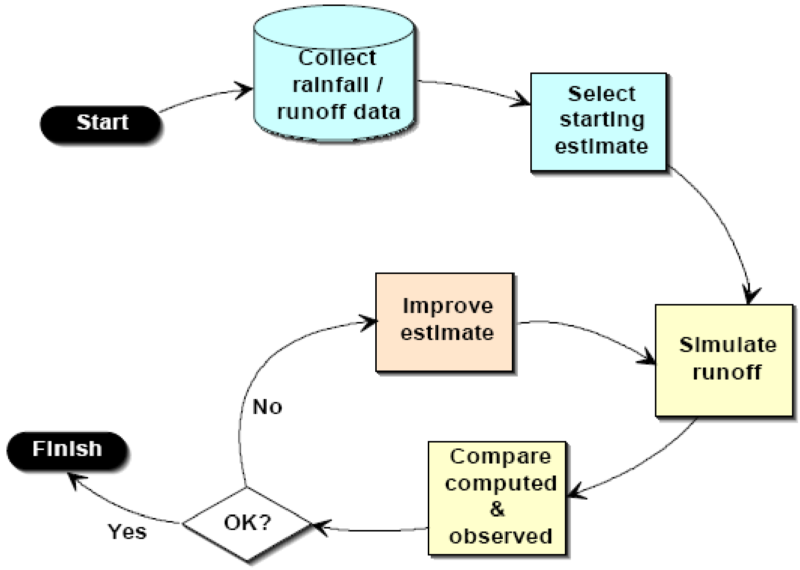

Figure 2-5 HEC-HMS Calibration Process (US Army Corps of Engineers 2000)

When calibrating runoff models, HEC-HMS can utilize one of four goodness-of-fit algorithms to compare the modeled results to the actual results (US Army Corps of Engineers 2000). These algorithms include the sum of absolute errors, sum of squared residuals, percent error in peak, or peak-weighted root mean square error. The algorithm used should be chosen based on what the main objective of the model is. More information regarding the various algorithms can be found in the HEC-HMS Technical Reference Manual (2000).

Chapter 3 Study Site

The pervious concrete and porous asphalt comparison site studied in this project is located on the campus of Villanova University in southeastern Pennsylvania. The site is a part of Villanova's Stormwater Research Park, which includes a number of studied stormwater BMPs. The drainage area for the site is divided into two sections, one that drains to the pervious concrete and one that drains to the porous asphalt. The drainage areas are roughly equal and consist of conventional asphalt parking areas. The site was designed to handle runoff from this drainage area and infiltrate it into the subsoil, while incorporating equipment for analysis and comparisons of the two porous pavements.

3.1 Villanova University Stormwater Park

The pervious concrete and porous asphalt comparison site covered by this research is located on the Villanova University campus as a part of the Villanova University Stormwater Park. This research park features demonstration projects of a number of innovative stormwater best management practices, including a green roof, pervious concrete, porous asphalt, bioinfiltration traffic islands, an infiltration trench, and a constructed stormwater wetland. Each site is, or has been, monitored and studied to provide valuable engineering insights for the design, construction, and operation of stormwater BMPs.

3.2 Site Watershed

The study site is located directly behind Mendel Hall on the campus of Villanova University. The watershed consists of a 0.07 hectare (0.18 acre) standard asphalt parking area. The watershed is, thus, 100 percent impervious. Roughly half of this area drains to the pervious concrete section and half to the porous asphalt section. The parking area is used by Villanova

University faculty and staff, resulting in an area that is utilized year round. All planted areas surrounding the study site are separated from the drainage area by curbs, thus limiting the amount of sediment reaching the porous pavements and preventing premature clogging of the pore spaces.

Figure 3-1 Single Ring Constant Head Infiltrometer

Soil analyses were performed on the soils beneath the infiltration beds. Once excavation was complete, infiltration rates were measured in-situ. A single ring constant head infiltrometer, as shown in Figure 3-1, was used for this task. Because of high compaction of the site during its history as a parking lot, poor infiltration results were obtained. Soil samples were also obtained and brought back to the soils laboratory for analysis. A soil gradation curve was developed and the Atterburg Limits of the soil were determined for soil classification. Figure 3-2 shows the gradation curve as well as the Atterburg Limit information obtained. These properties result in a classification of a silt with sand (ML) using the USCS classification system. Complete soil testing results can be found in Appendix A.

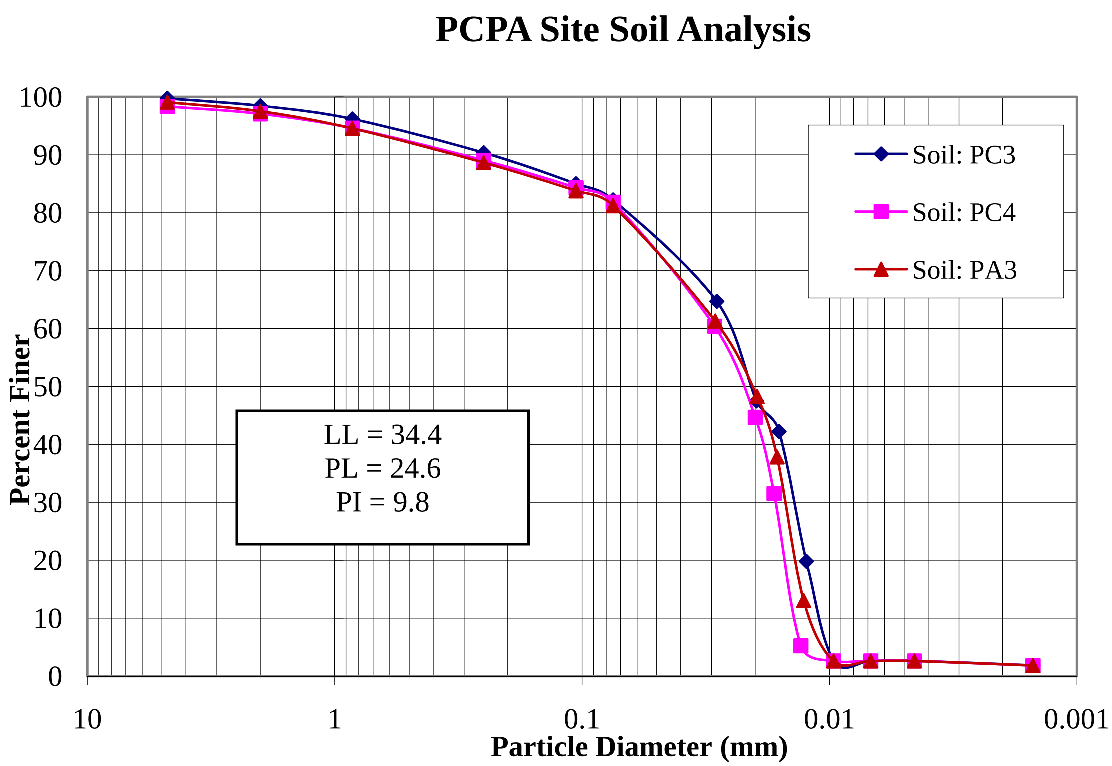

Figure 3-2 Soil Gradation Curves and Atterburg Limits

3.3 Site Design

The study site was designed primarily by Dr. Andrea Welker of Villanova University. There were several aspects to the design of the pervious concrete and porous asphalt comparison. The initial stages of the design required the selection of a geometry that could provide sufficient detention of runoff while infiltration occurs, as well as maintaining areas and volumes sufficient for comparisons of the two porous pavements. Next, adequate separation of the two pavements and their infiltration beds was necessary to ensure that cross contamination of pollutants and water volumes would not occur. Additionally, pavement mixes and thicknesses had to be developed to ensure proper strength, durability, and permeability.

Finally, instrumentation had to be selected to provide a comprehensive comparison of the two porous pavements.

3.3.1 Bed Geometry

The geometric design of the infiltration basins for the given project was governed primarily by site and financial constraints. In the existing parking lot used for the study, an area between two planted traffic islands provided the best area for the placement of porous pavements. This area allowed for adequate surface area for the two pavements, as well as room for manholes in the traffic islands for monitoring and overflow weirs. This area dictated the available surface area, 9.1 meters (30 feet) by 30.5 meters (100 feet). Half of this area was allotted for pervious concrete and half for porous asphalt. Next, to minimize excavation and backfilling costs, the depth of the beds was kept to a minimum depth. The minimum recommended depth for porous pavement infiltration beds is 0.5 meters (1.5 feet). Due to the slope of the site, and the desire to keep the bottom of the beds level, the depth for each infiltration bed ranges from the minimum of 0.5 meters (1.5 feet) to 1.5 meters (5 feet). Additionally, due to the slope, the pervious concrete bed bottom is located 0.5 meters (1.5 feet) below the porous asphalt bed bottom. Because the bed geometry and drainage area was dictated by site and financial constraints, the volume of water to be detained was not a design variable. However, the amount of runoff able to be stored by the infiltration beds is consistent with most designs in the southeastern Pennsylvania area. The infiltration bed geometry provides a volume of approximately 1,800 cubic meters (63,000 cubic feet), however it is filled with AASHTO #2 stone (approximately 102 millimeters, or 4 inches in diameter), with a void ratio of 0.4. Thus the storage volume for water is approximately 700 cubic meters (25,000 cubic feet). The size of the infiltration beds allow for 51 millimeters (2.0 inches) of rain to fall on the

0.07 hectare (0.18 acre) drainage area to be stored and infiltrated. This equates to approximately 80% of the annual rainfall volume for southeastern Pennsylvania (Ladd 2004).

3.3.2 Separation

There are two parts to the separation design for the comparison project. First, the subsoil should be separated from the stone infiltration bed. This prevents small soil particles from migration into the stone bed and reducing the storage volume. The commonly accepted method of providing this separation is to lay a non-woven geotextile fabric along the bottom of the infiltration bed. The fabric should have a high permittivity value to allow the transport of water across the geotextile and have a small opening size value to prevent soil particles from crossing through the geotextile. Any non-woven geotextile should match the required properties for most infiltration BMP sites. The geotextile used in this project is shown in Figure 3-3.

Figure 3-3 Geomembrane (Gray), Geotextile (Black), and Jersey Barrier (Beneath Geomembrane)

The second aspect of separation in the design of the Villanova pervious concrete / porous asphalt comparison site is the separation of the pervious concrete bed from the porous asphalt bed. This is important to eliminate the transfer of water and contaminants from one bed to the other, and resulting in inaccurate water quantity and quality data. This separation was achieved by placing a Jersey Barrier down the middle of the infiltration bed to create two equally sized infiltration beds. To provide added separation protection, a 2.0 millimeter (80 mil) geomembrane was placed over the Jersey Barrier. This design minimizes the potential for water to travel between the two infiltration beds. The Jersey Barrier and geomembrane are shown in Figure 3-3.

3.3.3 Pavement Design

The pavement design was performed by experts in pervious concrete and porous asphalt fields. Cahill Associates of West Chester, PA was chosen to complete the porous asphalt mix design. Phil Kresge, of the National Ready Mix Concrete Association (NRMCA) was chosen to complete a mix design for the pervious concrete. The porous asphalt and pervious concrete designs were chosen based on industry recommendations and common practices for the Mid-Atlantic region.

Cahill Associates has been completing porous asphalt designs across the country since 1974, and has a project close to the research site that has been in operation for 25 years. The mix design selected was one that they were using for a project down the road from Villanova University at the same time as the comparison project. The mix contains a narrow gradation of stone aggregate, an asphalt binder, and fibers. The gradation of the aggregate can be seen in Figure 3-4. The binder is a PG 64-22 binder, meaning that it is suitable for daily average high temperatures of 64˚C and daily average low temperatures of -22˚C. This binder makes up 5.8

percent of the total mix. Finally, the mix consists of 0.20 percent of fibers to make the mix stiffer and to prevent draindown of the asphalt binder.

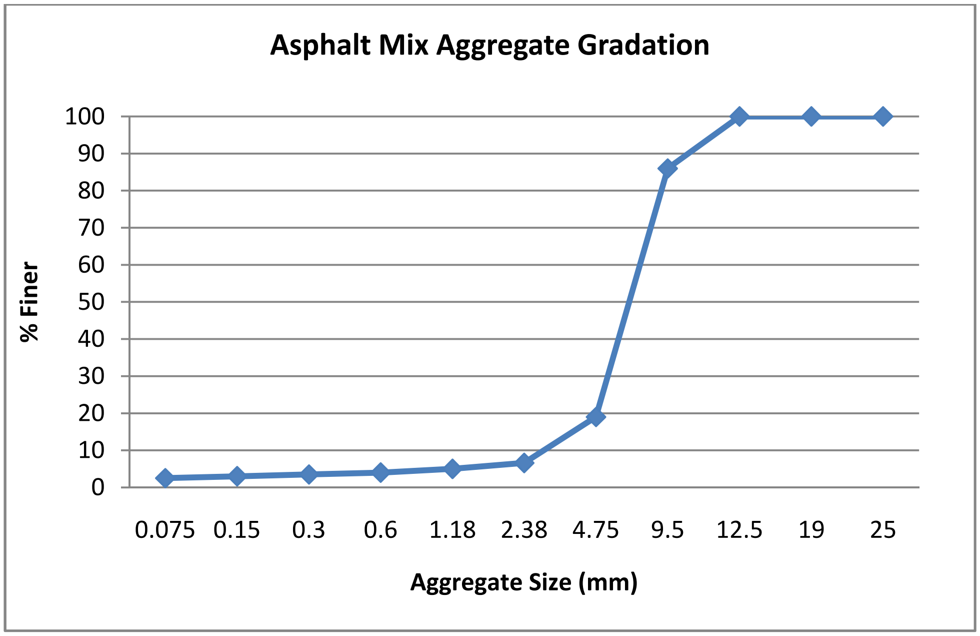

Figure 3-4 Asphalt Mix Aggregate Gradation

Phil Kresge, of the NRMCA, completed the pervious concrete mix design. The NRMCA is the leading concrete industry advocate and has conducted and sponsored concrete research since 1930. They also offer a number of training and certification courses regarding the installation of pervious concrete. The mix design for the current research project consists of stone aggregate, Portland cement, water, and several modifiers. 78.8% of the mixture consists of #8 stone aggregate, 16.9% of the mixture is Portland cement, and water makes up 4.2% of the pervious concrete. A high range water reducer (0.06%), viscosity modifier admixture (0.05%), and set retarding mixture (0.03%) were also added to the mix to improve workability of the concrete.

3.3.4 Monitoring Equipment

As the pervious concrete / porous asphalt comparison site is a research site, it is highly instrumented for data gathering. For water quality analysis there are first flush samplers for incoming runoff quality, manholes for bed water quality, and lysimeters for soil pore space water quality. For water quantity analysis there is a tipping bucket rain gage for recording precipitation, manholes equipped with pressure transducers for bed level monitoring, and a weir for overflow monitoring. An overview of the monitoring equipment placement is shown in Figure 3-5.

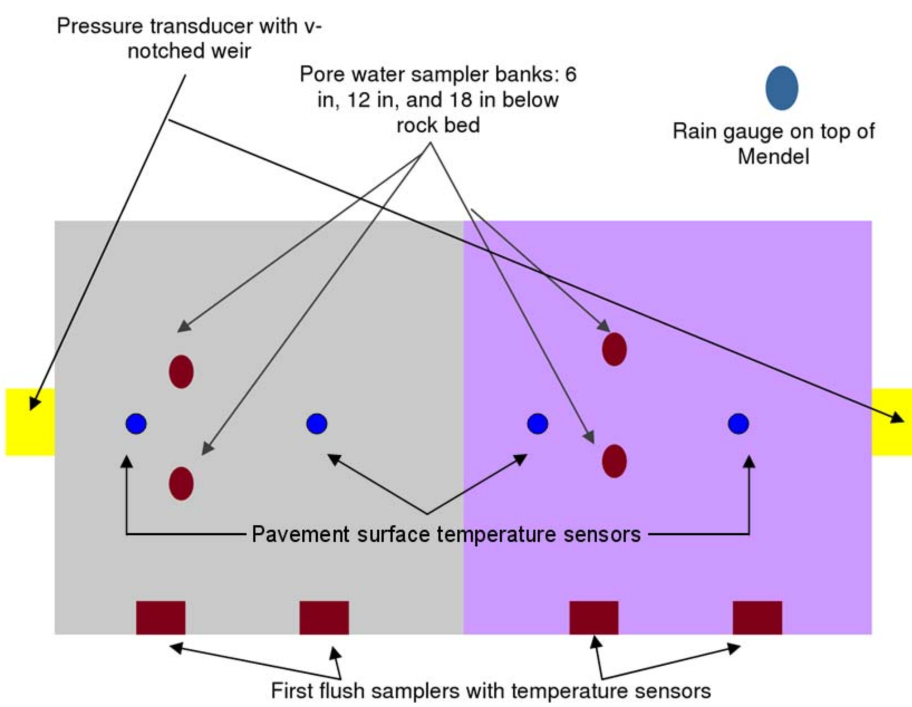

Figure 3-5 Monitoring Equipment Layout

3.3.4.1 First Flush Samplers

First flush samplers are designed to take a sample of runoff that occurs when precipitation first begins. This initial runoff is typically considered to be the "dirtiest" sample because it is picking up most of the pollutants that have accumulated on the pavement since the last storm event.

For the current study, GKY FirstFlush Samplers were employed to collect these samples. They utilize a plastic box with a perforated lid, where runoff can enter the sample container. Once the sample container is filled, buoyant closing mechanisms block the perforations, sealing off the collected sample. An illustration of these samplers can be found in Figure 3-6. Four of these first flush samplers were placed along the uphill edge of the project site, two entering the pervious concrete section and two entering the porous asphalt section.

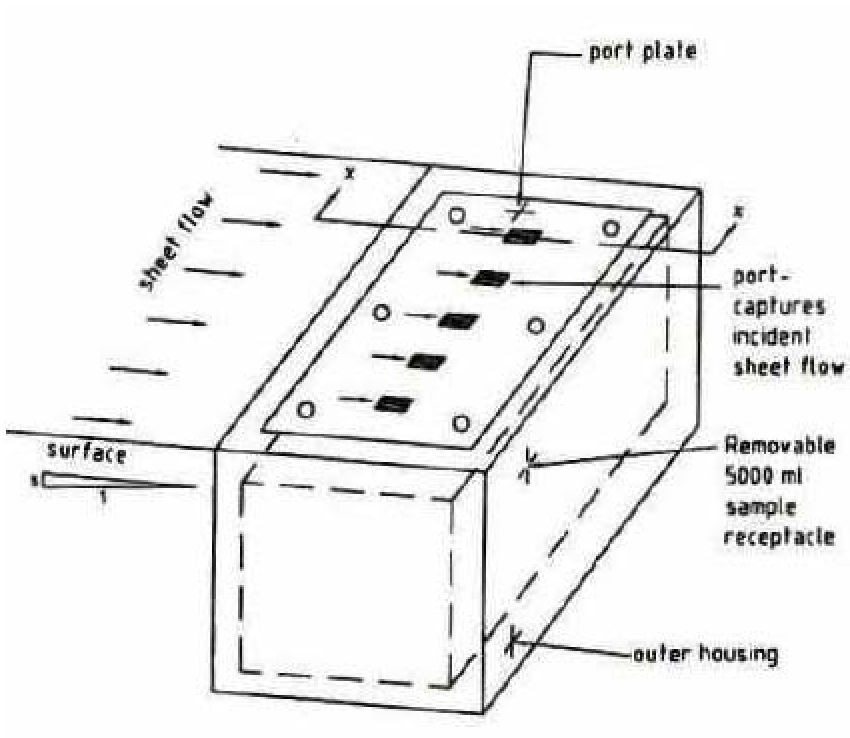

Figure 3-6 First Flush Samplers (GKY & Associates 2005)

3.3.4.2 Observation Manholes

Two observation manholes were utilized for the comparison study, one on the pervious concrete side and one on the porous asphalt side. These manholes were precast structures that were open on one side. This open side was covered with a galvanized steel mesh screen. The manhole was set alongside the infiltration bed such that water could freely pass through the mesh screen into the manhole. This resulted in a water level in the manhole equal to that of the infiltration bed. A steel plate was set vertically inside of the manhole to create two separate sections within the manhole. Thus the water level would have to rise higher than the plate for water to enter the back section of the manhole, where an outlet pipe would convey the overflowing water to a conventional storm sewer. These manholes are illustrated in Figure 3-7. The manholes provide a location to take water samples for qualitative analysis, as well as a place to implement depth and overflow monitoring equipment.

Figure 3-7 Observation Manholes

3.3.4.3 Lysimeters

Lysimeters are used to collect water samples from the pore spaces of soil. They consist of a small chamber that is buried in the soil, a plastic tube that runs to the surface, and a sampling container above the surface to collect and store water samples. The chamber has a filter over it such that water is drawn in without the accompanying soil particles. In order to collect a sample, a vacuum is applied to the entire system via the sample container. This causes water to be drawn into the below ground chamber and travel up the plastic tube to the sample container.

For the current study, six lysimeters were installed for each pavement, pervious concrete and porous asphalt. two lysimeters were placed at three depths below the bottom of the infiltration bed, 152 mm (6 inches), 305 mm (12 inches), and 457 mm (18 inches). The plastic tubes for the lysimeters were run through conduit to sample containers located near the observation manhole on the pervious concrete side. The duplication of lysimeters was due to past experiences with approximately 50% of installed lysimiters not functioning after installation. Causes of this include pinched tubes or breaks in the buried chamber. The lysimeters are shown in Figure 3-8.

Figure 3-8 Lysimeters

3.3.4.4 Tipping Bucket Rain Gage

Tipping bucket rain gages are used to measure precipitation at a particular location. They consist of a bucket with a seesaw like balance located within it. Precipitation falls onto one end of the seesaw and accumulates until enough has fallen to tip the scale. This amount needed is predetermined via calibration and is usually .25 mm (0.01 inches). Once the scale tips, the other end of the scale moves in place to receive more precipitation.

The tipping bucket rain gage used in this study was already in place on the rooftop of building adjacent to the project site. It is operated and maintained by the Villanova University Department of Astronomy. The data is collected and displayed on the department webpage, where it could be accessed and utilized. A tipping bucket rain gage is illustrated in Figure 3.9.

Figure 3-9 Tipping Bucket Rain Gage (Rainwise Inc. 2008)

3.3.4.5 Pressure Transducers

Pressure transducers are used to measure the depth of water in submerged locations, such as infiltration beds. Pressure transducers work by measuring the pressure at the bottom of the bed, and correcting for atmospheric pressure. The resulting pressure differential can be adjusted to a depth of water by dividing by the specific gravity of water.

This study utilized PT2X pressure transducers from Instrumentation Northwest, shown in Figure 3-10. These sensors measure the temperature as well as the water depth and store the data in a self contained datalogger that can be accessed to download the data. Pressure transducers were placed in each of the two observation manholes to record the depth of water in the infiltration beds.

Figure 3-10 Pressure Transducer

3.3.4.6 Overflow Weir

Weirs provide an effective way to measure flow through a given location. Given the geometry of the weir and the depth of water flowing through it, an equation can be developed that will describe the flow rate.

For the current project, weirs were incorporated into the observation manholes to measure the amount of water overflowing from the infiltration beds into the conventional stormwater system. The weirs used at the project site were v-notch weirs with a 60 degree angle. The previously described pressure transducer was used to measure the depth of water in the bed, and thus the depth of water flowing over the weir.

Chapter 4 Construction

The Villanova Pervious Concrete / Porous Asphalt comparison site was constructed over a 2 month period in the fall of 2007. Scott Construction was chosen to complete the project, with the exception of pavement installation. This included site demolition, excavation, and preparation for paving. Engelman Construction, a National Ready-Mix Concrete Association (NRMCA) pervious concrete certified company recommended to us by the NRMCA, was selected to install the pervious concrete. Finally, Burkholder Pavement, recommended to by the National Asphalt Pavement Association (NAPA), was chosen for the porous asphalt paving.

4.1 General Construction

Figure 4-1 Existing Pavement Demolition

Construction began on September 17, 2007 with demolition of the existing asphalt parking lot that was to be converted to porous pavement. The 30.5 m by 9.1 m (100 ft by 30 ft) parking lot was stripped of the existing 152 mm (6 inches) of asphalt cover using an asphalt grinder, shown in Figure 4-1.

The following three days were spent excavating the infiltration bed to the required depth. Due the fairly steep slope of the site and the desire to keep the bottom of the bed level, this resulted in depths ranging from 0.6 m to 1.5 m (2 feet to 5 feet). It was found that during the course of the site's life as a parking lot, significant compaction of the soil had already been experienced, and a backhoe was permitted to drive within the bed for excavation and grading. A heavier Gradall was also used in excavation, but was kept out of the bed as much as possible to avoid further compaction of the subsoil.

Once the site was excavated to proper grade, infiltration tests were performed on the soil lining the bottom of the bed. A single ring constant head infiltrometer, as shown earlier in Figure 3-1, was used for this task. As expected from the preexisting compaction of the site, poor infiltration results were obtained. Additionally, soil samples were taken at this time for classification in the laboratory.

The next step in construction was the placement and installation of the manholes on each side of the infiltration bed for water level observation and allowance for overflows. The manholes were open on one end, covered only by a steel mesh screen. This allows for free flow of water between the infiltration bed and the manholes. The manholes were divided down the middle with a steel plate containing a v-notch weir at the top. This allows water to overflow over the weir and outflow through a HDPE pipe on the backside of the manhole. The overflow HDPE pipes were tied into a nearby existing stormwater drain. A photograph of the manholes used on the project is shown earlier in Figure 3-7.

The second week of construction began with placing the Jersey Barrier down the center of the infiltration bed to separate the porous asphalt bed from the pervious concrete bed. PVC conduit was run through the barrier to allow for instrumentation lines. Lysimeters were installed on each side of the infiltration bed. Six lysimeters were installed on each side of the bed at depths of 152 mm, 305 mm, and 457 mm (6 inches, 12 inches, and 18 inches) below the bottom of the bed. All of the data lines and lysimeter tubing were run to the pervious concrete side of the bed where a datalogger and rack for lysimeter sample bottles were located. The datalogger was located within an encasement and the lysimeter sample bottles were mounted within the manhole on the pervious concrete side. Finally self datalogging pressure transducers were placed in each of the manholes to measure and record bed water depths. The Jersey Barrier and instrumentation lines are shown in Figure 4-2.

Figure 4-2 Jersey Barrier & Instrumentation Conduit

Upon completion of instrumentation, a 2.0 mm (80 mil) geomembrane was laid over the Jersey Barrier to provide extra separation between the beds. Also, a nonwoven geotextile was placed along the bottom of the infiltration bed to prevent clogging of the bed from subsoil particles. Figure 3-3, shown earlier, illustrates the geomembrane and geotextile.

The second week was completed by filling the infiltration bed with clean, washed #2 stone. This results in a void space of approximately 40%. On the porous asphalt side of the bed, a #57 stone choker course was laid on top of the #2 stone. Once the beds were filled, the stone was compacted using a flat plate vibratory compactor. The stone filled beds are shown in Figure 4-3.

Figure 4-3 Infiltration Bed Filled With Stone

4.2 Porous Asphalt Installation

The porous asphalt was placed on October 1st 2007. The installation of the asphalt occurred in one day and took approximately three hours to complete. Prior to installation, two first flush samplers were placed at the up slope end of the pavement to collect first flush runoff samples. The porous asphalt was installed around the first flush samplers. A team of five used standard asphalt equipment and procedures in the installation. The standard asphalt procedure uses an asphalt paver which can hold large quantities of the hot asphalt. This paver spreads a level strip of asphalt that is approximately 2.4 m (8 feet) in length. The depth of the asphalt was 63.5 mm (2.5 inches). For the tight areas and the edges where the paver could be used the asphalt was placed by hand. Part of the standard installation procedure is using diesel fuel as a lubricant on the equipment to prevent the hot asphalt from sticking to the rakes and other pieces of equipment, and allowing for the even distribution of asphalt throughout the site. Consequently, the spraying of diesel fuel over the site was done quite frequently over the course of the installation. After the asphalt was laid a mechanical roller was used to compact the asphalt surface. The result of this compaction left some small areas where there is no visible pore space. These areas are small and sporadically spaced, and do not affect the overall performance of the asphalt surface. A photograph illustrating the porous asphalt installation can be found in Figure 4-4.

Figure 4-4 Porous Asphalt Installation Using Asphalt Paver

4.3 Pervious Concrete Installation

The pervious concrete was installed by Engelman Construction on October 8th and 9th, 2007. The pervious concrete installation was carried out over two 4-hour days, with a 4.6 m by 15.2 m (15 feet by 50 feet) area being poured each day. Prior to installation, two first flush samplers were placed at the up slope end of the pavement to collect first flush runoff samples. The pervious concrete was poured around the first flush samplers. The process began with setting up forms and spraying them with a diesel fuel lubricant. While the forms were being set up the stone bed was wetted thoroughly so that the concrete would not dry too quickly and crack after being laid. Once the gravel was soaked, the concrete was poured from a mixer to cover an approximately 4.6 m by 2.1 m (15 feet by 7 feet) area at a depth of 152 mm (6 inches). A three person crew spread this concrete to approximately level using hand shovels and rakes. Next, another three person crew ran a 4.9 m (16 feet) long roller screed, lubricated with diesel fuel, over the poured area to level the concrete. Finally, a tarp was pulled over the finished area to prevent quick drying. This tarp must be placed over the finished area within 15 minutes of the concrete mix leaving the mixer to ensure successful results. This process was then repeated until the entire 4.6 m by 15.2 m (15 feet by 50 feet) area was poured and leveled. Two evenly spaced control joints were grooved in the fresh concrete across the 15.2 m (50 feet) dimension to allow for expansion of the concrete. Figure 4-5 shows the pervious concrete installation.

Figure 4-5 Pervious Concrete Installation Using Roller Screed

After the first half of the bed was poured, it was allowed to cure for 1 day before the second half of the bed was poured. This was to allow the first half to harden enough for the crew to walk and run the end of the roller screed over. At the completion of the two pours, the concrete was cured with the tarp still covering it for 1 week before it was open for traffic.

Chapter 5 Durability & Maintenance

The durability of porous pavements is a key concern for many people when deciding on their use. This study looked at the durability of both porous asphalt and pervious concrete over the period of one year, focusing on the structural performance, aesthetic qualities, and infiltration performance of the pavements. Furthermore, the maintenance requirements of these pavements were documented.

5.1 Product Durability

The durability of porous pavements is largely dependent on the mix design chosen. A mix that maximizes pore space will be able to maintain excellent infiltration capabilities, but will have less compressive strength and may experience structural deterioration. The opposite is true as well; a mix with less pore space will have poorer infiltration capabilities and more strength. The porous asphalt and pervious concrete mixes used in this project were evaluated for their durability over a one year period with respect to structural and infiltration performance as well as aesthetic qualities. The inspection forms for the project can be found in Appendix B.

5.1.1 Structural Performance

Over the first year of use, the porous pavement parking lot has structurally held up well. The site has experienced light traffic by cars parking over the porous pavement. This light traffic has caused a few stones to come loose on both pavements; however this is not a visible defect.

Over the winter of 2007-2008 one snow storm was large enough to require plowing on the project site. The plow was left too close to the pavement at several spots and left visible scrape marks across the pavement, but no structural damage. These scrape marks are shown in Figures 5-1 and 5-2.

Figure 5-1 Plow Marks on Porous Asphalt

Figure 5-2 Plow Marks on Pervious Concrete

While attempting to repair a leak in the observation manholes, a backhoe was brought in to the site to perform some excavation. The backhoe sat over both of the porous pavements during this excavation. No damage was done to the pervious concrete, but two depressions were made on the porous asphalt. These depressions were approximately 1 cm deep, and can be seen in Figure 5-3.

Figure 5-3 Depression in Porous Asphalt

5.1.2 Aesthetic Quality

The aesthetic quality of a pavement is another important aspect of pavement durability. Several issues can affect the appearance of porous pavements over time. In the current study, these issues included some clogging of the pavement pore spaces, scraping of the pavements due to plowing, and oil spots from cars parking over the pavement.

Figures 5-4 and 5-5 illustrate both pavements following installation. These original photographs show the original condition of the pavements for comparison to the aesthetic issues shown later.

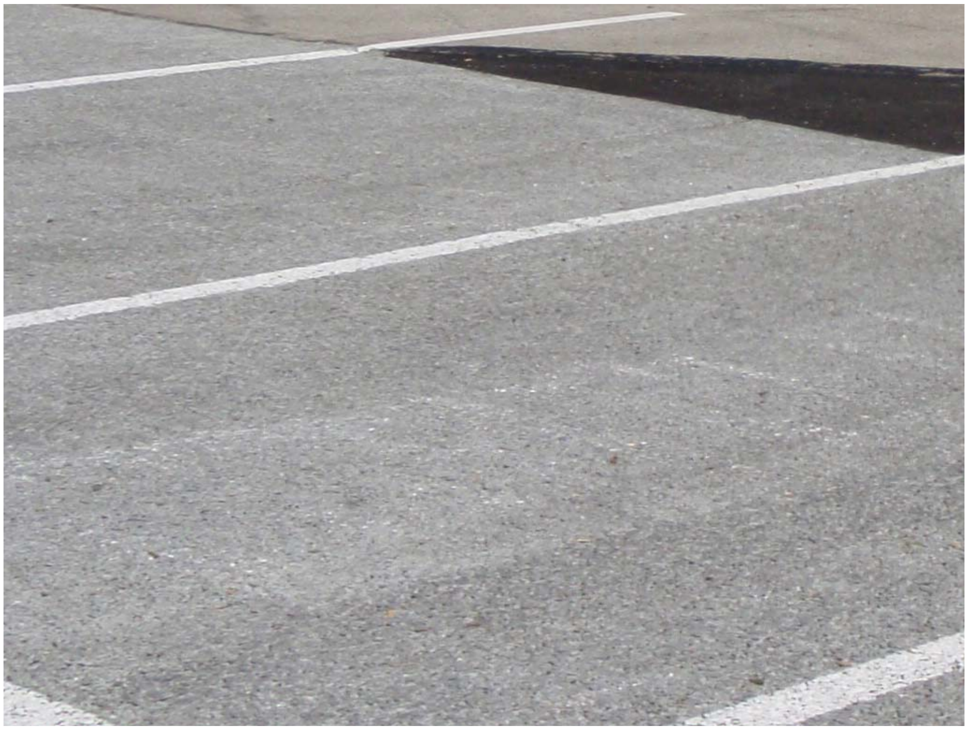

Figure 5-4 Original Pervious Concrete

Figure 5-5 Original Porous Asphalt

Figures 5-6 and 5-7 show porous pavements that have become clogged with sediments. The pavements show a tan color from the sediments that are clogging the pore space. This is less attractive than the surrounding unclogged pavement, and can be partially remedied by maintenance such as vacuum sweeping.

Figure 5-6 Clogged Porous Asphalt

Figure 5-7 Clogged Pervious Concrete

Oil spots left on the pavements also take away from the aesthetics of the porous pavements. These oil spots are more evident on the concrete than the asphalt, due to the contrast between the dark spots and the lighter concrete. These oil spots are illustrated in Figures 5-8 and 5-9.

Figure 5-8 Oil Spot on Pervious Concrete

Figure 5-9 Oil Spot on Porous Asphalt

5.1.3 Infiltration Performance

The infiltration performances of the two porous pavements were evaluated using a method developed by researchers at Cleveland State University (Delatte, et al. 2007). Here, researchers utilized a small a 10.2 x 20.3 cm (4 x 8 in) concrete cylinder mold with a 2.2 cm (7/8 in) diameter hole drilled in the bottom to estimate the hydraulic conductivity of pervious concrete samples. An image of this apparatus is shown in Figure 5-10. The mold was filled with water, placed over a pervious concrete sample, and timed for how long it took to drain. Delatte, et al. derived an equation to relate the drain time (t, in seconds) to the hydraulic conductivity (k, in inches per hour):

$$k = 2533 * exp(-0.062 * t) \quad \text{Eq. 5-1}$$

Figure 5-10 Infiltration Testing Apparatus

Pavement Drainage Times (seconds)

	5/13/2008	8/5/2008	11/17/2008
Concrete - Good Condition	8	26	21
Concrete - Poor Condition	13	106	62
Asphalt - Good Condition	16	49	42
Asphalt - Poor Condition	40	183	80
Non-Porous Asphalt	--	270	405

Pavement Hydraulic Conductivity (cm/hr)

	5/13/2008	8/5/2008	11/17/2008
Concrete - Good Condition	3917	1283	1750
Concrete - Poor Condition	2872	10	137
Asphalt - Good Condition	2385	307	475
Asphalt - Poor Condition	538	0	46
Non-Porous Asphalt	--	0	0

Table 5-1 Pavement Drainage Times and Hydraulic Conductivities

The infiltration testing results for the porous pavement in the current study are shown in Table 5-1. Tests were done on pavement in good quality (unclogged) and in poor quality (clogged) for both the porous asphalt and pervious concrete. The results show that the pervious concrete tended to have greater hydraulic conductivities, however when the pavements were in good condition (and sometimes in poor condition) the hydraulic conductivities were far greater than could be produced by a local rainfall. Also, it should be noted that between the May and August tests the hydraulic conductivities decreased due to the buildup of sediments in the pavements. Between the August and November tests the hydraulic conductivities increased. This increase is due to vacuum sweeping of the pavements that took place in late October.

5.2 Maintenance Requirements

As with any stormwater BMP, maintenance is an important issue for both porous asphalt and pervious concrete. For the current study, several measures were taken to maintain the useful life of the porous pavements, including proper landscaping layouts, snow removal techniques, and vacuum sweeping.

To prevent significant clogging of the porous pavements, landscaped areas were separated from the drainage area for the porous pavements. This was accomplished by ensuring that all landscaped areas were enclosed within a curb. Separating landscaped areas reduces the quantity of sediments in stormwater runoff and prolongs the life of the porous pavements.

During the winter, snow removal was required for the porous pavement parking area. Salt use was avoided during the first year due to its potential to corrode concrete. Only once did the snow accumulate enough on the porous pavements to require formal snow removal. In this instance a plow truck was used. Unfortunately, the plow was placed too close to the pavement at several locations where plow marks were left on the pervious concrete and porous asphalt. When plowing porous pavements, the plow should be raised approximately 25 mm (1 inch) above the pavement (Pennsylvania Department of Envirionmental Protection 2006).

Near the end of the first year of use of the porous pavement parking area the infiltration capacity of the porous pavements had been reduced by 60 to 100% (see Figure 5-11 for actual infiltration rates). Although the infiltration capacity was still significantly greater than could be expected from a rain storm, it was decided to utilize a vacuum truck to clean the pore space of the porous pavements. This maintenance took place in October 2008. In the following inspection, infiltration rates were found to improve significantly. The porous pavement areas that were already in good condition improved by 30 to 50%, while the areas that were in poor condition improved by at least 1200%.

5.3 Public Opinion

In order to determine the public opinion regarding the porous pavements used in this study, a survey was conducted. The survey was distributed to people who had parking permits for the studied parking lot and returned 22 responses. The questions fell into three categories, aesthetics, performance, and the overall opinion of the pavements. The full survey and results can be found in Appendix C.

5.3.1 Aesthetics

Survey participants were asked whether they preferred the appearance of conventional asphalt or porous pavements. 14% of respondents preferred the look of porous pavements, 18% preferred the look on conventional asphalt, and 54% felt that the pavements looked the same, and 14% had no observation.

Additionally, survey participants were asked whether they preferred the appearance of porous asphalt or pervious concrete. 18% of respondents preferred the look of porous asphalt, 23% preferred the look of pervious concrete, and 59% had no opinion.

5.3.2 Performance

Three questions were asked regarding users experience with the performance of the porous pavements. Of those surveyed 24% felt that the porous pavements provided more traction than the conventional asphalt, 14% felt the traction was the same, and 62% had no observation.

When asked about the amount of snow and ice on the porous pavements, 5% respondents felt that there was less snow than on conventional asphalt and 5% stated that the amount of snow and ice was the same as on conventional asphalt. 90% of respondents had no observation. This is likely due to the fact that few snow storms have occurred at the site, and those that did occur were nearly a year before the survey was conducted. For more information on this question, another survey at the end of the winter season would be beneficial.

Finally, survey participants were asked about the roughness of the porous pavements. 100% of those surveyed stated that they had no difficulties associated with the roughness of the pavements.

5.3.3 Overall Opinion

The final question of the survey was whether users had a generally positive or negative opinion of the porous pavement parking lot. 73% of respondents have a positive opinion of the parking lot, while 27% had a neutral opinion. No survey participants had a negative opinion of the porous pavement parking lot. When asked to comment on this, most participants cited the environmental benefits of the project as their reason for having a positive opinion.

Chapter 6 Modeling

Computer software makes mathematical models much easier to use and visualize. Therefore Hydrologic Engineering Center – Hydrologic Modeling System, more commonly known as HEC-HMS, was utilized to model the porous pavement project discussed in this paper. HEC-HMS is the most extensively used computer software package that models stormwater processes, and was developed by the US Army Corps of Engineers to model precipitation-runoff processes within a watershed (US Army Corps of Engineers 2000). The software allows users to provide hydrologic characteristics of their site and analyze the performance under a variety of conditions. Figure 6-1 provides a schematic to illustrate the HEC-HMS model of an infiltration basin. Runoff originates from the site watershed and the pavement itself. This runoff enters the infiltration bed where a portion is lost due to infiltration and the remainder is conveyed to conventional stormwater systems via overflow. There are four steps to creating such an infiltration basin HEC-HMS model; runoff volume calculations, runoff modeling, reservoir modeling, and calibration.

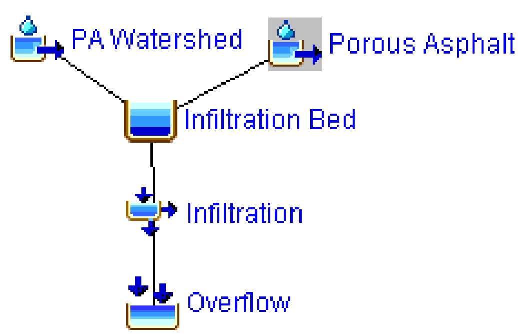

Figure 6-1 HEC-HMS Schematic of Infiltration Basin

6.1 Runoff Volume Calculations

HEC-HMS begins modeling by computing runoff volumes for the watershed (US Army Corps of Engineers 2000). This requires that the user provide various watershed characteristics, which vary based on the modeling method chosen by the user, as well as precipitation information. Precipitation data can be entered as a design storm to analyze performance under hypothetical conditions, or can be actual data to analyze performance under real conditions.

Runoff volumes are calculated by watershed characteristics. All watershed areas are either classified as directly-connected impervious area, or pervious area (US Army Corps of Engineers 2000). Directly-connected impervious area is land that experiences no infiltration or evaporation and all precipitation becomes runoff. Pervious areas experience some loss of volume. This loss can be quantified based on several methods; however the small storm method developed by Pitt (1999) was used in this study. This method is similar to the SCS Curve Number method, with the only difference being the curve numbers used. Additional information on various methods of computing runoff volumes and the computations involved can be found in Chapter 2 of this paper. Table 6-1 lists the watershed areas for the porous pavement comparison site and the curve numbers utilized for modeling.

Watershed Area	Curve Number
Porous Asphalt Drainage Area	97
Porous Asphalt Pavement	99
Pervious Concrete Drainage Area	97
Pervious Concrete Pavement	99

Table 6-1 Watershed Curve Numbers

6.2 Runoff Modeling

After computing the amount of excess precipitation within a watershed, HEC-HMS uses a runoff model to demonstrate the effects of excess precipitation (US Army Corps of Engineers

2000). This study used the SCS Unit Hydrograph method to model the site runoff due to its popularity and applicability to watersheds that have sufficient data to perform calibration measures. The SCS Unit Hydrograph method of runoff modeling assumes that the runoff hydrograph can be constructed by scaling a single peaked dimensionless hydrograph to the desired watershed. Additional information on various methods of modeling runoff and the computations involved can be found in Chapter 2 of this paper. The required site information for this type of model is the area of each watershed area and the lag time for runoff flow. The values utilized in this project are shown in Table 6-2.

Watershed Area	**Area (m^2)**	**Lag Time (min)**
Porous Asphalt Drainage Area	362	1
Porous Asphalt Pavement	139	0.1
Pervious Concrete Drainage Area	362	1
Pervious Concrete Pavement	139	0.1

Table 6-2 Watershed Runoff Model Variables

6.3 Reservoir Modeling

A reservoir stores flow from the watershed and releases it at a slower rate based on the method of outflow. For a porous pavement infiltration bed, the inflow is the runoff from the drainage area and the outflow is the infiltration into the subsoil as well as any overflow. For HEC-HMS to model the storage, infiltration, and overflow, several pieces of information must be provided. HEC-HMS requires that the user specify depth-storage, depth-infiltration, and depth-outflow curves for the reservoir. The depth-storage curve will simply be a function of the geometry and the porosity of the media used to fill the infiltration bed. The depth-infiltration curve will be a function of the subsoil infiltration rate. The depth-outflow curve will depend on the infiltration rate of the subsoil and the method of overflow utilized. The outflow will simply be the infiltration rate until large depths cause an overflow from the reservoir. If a weir is used, an outflow equation can be developed based on the weir geometry and incorporated into the depth-outflow curve. More information on these curves and calculations can be found in Chapter 2 of this paper.

A depth-storage curve for the project site is shown in Figure 6-2. The bed is a simple rectangular prism filled with uniformly graded stone (40% pore space). Therefore the storage is simply the surface area of the pavement multiplied by the depth and 40%.

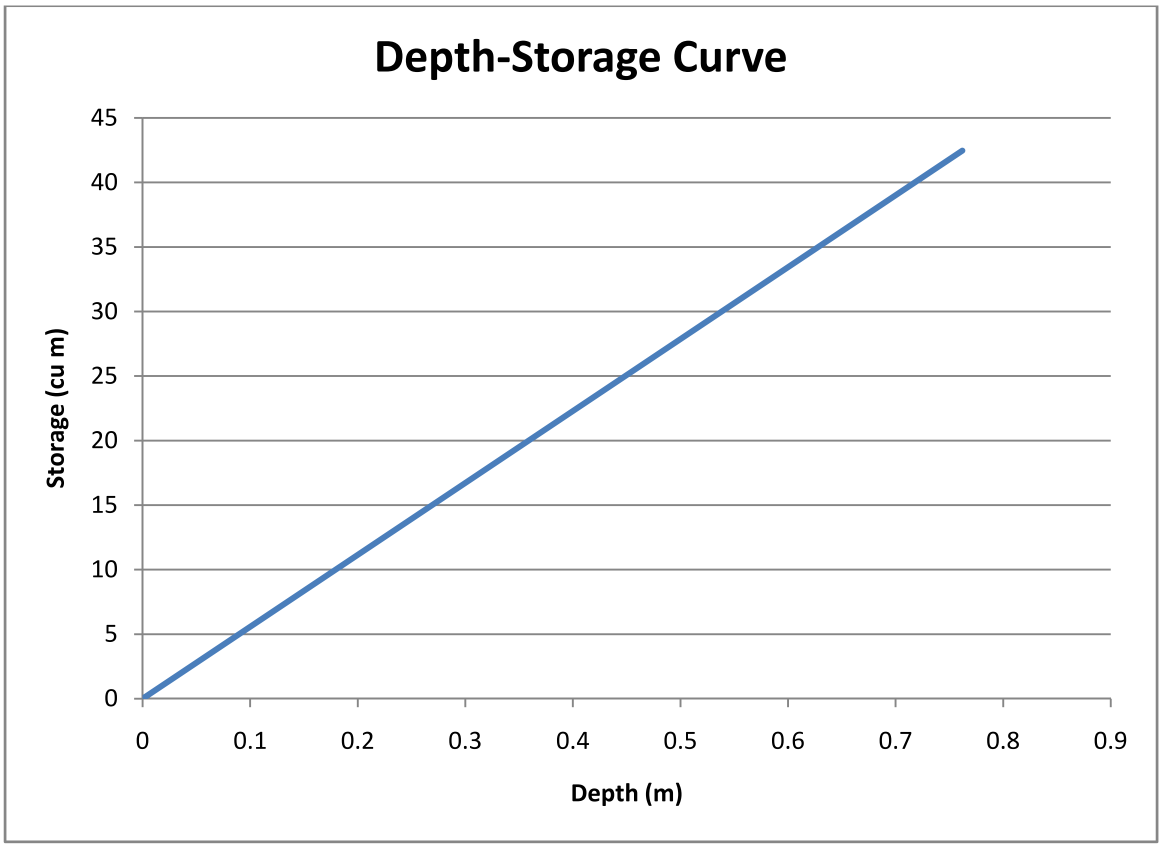

Figure 6-2 Depth-Storage Curve

A depth-infiltration curve for the project site is shown in Figure 6-3. The infiltration rate was assumed to be constant with respect to bed depth. A constant head infiltration test during site construction revealed very poor infiltration due to preexisting compaction during the sites life as a parking lot. Therefore, an infiltration rate of 0.7 mm/hr (0.03 in/hr) was used in modeling.

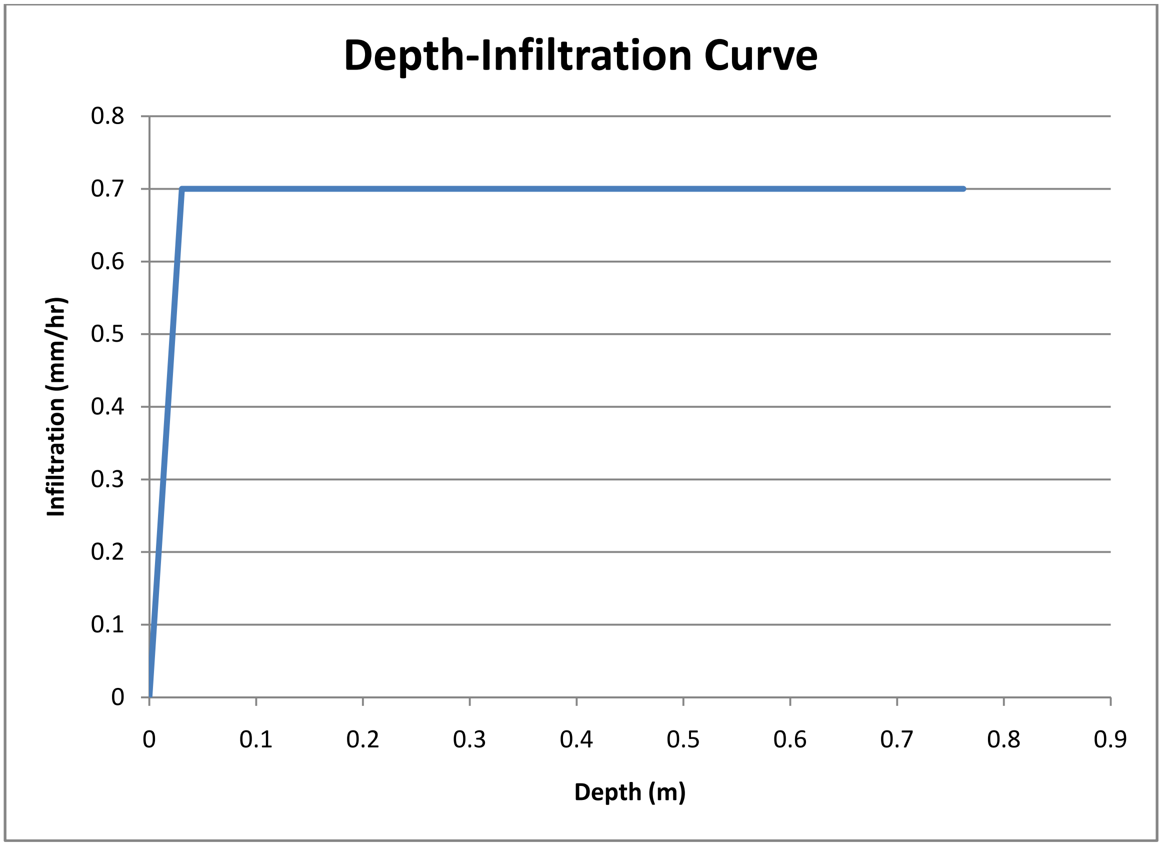

Figure 6-3 Depth-Infiltration Curve

A depth-outflow curve is shown in Figure 6-4. The outflow is simply the infiltration rate until the depth reaches the level of the overflow weir. Once the level reaches the overflow weir, the outflow will increase according the equation for the chosen weir. The weirs used in this project were v-notch weirs with a 60˚ angle. Therefore, the flow over them will be governed by the following equation (US Bureau of Reclamation 1997):

$$Q = 4.28\, C \tan\left(\frac{\theta}{2}\right)(h + k)^{5/2} \qquad \text{Eq. 6-1}$$

Where Q is the flow through the weir in cubic feet per second, C and k are coefficients that depend on the notch angle, θ, and h is the height of the water above the notch in feet. For a 60˚ notch angle C and k are 0.58 and 0.004, respectively (US Bureau of Reclamation 1997).

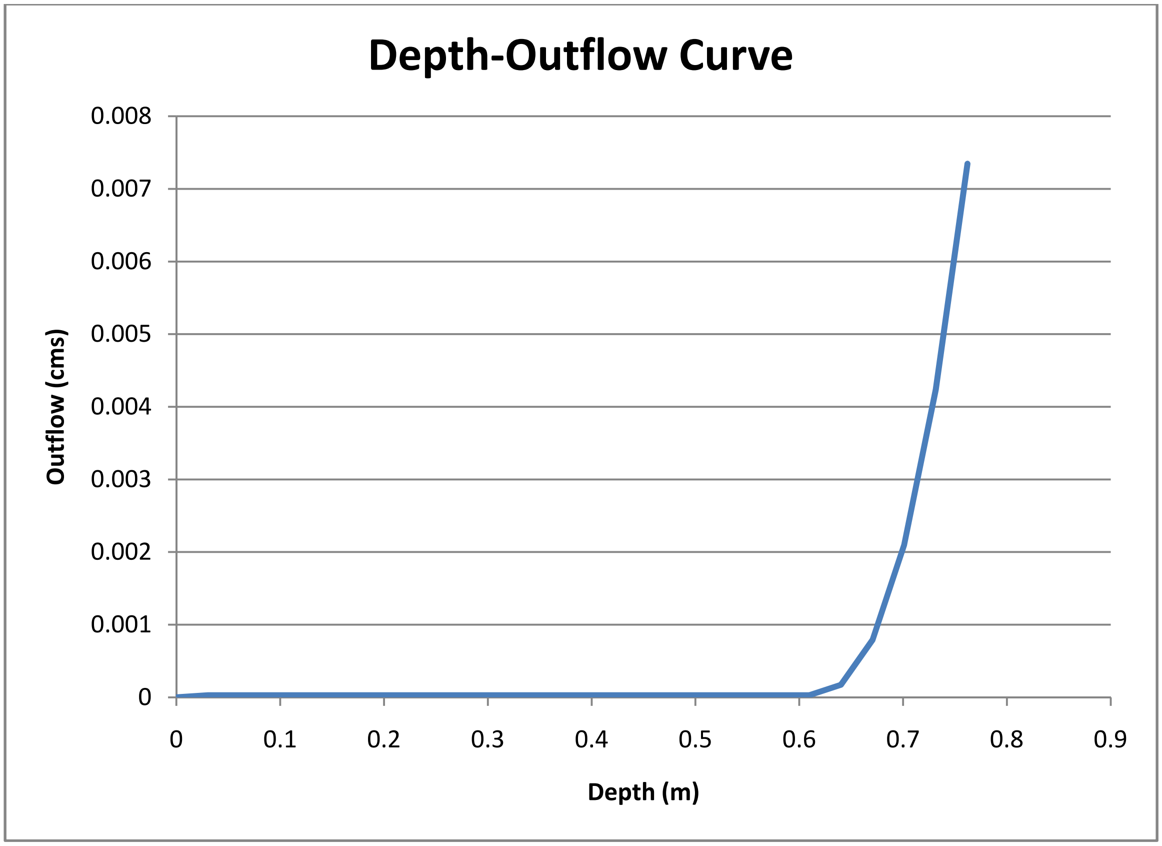

Figure 6-4 Depth-Outflow Curve

6.4 Calibration

Because many of the parameters used in HEC-HMS models are estimations of what is occurring in the physical watershed, calibration of HEC-HMS models are very important. Calibration requires the user to obtain observed rainfall and runoff values from the modeled watershed (US Army Corps of Engineers 2000). For an infiltration basin, this can include precipitation and bed depths for a series of storms. When creating a HEC-HMS model, the user should select estimates of the required parameters to create an initial simulation of runoff in the watershed. HEC-HMS will then compare the simulation to the actual data, and iterate on the input parameters until a simulation that most accurately reflects the actual data is obtained. More information on calibration in HEC-HMS can be found in Chapter 2 of this paper.

For the current project, a calibration has not been able to be done at this point. Several leaks in the overflow pipes have prevented the collection of infiltration data, which will be discussed in more depth in Chapter 7. A calibration will have to be postponed until all repairs have been made.

Chapter 7 Infiltration Results

The infiltration results for both the porous asphalt and pervious concrete infiltration beds were monitored and recorded to provide greater insight to the functioning of porous pavement infiltration beds. The infiltration rates were determined from the change in bed water level with time. Because a poor infiltration rate was obtained during the constant head infiltrometer testing, a poor infiltration rate was expected to be observed during storms. This was, however, not the case. Therefore several explorations into the functioning of the site were conducted, and several issues were identified.

7.1 Initial Infiltration

Following construction of the porous asphalt and pervious concrete infiltration beds, recording of the bed water level during storms began. Figure 7-1 illustrates the bed water level for both infiltration beds, as well as the predicted bed water level from HEC-HMS. For more information on the HEC-HMS model, see chapter 6 of this paper.

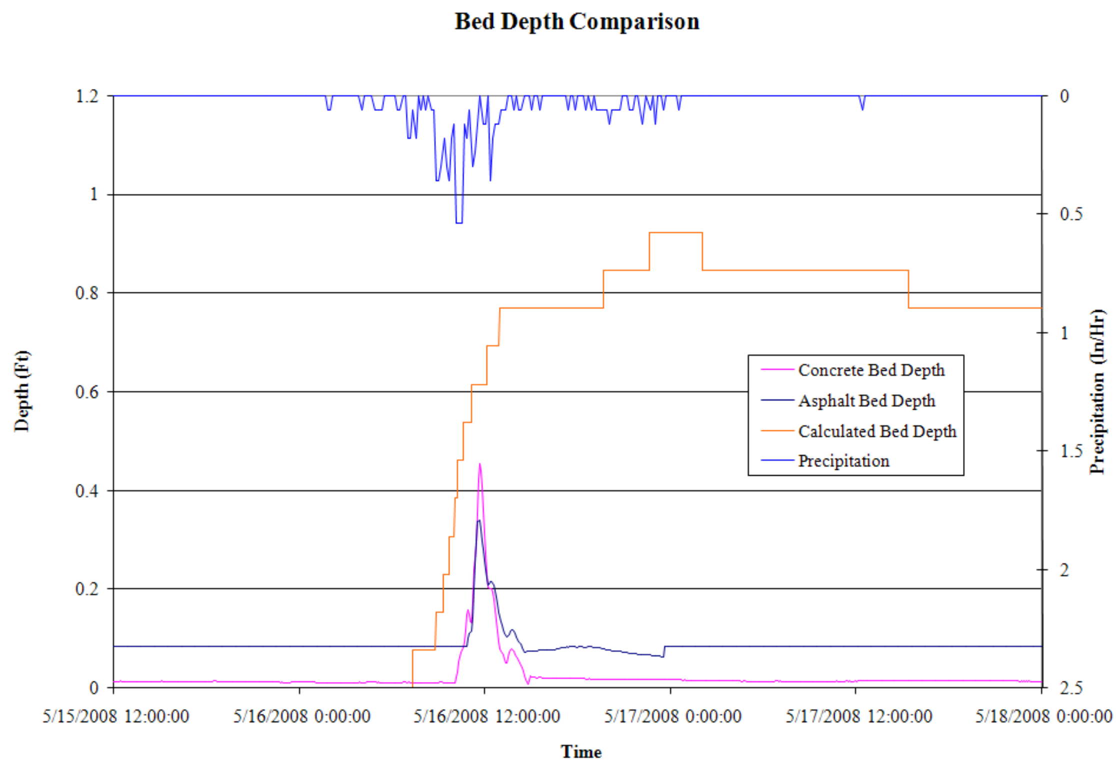

Figure 7-1 Initial Infiltration Graph

It is obvious from this graph that there is a discrepancy between the infiltration bed model and the actual results. This discrepancy arises because of a difference in the infiltration rate. While the model uses an infiltration rate of 0.7 mm/hr (0.03 in/hr), the actual results indicate an infiltration rate of 28.2 mm/hr (1.1 in/hr).

7.2 First Solution

As a result of the large difference between the modeled infiltration rate and the observed infiltration rate, several explorations were made into the functioning of the infiltration beds. These explorations led to the conclusion that water was exiting the infiltration bed via means other than infiltration. Somehow, water was bypassing the overflow weir and exiting via the overflow pipes. Several controlled experiments involving the observation of water flow through and around the infiltration beds revealed that water was flowing around the outside of the observation manholes and into the overflow pipe via a gap around the overflow pipe. This scenario is illustrated in Figure 7-2. The area around the observation manholes was then excavated and the gaps were filled with hydraulic cement. Figure 7-3 illustrates the infiltration performance of the beds following this solution.

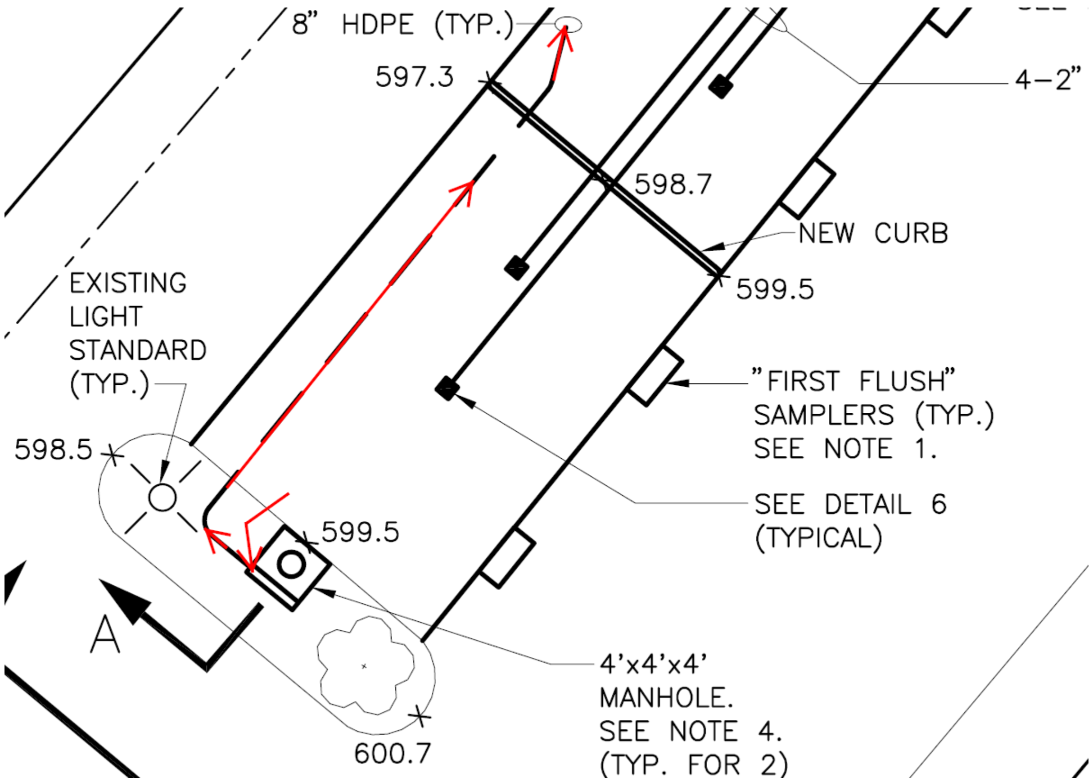

Figure 7-2 Flow of Water around Observation Manhole

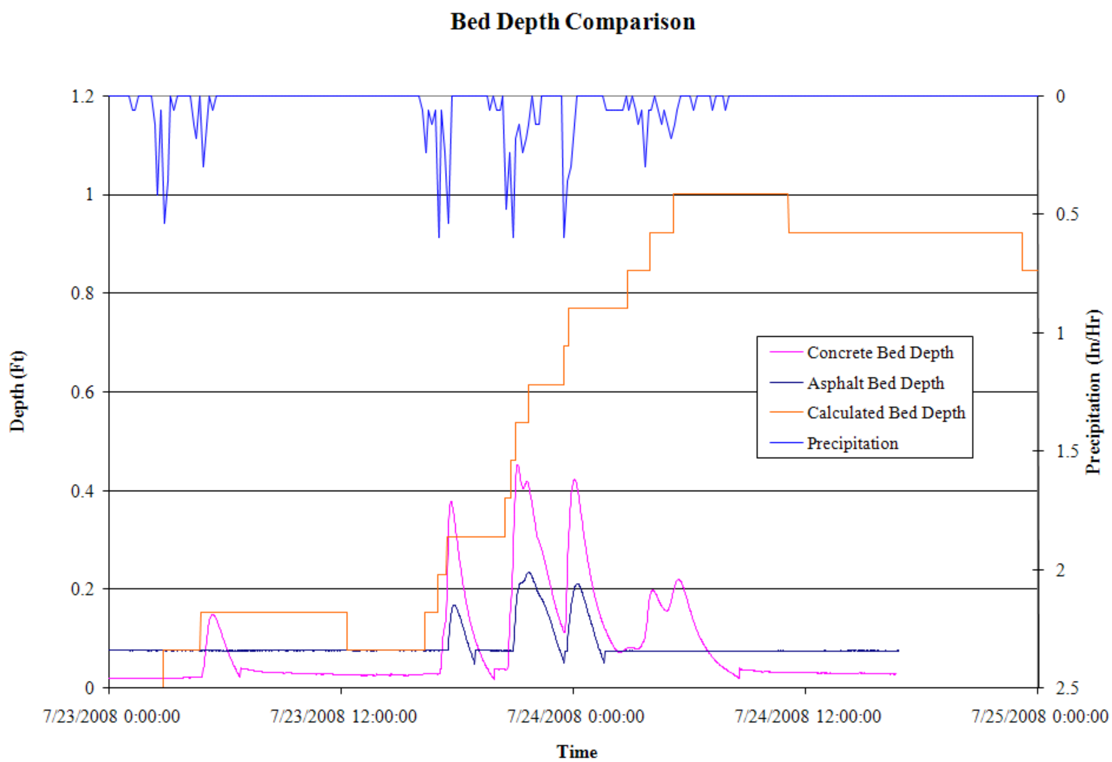

Figure 7-3 Infiltration Graph Following First Solution

Once again, it is clear that there is a discrepancy between the modeled infiltration rate and the observed infiltration rate. Eliminating the flow of water around the observation manholes slightly reduced the observed infiltration rate to 21.0 mm/hr (0.8 in/hr). However, this is still significantly greater than the infiltration rate that was expected based on soils testing. Additionally, Figure 7-3 illustrates that there is a greater problem on the porous asphalt side of the infiltration bed than on the pervious concrete side. This is evident because of the far lesser water levels achieved in the porous asphalt bed.

7.3 Second Solution

In order to determine the cause of the excessive infiltration rate, a pipe camera was utilized to track the flow of water in the overflow pipes. This study revealed a crack in the overflow pipe immediately beneath the jersey barrier used to separate the two infiltration beds.

This crack was likely formed when the jersey barrier was lowered into the bed, and allowed water from both beds to drain into the overflow pipe. It drained the porous asphalt bed more rapidly because there is a downhill gradient from the porous asphalt infiltration bed to the jersey barrier. This flow scenario is illustrated in Figure 7-4. To fix the crack, a small section of porous asphalt was removed and excavation was performed around the overflow pipe to make a patch. Figure 7-5 illustrates the infiltration performance of the beds following this solution.

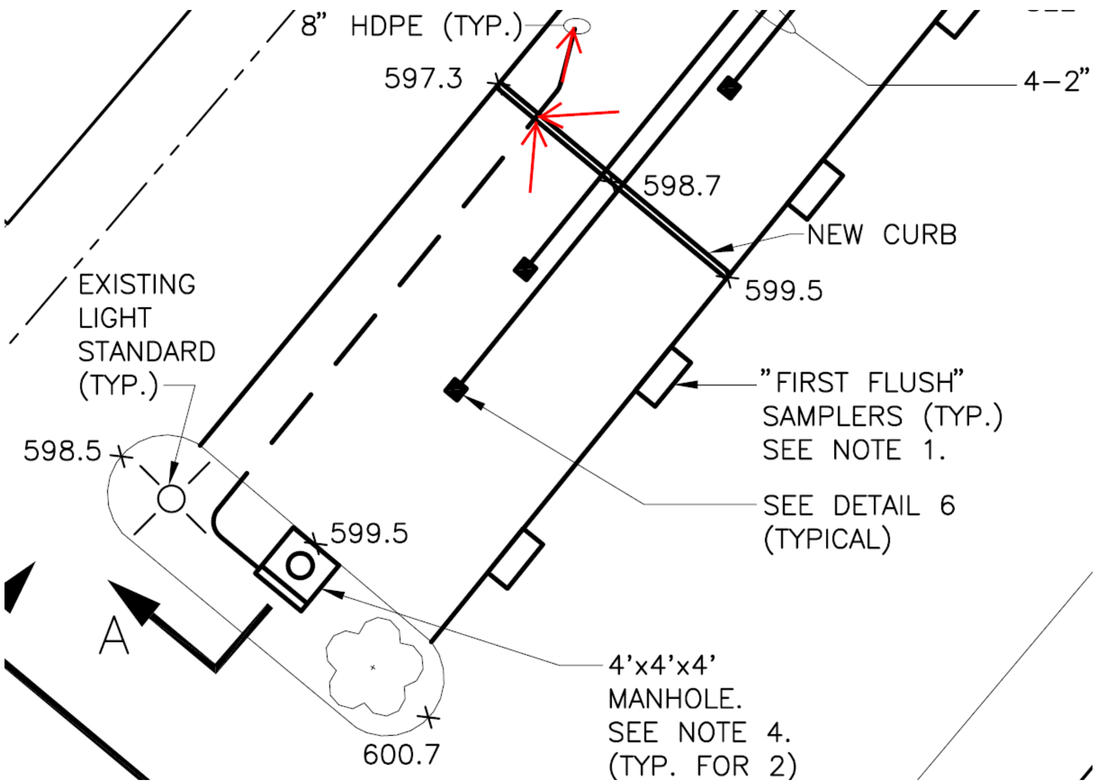

Figure 7-4 Flow of Water into Cracked Overflow Pipe

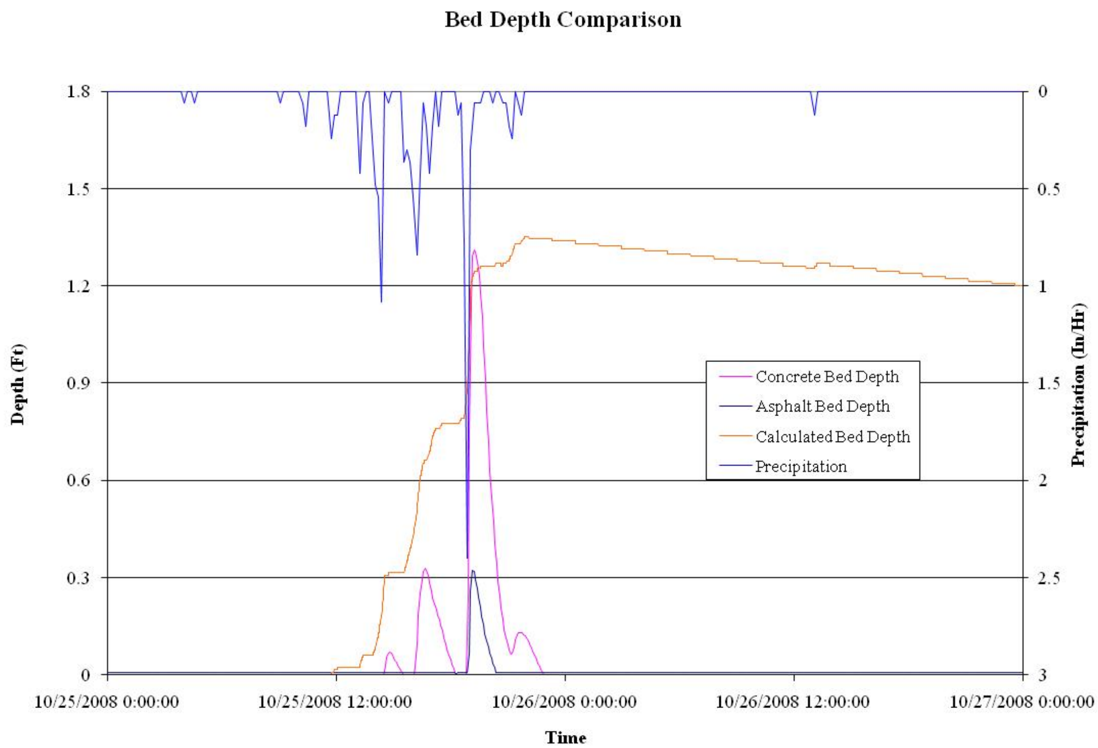

Figure 7-5 Infiltration Graph Following Second Solution

There is still a discrepancy in the infiltration rate shown by the beds and the infiltration rate used in the model. This storm showed an infiltration rate of 26.6 mm/hr (1.1 in/hr). The concrete bed reached a maximum depth equal to that predicted by the model; however the asphalt bed was significantly less deep. These issues show yet another challenge to overcome in the infiltration beds.

7.4 Third Solution

During excavation for repairing the leak beneath the jersey barrier, it was evident that the joints between the sections of drainage pipe were not sealed properly. This results in water draining from the beds into the overflow pipes. This is more pronounced on the asphalt side because there is significantly more pipe running along the bed on the asphalt side. In November 2008 overflow pipes were completely filled with grout, eliminating their functionality at the project site. This has eliminated the possibility of leaks into the overflow pipes, and should ensure more accurate infiltration results. In order to provide overflow from the infiltration beds, a pump has been placed in each of the observation manholes. Any water that passes through the overflow weir is pumped out of the manhole and diverted towards the existing stormwater system. Figure 7-6 illustrates the infiltration performance of the beds following this solution.

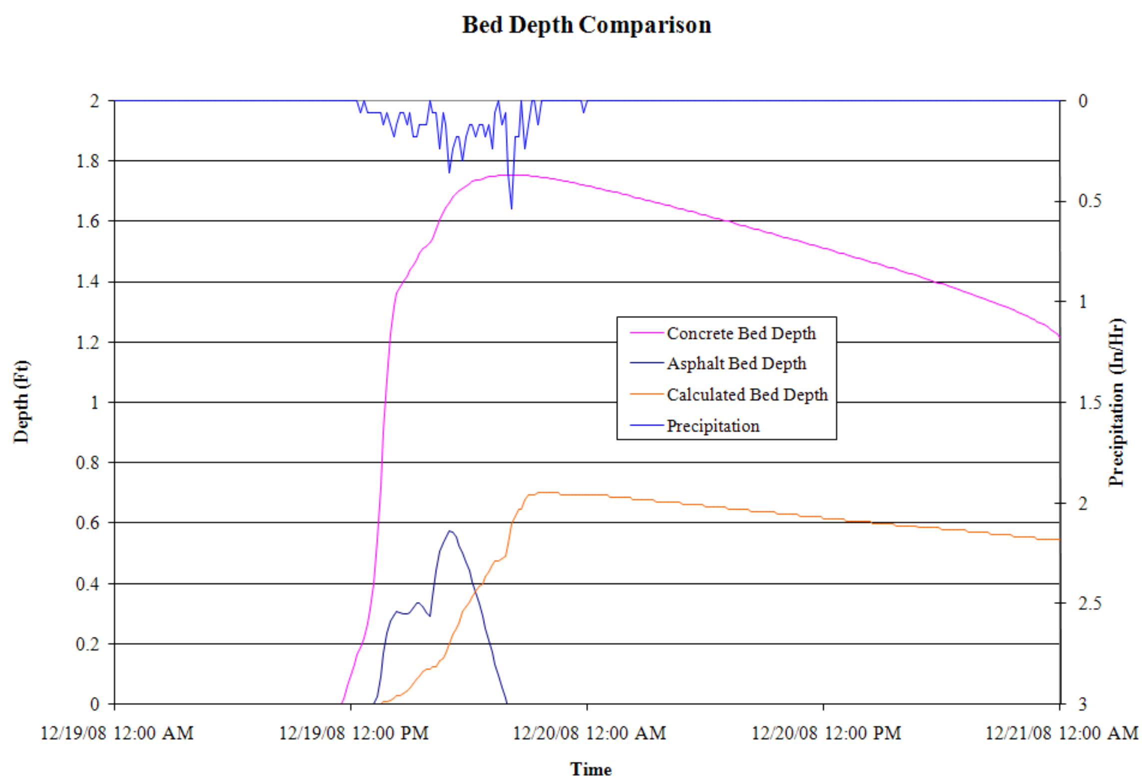

Figure 7-6 Infiltration Graph Following Third Solution

Figure 7-6 shows that the infiltration rate for the concrete bed closely matches the expected rate. The concrete bed infiltrates at a rate of 2.0 mm/hr (0.08 in/hr). However, the asphalt bed drains much more quickly than is expected. This is likely explained by a leak around the jersey barrier from the higher asphalt bed into the lower concrete bed. This would also explain the much greater depth of water achieved in the concrete bed than would have been expected. It has been determined that this repair would be too expensive, and infiltration rates will only be measured on the concrete side.

Chapter 8 Conclusions

This section attempts to highlight some of the differences between porous asphalt and pervious concrete, as were seen in this study. These differences are broken down into a number of categories: design, construction, maintenance and durability, and quantity performance.

8.1 Design

The design of porous pavement BMPs requires attention to both the infiltration bed and the pavement. However, the infiltration bed design will be the same for both porous asphalt and pervious concrete. Chapter 2 of this document provides detailed analysis of infiltration bed design.

Design of the surface pavement must ensure proper strength and infiltration capacity. These factors are controlled by the thickness and the mix design of the porous pavement. For guidance on specifying a proper asphalt or concrete pavement thickness the American Association of State Highway and Transportation Officials (AASHTO) offers a “Guide for Design of Pavement Structures” document (1993).

Mix designs can be an extensive process involving many mix preparations and subsequent testing. Porous asphalt mix design focuses on several key parameters: the aggregate gradation, the binder content, the binder grade, and the presence of additives such as fibers. Adjusting these parameters will affect the strength, durability, and infiltration capacity of the asphalt. Pervious concrete mix design is based upon aggregate gradation, cement content, water content, and the addition of admixtures. Likewise, adjusting these parameters affects the strength, durability, and infiltration capacity of the concrete. The easiest way to choose a mix design for a project is to contact local industry representatives or experienced design consultants for their experience with mixes suitable for a given locale. For the current project the National Ready Mix Concrete Association (NRMCA) provided concrete mix design and thickness specifications and Cahill Associates provided asphalt mix design and thickness specifications.

8.2 Construction

The construction of both the porous asphalt and pervious concrete parking areas began in the same manner, demolition of the existing pavement and excavation and creation of the stone infiltration bed. The only differences came in the installation of the pavements themselves. It should be noted that paving was conducted by qualified installers, as is recommended for porous pavement installations.

Paving the porous asphalt side required a five person crew, one five hour day, and conventional asphalt paving equipment. This process involved using an asphalt paver to spread the asphalt, hand spreading to spread the asphalt in corners and tight areas, and mechanically rolling the surface to provide a smooth finished surface. Pouring the pervious concrete required a six person crew, two four hour days, and an array of equipment. This process involved the setting up of forms, pouring the concrete from a truck, spreading the concrete with hand tools, and finishing the surface with a roller screed.

8.3 Maintenance & Durability

Maintenance requirements for porous pavements include following proper landscaping guidelines, vacuum sweeping, pressure washing, and proper snow removal practices. These maintenance activities are largely the same for both types of porous pavement, and are summarized below:

- Landscaped areas should be separated from porous pavements to prevent sediment laden runoff from clogging the pavement
- Vacuum sweeping and/or pressure washing should be used to maintain porosity of porous pavements at regular intervals or as needed
- Snow removal can be accomplished by two methods
    - Plowing with the plow raised approximately 25 mm (1 inch) to prevent damage to the pavement
    - Salting (note concrete should not be salted in the first year to avoid corrosion problems)

The current study utilized proper landscaping, vacuum sweeping, and snow plowing to maintain the porous parking lot for its first year of use. Only one vacuum sweeping was required in the first year. This vacuum sweeping resulted in 30 to 50% increases in infiltration capacity for areas that were in good condition prior to sweeping, and at least a 1200% infiltration capacity increase for areas in poor condition.

Both the porous asphalt and pervious concrete used in the current study proved durable for use in a parking lot over the first year. The asphalt suffered some minor depressions where large loads were experienced. Both pavements showed some minor loss of material, oil stains, plow scrape marks, and minor clogging after a year of use. More information on these issues can be found in Chapter 5 of this study.

With regards to public opinion about the porous pavement parking lot, the majority of users did not notice a difference between the porous parking and conventional parking areas. Neither did the majority of users have a preference between asphalt or concrete pavements.

However, 75% of those surveyed had a positive opinion of the porous pavements. This was largely attributed to the environmental benefits of the pavements.

8.4 Quantity Performance

As discussed in Chapter 7 of this study, the infiltration beds beneath both porous pavements continue to leak into the outlet pipes. Therefore, no conclusions can be made regarding the infiltration rates of the systems. However, the drainage tests on the pavements discussed in Chapter 5 provide insights into the infiltration rates of the porous asphalt and pervious concrete surface layers. Overall, the pervious concrete used in this project tends to have greater infiltration rates than the porous asphalt used. Additionally, the porous asphalt lost a greater percentage of its infiltration capacity over the first year than the pervious concrete. This is likely a result of the greater pore space that is available in the pervious concrete mix. However, it should be noted that the infiltration rates of the pavements are well in excess of local precipitation potential.

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Appendices

PCPA Site Soil Analysis

Soil: PC3

Total Mass (g): 500
Mass > #200 (g): 102.16

Sieve Size	Mass Retained	Percent Passing
mm	g	%
4.75	1.21	99.76
2	6.47	98.46
0.85	11.35	96.19
0.25	29.16	90.36
0.106	26.74	85.01
0.075	13.95	82.22
0.029	Hydrometer	64.69
0.020	Hydrometer	47.53
0.016	Hydrometer	42.25
0.012	Hydrometer	19.80
0.010	Hydrometer	2.64
0.007	Hydrometer	2.64
0.005	Hydrometer	2.64
0.002	Hydrometer	1.85

F200	82.224
R4/R200	0.01
D60	0.025
D10	0.012
D30	0.015
Cu	2.08
Cz	0.75
LL	34.40
PL	24.60
USCS	ML - Silt with sand

Soil: PC4

Total Mass (g): 500
Mass > #200 (g): 114.41

Sieve Size	Mass Retained	Percent Passing
mm	g	%
4.75	8.11	98.38
2	6.56	97.07
0.85	12.40	94.59
0.25	27.78	89.03
0.106	23.56	84.32
0.075	12.64	81.79
0.029	Hydrometer	60.43
0.020	Hydrometer	44.67
0.017	Hydrometer	31.53
0.013	Hydrometer	5.26
0.010	Hydrometer	2.63
0.007	Hydrometer	2.63
0.005	Hydrometer	2.63
0.002	Hydrometer	1.84

F200	81.79
R4/R200	0.09
D60	0.03
D10	0.015
D30	0.018
Cu	2.00
Cz	0.72
LL	
PL	
USCS	

Soil: PA3

Total Mass (g): 500
Mass > #200 (g): 107.68

Sieve Size	Mass Retained	Percent Passing
mm	g	%
4.75	4.50	99.10
2	7.85	97.53
0.85	14.86	94.56
0.25	29.50	88.66
0.106	24.37	83.78
0.075	12.85	81.21
0.029	Hydrometer	61.29
0.020	Hydrometer	48.25
0.016	Hydrometer	37.82
0.013	Hydrometer	13.04
0.010	Hydrometer	2.61
0.007	Hydrometer	2.61
0.005	Hydrometer	2.61
0.002	Hydrometer	1.83

F200	81.214
R4/R200	0.05
D60	0.03
D10	0.013
D30	0.016
Cu	2.31
Cz	0.66
LL	
PL	
USCS	

Grain Size Analysis - Hydrometer Method

Project: PAPC *Sample ID:* PC3 *Sample Depth:* 3 ft *Test Date:* 4/29/2008 *Tested By:* PAJ

Hydrometer Type: 151H *Gs of Soil:* 2.65 *Percent Finer (%):* 82.2 *Agent:* 4% NaPO3
Zero Correction: 4 *Mass of Soil (g) :* 50 *Control Sieve #:* 200 *Amount (ml):* 125

Date	*Time*	*Elapsed Time*	*Temp*	*Ra*	*Rc*	*% Finer*	*Rm*	*L*	*L/t*	*K*	*D*
		min	*C*			*%*					*mm*
29-Apr	1:00	0									
	1:02	2	20	28.5	24.5	64.7	28.5	8.76	4.38	0.0136	0.029
	1:05	5	20	22.0	18	47.5	22.0	10.48	2.10	0.0136	0.020
	1:08	8	20	20.0	16	42.2	20.0	11.01	1.38	0.0136	0.016
	1:16	16	20	11.5	7.5	19.8	11.5	13.25	0.83	0.0136	0.012
	1:30	30	20	5.0	1	2.6	5.0	14.97	0.50	0.0136	0.010
	2:00	60	20	5.0	1	2.6	5.0	14.97	0.25	0.0136	0.007
	3:15	135	20	5.0	1	2.6	5.0	14.97	0.11	0.0136	0.005
30-Apr	10:00	1260	19	5.0	0.7	1.8	5.0	14.97	0.01	0.0138	0.002

Grain Size Analysis - Hydrometer Method

Project: PAPC *Sample ID:* PC4 *Sample Depth:* 3 ft *Test Date:* 4/29/2008 *Tested By:* PAJ

Hydrometer Type: 151H *Gs of Soil:* 2.65 *Percent Finer (%):* 81.8 *Agent:* 4% NaPO3
Zero Correction: 4 *Mass of Soil (g) :* 50 *Control Sieve #:* 200 *Amount (ml):* 125

Date	*Time*	*Elapsed Time*	*Temp*	*Ra*	*Rc*	*% Finer*	*Rm*	*L*	*L/t*	*K*	*D*
		min	*C*			*%*					*mm*
29-Apr	1:00	0									
	1:02	2	20	27.0	23.0	60.4	27.0	9.15	4.58	0.0136	0.029
	1:05	5	20	21.0	17.0	44.7	21.0	10.74	2.15	0.0136	0.020
	1:08	8	20	16.0	12.0	31.5	16.0	12.06	1.51	0.0136	0.017
	1:16	16	20	6.0	2.0	5.3	6.0	14.71	0.92	0.0136	0.013
	1:30	30	20	5.0	1.0	2.6	5.0	14.97	0.50	0.0136	0.010
	2:00	60	20	5.0	1.0	2.6	5.0	14.97	0.25	0.0136	0.007
	3:15	135	20	5.0	1.0	2.6	5.0	14.97	0.11	0.0136	0.005
30-Apr	10:00	1260	19	5.0	0.7	1.8	5.0	14.97	0.01	0.0138	0.002

Grain Size Analysis - Hydrometer Method

Project: PAPC *Sample ID:* PA3 *Sample Depth:* 3 ft *Test Date:* 4/29/2008 *Tested By:* PAJ

Hydrometer Type: 151H *Gs of Soil:* 2.65 *Percent Finer (%):* 81.2 *Agent:* 4% NaPO3
Zero Correction: 4 *Mass of Soil (g) :* 50 *Control Sieve #:* 200 *Amount (ml):* 125

Date	*Time*	*Elapsed Time*	*Temp*	*Ra*	*Rc*	*% Finer*	*Rm*	*L*	*L/t*	*K*	*D*
		min	*C*			*%*					*mm*
29-Apr	1:00	0									
	1:02	2	20	27.5	23.5	61.3	27.5	9.02	4.51	0.0136	0.029
	1:05	5	20	22.5	18.5	48.3	22.5	10.34	2.07	0.0136	0.020
	1:08	8	20	18.5	14.5	37.8	18.5	11.40	1.43	0.0136	0.016
	1:16	16	20	9.0	5.0	13.0	9.0	13.91	0.87	0.0136	0.013
	1:30	30	20	5.0	1.0	2.6	5.0	14.97	0.50	0.0136	0.010
	2:00	60	20	5.0	1.0	2.6	5.0	14.97	0.25	0.0136	0.007
	3:15	135	20	5.0	1.0	2.6	5.0	14.97	0.11	0.0136	0.005
30-Apr	10:00	1260	19	5.0	0.7	1.8	5.0	14.97	0.01	0.0138	0.002

Site Observation Report

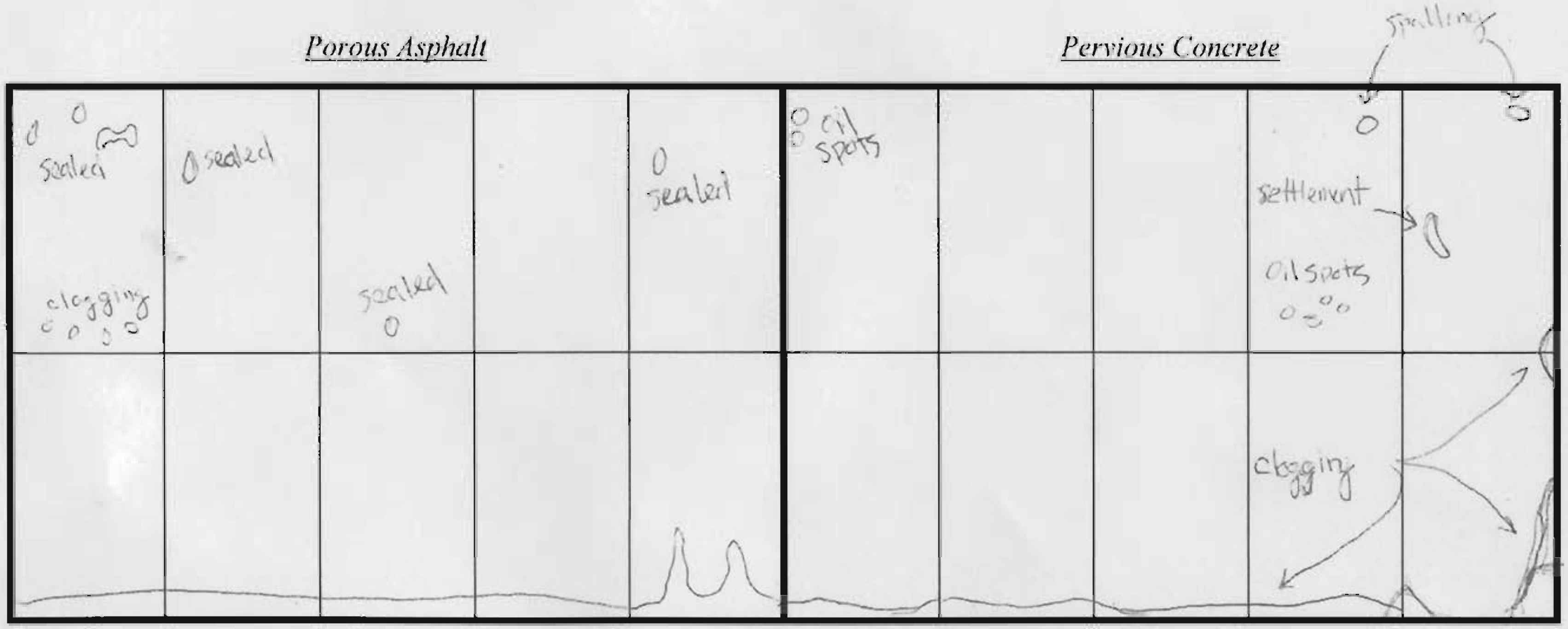
Date: 2/16/2008

Observer(s) Pat Jeffers & James Barbis

Procedure: 5 gpm from hose for check

Walk around site with a hose and note on the drawing below any locations where clogging, sealing, ponding, icing, spalling, or any other features of interest are observed. Attach site pictures.

Porous Asphalt *Pervious Concrete*



Mendel Hall

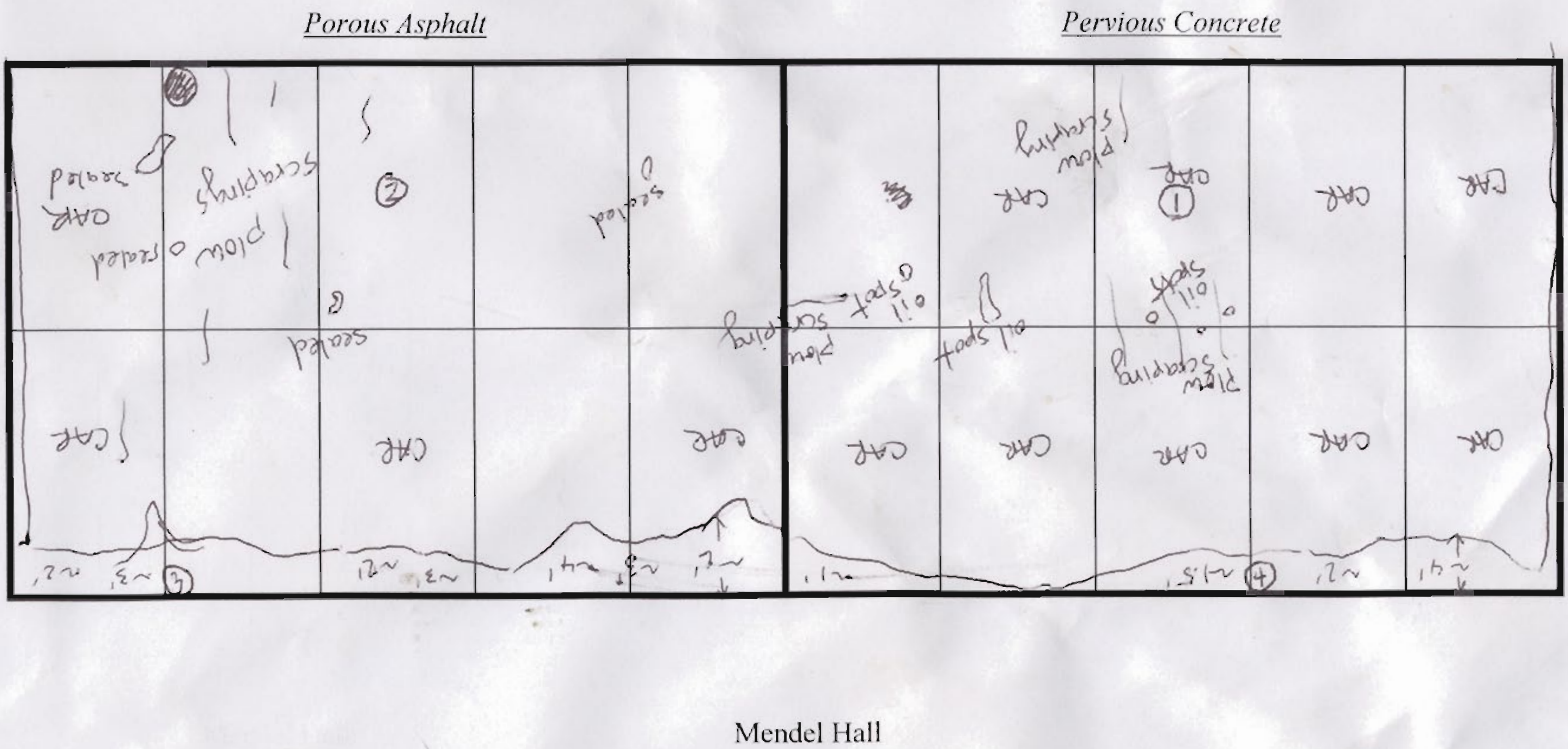
↓

Site Observation Report

Date: 5/13/08 Observer(s) JB, PJ

Procedure:

Walk around site with a hose and note on the drawing below any locations where clogging, sealing, ponding, icing, spalling, or any other features of interest are observed. Attach site pictures.



Drain Time Tests (6 seconds free drain)

① 8 seconds

② 16 seconds (dry)
16 seconds (wet)

③ 60 seconds (dry)
40 seconds (wet)

④ 13 seconds (dry)
13 seconds (wet)

Site Observation Report

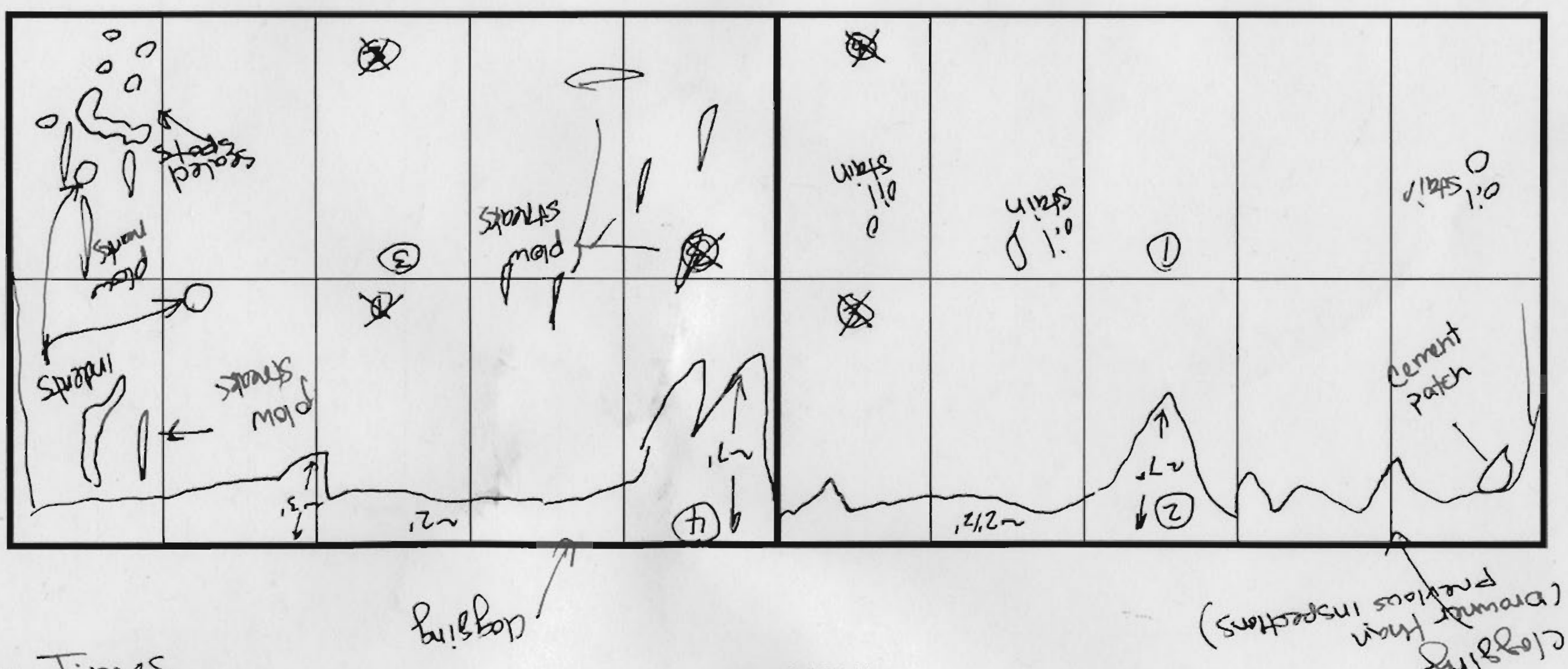
Date: 6/5/2008

Observer(s) Pat Jeffres & James Barbis

Procedure:

Walk around site with a hose and note on the drawing below any locations where clogging, sealing, ponding, icing, spalling, or any other features of interest are observed. Attach site pictures.

Porous Asphalt *Pervious Concrete*



Mendel Hall

↓

Drain Times

1. good concrete 0:26:46
2. bad concrete 1:46:81
3. good asphalt not wet 0:45:67 wet 0:48:84
4. bad asphalt not wet 4:30:30 wet 3:02:99

no pavement 0:5:50

reg. asphalt 4:29:15

Site Observation Report

Date: 11/17/08 Observer(s) Pat Jeffers & James Barbis

Procedure:

Walk around site with a hose and note on the drawing below any locations where clogging, sealing, ponding, icing, spalling, or any other features of interest are observed. Attach site pictures.

Porous Asphalt *Pervious Concrete*

O—control

Mendel Hall

↓

C.C - 1:02 min
UCC - 20.74 sec
CA - 1:20 min
UCA - 42 sec
control - 6:45 min

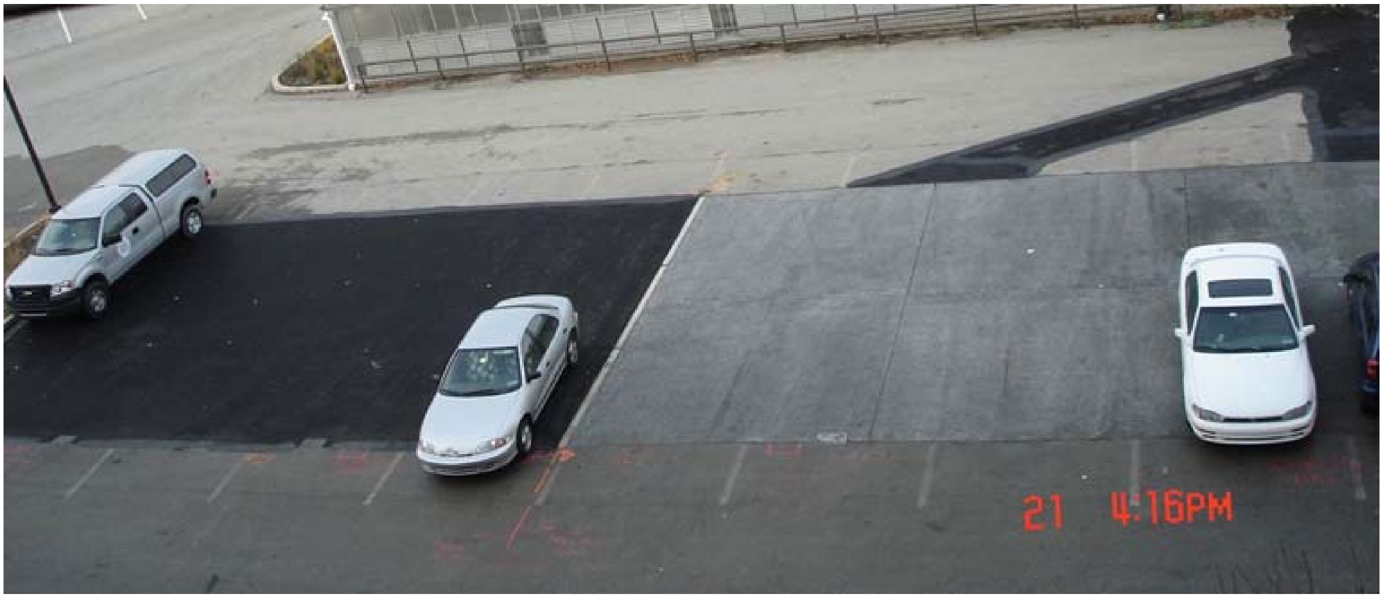
Appendix C

Mendel Parking Survey

Exit this survey

Thank you for agreeing to take this brief survey. Your assistance is helping to support research at Villanova University. Please answer the following questions to the best of your ability.

The porous parking area referred to in this survey is pictured here. It is the area between the Greenhouse and Mendel Hall. There is a concrete section (gray colored) and an asphalt section (black colored).



1. How often do you park on the recently constructed porous pavements?

Never
1-2 times per month
3-5 times per month
More than 5 times per month

2. How do you feel about the appearance of the porous parking area? Provide comments if possible.

More aesthetic than regular parking lots
The same as regular parking lots
Less aesthetic than regular parking lots
No observation
Comments

3. Have you noticed a difference in the amount of snow/ice on the porous pavements compared regular parking areas?

Less snow on porous area
Same amount of snow on porous area
More snow on porous area

No observation

4. Have you noticed a difference in the traction on the porous pavements compared to regular parking areas?

More traction on porous area
Same traction on porous area
Less traction on porous area
No observation

5. Have you experienced any difficulties with the roughness of the porous parking area? If so, please explain.

No
Yes
Comments

6. What is your general opinion of the porous parking lot? Provide comments if possible.

Positive
Neutral
Negative
Comments

7. Do you prefer one of the types of porous pavement over the other?

I prefer the porous asphalt (black pavement in picture)
I prefer the pervious concrete (gray pavement in picture)
I have no preference
Please Explain If Possible...

Done

Response Summary

Total Started Survey: 22

Total Completed Survey: 22 (100%)

Page: Mendel Parking Survey

1. How often do you park on the recently constructed porous pavements?

	Response Percent	Response Count
Never	**36.4%**	8
1-2 times per month	18.2%	4
3-5 times per month	18.2%	4
More than 5 times per month	27.3%	6
	answered question	**22**
	skipped question	**0**

2. How do you feel about the appearance of the porous parking area? Provide comments if possible.

	Response Percent	Response Count
More aesthetic than regular parking lots	13.6%	3
The same as regular parking lots	**54.5%**	12
Less aesthetic than regular parking lots	18.2%	4
No observation	13.6%	3
	answered question	**22**
	skipped question	**0**

2. How do you feel about the appearance of the porous parking area? Provide comments if possible.

Comments view	7
answered question	**22**
skipped question	**0**

3. Have you noticed a difference in the amount of snow/ice on the porous pavements compared regular parking areas?

	Response Percent	Response Count
Less snow on porous area	4.8%	1
Same amount of snow on porous area	4.8%	1
More snow on porous area	0.0%	0
No observation	**90.5%**	19
answered question		**21**
skipped question		**1**

4. Have you noticed a difference in the traction on the porous pavements compared to regular parking areas?

	Response Percent	Response Count
More traction on porous area	23.8%	5
Same traction on porous area	14.3%	3
Less traction on porous area	0.0%	0
No observation	**61.9%**	13
answered question		**21**
skipped question		**1**

5. Have you experienced any difficulties with the roughness of the porous parking area? If so, please explain.

	Response Percent	Response Count
answered question		**21**
skipped question		**1**

5. Have you experienced any difficulties with the roughness of the porous parking area? If so, please explain.

No		**100.0%**	21
Yes		0.0%	0
		Comments view	1
		answered question	**21**
		skipped question	**1**

6. What is your general opinion of the porous parking lot? Provide comments if possible.

		Response Percent	Response Count
Positive		**72.7%**	16
Neutral		27.3%	6
Negative		0.0%	0
		Comments view	7
		answered question	**22**
		skipped question	**0**

7. Do you prefer one of the types of porous pavement over the other?

		Response Percent	Response Count
I prefer the porous asphalt (black pavement in picture)		18.2%	4
I prefer the pervious concrete (gray pavement in picture)		22.7%	5
I have no preference		**59.1%**	13
		Please Explain If Possible... view	7
		answered question	**22**
		skipped question	**0**

