# Choosing Permeable Pavement Design to Maximize Stormwater Management Capabilities

Elizabeth Shaloka

Source: http://blog.petersoncompanies.net/how-do-permeable-pavers-work

Honors Technical Communication ENGR 2996 Sec. 001

December 10, 2017

# Abstract

The goal of this project proposal is to compare current permeable pavement designs, and suggest the best design to limit pollution due to stormwater runoff from impervious surfaces. Permeable pavements are pavements with increased pore space for water to pass through. There are three considered pavement types: porous asphalt, porous concrete, and permeable interlocking concrete pavers. The specific focus is to analyze the impact of material choice on the success of the pavement. The first priority is optimizing permeability by comparing hydrological properties of each pavement design including porosity, flow rate, and hydraulic conductivity. Other parameters investigated affect feasibility of the design such as compressive strength, cost, storage capacity, and reparability. The assessment is based on the results of research studies and recommendations in construction manuals. The best pavement design utilizes porous concrete. Porous concrete has higher permeability, the main requirement for success in limiting runoff. Porous concrete also boasts reasonable cost, structural integrity, and reparability. A successful porous concrete pavement would lead to improved water quality in streams, decreased erosion of stream banks, and a decreased need for additional costly wastewater management structures. Most importantly, success would lead to long term cost benefits and public and environmental health improvements.

Keywords: permeable pavement, porous asphalt, PA, porous concrete, PC, permeable interlocking concrete pavers, PICP, stormwater management, runoff

*Document Scenario: This document proposes the use of porous concrete pavements, specifically in urban parking lots. I ultimately envision many small scale permeable pavement projects taken on by multiple organizations. The Executive summary is therefore meant to be read by company owners, and local government officials of a proposed urban community.*

# Executive Summary

This project seeks to limit the amount of pollutants that reach streams due to runoff from impervious surfaces. Landcover in urban areas is largely impervious, which contributes to reduced water quality, reduced amounts of suitable habitats for wildlife, increased flood risks, and other issues of major concern. The challenge is to reduce pollution in urban areas to comply with standards set by the Clean Water Act. This project aims to meet the challenge by rerouting the runoff from impervious areas such as parking lots and sidewalks so that it filters naturally through soil instead of polluting streams.

This project aims to achieve these goals by supporting the implementation of permeable pavement. Permeable pavement would decrease the amount of impervious land cover, while still providing the functions of traditional impervious pavements. Design constraints are primarily based on cost and location feasibility, as well as balancing the optimization of permeability and compressive strength. The permeability, which allows for pollution reduction, opposes compressive strength and cost, so a reasonable balance must be found for project success. Other main constraints deal with maintenance requirements to ensure pavement longevity, and lasting project success.

It is proposed that the best permeable pavement design is porous concrete. It has the potential for high permeability, and therefore a good potential to reduce runoff. While optimizing permeability can mean cutting corners in areas such as compressive strength and cost, porous concrete has reasonable projected costs and compressive strengths. Porous concrete is also long lasting and able to be maintained, so the benefits of the porous concrete can continue to be reaped for several years after initial installation. Porous concrete is feasible in small scale projects in urban environments.

The biggest threat to project success is a lack of education. Porous concrete pavement has unique and complex design, installation, and maintenance requirements that determine pavement success. If the concrete is not created using recommended procedures, it is likely that the pavement will be defective and will not have the same capabilities as the initial design. It is paramount that all parties involved in the project be fully educated on specific requirements for porous concrete pavement for project success. Public and private communities will benefit from successful installation of concrete permeable pavement. The owners of a parking lot fitted with permeable pavement will immediately benefit by gaining three points towards LEED® certification. The main immediate benefit to project sponsors is the positive publicity, and possible business gained through support and respect of their environmental consideration. Porous concrete installation would result in numerous environmental benefits including the reduction of pollution in surface water due to runoff, and the reduction of the volume of runoff. These environmental benefits are necessary to improve the health of streams, and water quality. Ultimately, this will benefit the general public by providing them with cleaner water, an opportunity for education in stormwater management, increased job opportunities, and increased safety. For these reasons, it is beneficial to private and public entities to pursue the project.

# Contents

## List of Tables

## List of Figures

## List of Equations

## List of Abbreviations

BMP – Best Management Practice

EPA – Environmental Protection Agency

ICPI – Interlocking Concrete Pavement Institute

LEED® – Leadership in Energy and Environmental Design

PA – Porous Asphalt

PC – Porous Concrete

PICP – Permeable Interlocking Concrete Pavers

PWSR – Philadelphia Water Stormwater Plan Review

SWMM – Stormwater Management Model

USACE – U.S. Army Corps of Engineers

# Problem Analysis

This project is a proposal to limit non-point source pollution that affects stream ecosystems, and the quality of life in surrounding communities. This project is beneficial to all parties involved, as it improves overall quality of life and environmental health.

## Overview of problem and its significance

Pollution, specifically due to runoff from impervious surfaces including streets, pavements, roofs, and parking lots, is a detriment to the health of urban streams. A study in Northeastern Kansas found that water quality changed dramatically due to runoff during storm events as the bacteria density recorded for the indicator bacteria E. coli "increased from 180 colonies per 100 milliliters of water to about 100,000 col/100mL during a 12-hour period." (Rasmussen, Johnson County Stormwater Management Program, & U.S. Geological Survey, 2008). This pollution has multiple negative impacts on water quality and the health of stream ecosystems. In urban areas, stormwater runs off without the possibility of filtration through vegetation. Because of this, rainwater empties into streams at higher velocities, eroding the riverbanks. The increased velocity of water can even cause flooding. Thermal Pollution from water running over streets also affects the organisms living in the stream. Urbanization is associated with loss of vegetation, increased pollution, increased dirt and sediment production, and increased runoff among other issues (Kibler, 1982 & Urban Runoff Population Prevention and Control Planning, 1993). However, decreasing runoff in urban areas is difficult because impervious surfaces that lead to runoff are necessary for transportation, housing and other purposes. This problem, if not addressed, will continue to cause safety issues, and bring harm to the environment.

### Engineering fundamentals of problem

Evaluation of the success of permeable pavement for stormwater management depends on several factors. Hydraulic Conductivity, which is directly related to porosity according to Montes and Haselbach, is a major factor in determining success (2006). The hydraulic conductivity ($K_{Sat}$) can be predicted through the Carman-Kozeny equation:

$$K_s = \frac{gC_o}{vM_s}\left[\frac{p^3}{(1-p)^2}\right]$$

*Equation 1: Carman-Kozeny equation*

In this equation, "g is gravitational acceleration (cm $s^{-2}$), v is the kinematic viscosity of water ($cm^2$ $s^{-1}$), $M_s$ is the specific surface area of the material $cm^{-1}$, and $C_o$ is an empirical constant." (Montes & Haselbach, 2006, p. 963). In a study conducted by Montes and Haselbach which utilized this equation, the relationship between porosity and hydraulic conductivity was found to be approximately:

$$K_s = 18\frac{p^3}{(1-p)^2}$$

*Equation 2: Relationship between Hydraulic Conductivity and Porosity*

The constant 18 was determined by looking at different regression fits for their data. The trend is applicable for a range of porosity from 12-36% (Montes & Haselbach, 2006).

Storage Capacity is also a consideration with permeable pavements, as it dictates the amount of rainfall the pavement can handle before flooding. This can be calculated through adding the capacity of the pavement itself, and the subbase (Tennis, Leming, & Akers, 2004). These can both be estimated by multiplying the thickness of the section by its effective porosity (Tennis et al., 2004).

$$Storage\ Capacity = pavement\ void\ \%\ * pavement\ thickness + subbase\ void\ \%\ * subbase\ thickness$$

*Equation 3: Storage Capacity*

The effective porosity describes how much void space is available for holding water within the material (Tennis et al., 2004). For our purposes of analyzing the topmost pervious layer, we will not consider the storage capacity of the subbase.

## Lessons from historical solutions

In optimization of concrete design, one study conducted by Schaefer, Wang, Suleiman, and Kevern showed that lower compaction and increased void ratio caused a decrease in the compressive strength of the pervious concrete. This same study also found that when the void ratio, or porosity was greater the 25%, the permeability increased exponentially (Kayhanian, Peter, Gulliver, & Khazanovich, 2015). This suggests that when designing permeable pavement, it is good to design the pavement to have a high porosity to maximize benefits. However, the pavement must be carefully designed to have acceptable compressive strength as well.

## Project Objectives and Constraints

The main project objective is to enhance the quality of surface water by minimizing runoff from roadways, sidewalks, and parking lots. If this objective is satisfied, it will benefit the public, and private companies that choose to install permeable pavement. Current goals for the project comply with expectations outlined in the Clean Water Act and Total Maximum Daily Loads established by the Environmental Protection Agency (Pennsylvania Department of Environmental Protection, n.d.). Each state has its own commitment based on specific concerns in the area and current pollution levels. For example, Pennsylvania plans to "reduce its urban/suburban stormwater load for nitrogen by 41 percent, phosphorus by 45 percent and sediment by 50 percent by 2025" (Pennsylvania Department of Environmental Protection, n.d.).

If the project is carried out successfully, it will also help to:

- Minimize flooding in streams
- Minimize erosion of streambanks
- Maximize safety of drinking water
- Make streams more suitable for wildlife
- Beautify the area
- Create jobs in construction and maintenance of new permeable pavements
- Help companies gain LEED® certification and associated benefits
- Maximize road safety

The project success in limiting pollutants is dictated by cost. Higher quality design would require more costly materials and maintenance. Since increasing the strength of porous pavement would decrease the permeability of the pavement, finding the correct balance between the two parameters is necessary (Eisenberg, Lindow, Smith, Permeable Pavements Task Committee, & American Society of Civil Engineers, 2015). While designing for a high permeability is important for meeting pollutant reduction goals, strength to support traffic loads is required so that the design can also serve its purpose as pavement.

The project is also limited by location, as each type of permeable pavement is suited for different existing conditions related to the slope of the environment, the material of the existing subbase, material availability, and the depth of the water table among others (Eisenberg et al., 2015). The pavement development is also controlled by the expected traffic and rainfall patterns for the area (Swan & Smith, 2010).

This project is also limited by funding and support. The project will only be successful if the public, private industries, and government officials push for a better quality of life.

Another constraint for project success is the fact that maintenance is needed as each permeable pavement type becomes clogged overtime. The effect of the clogging can be seen by a drop in the hydraulic conductivity. Despite maintenance through techniques such as vacuuming, research shows that it is difficult to restore the hydraulic conductivity to its original value, and one Stormwater Management Model (SWMM) estimates only 90% recovery after each vacuum (Sansalone, Kuang, Ying, & Ranieri, 2012). This means that the permeability of the pavement would decrease continually with time even when the pavement is being properly maintained.

If the proposed solution, porous concrete, is implemented with consideration for these constraints, the project can be successful, and beneficial to the parties involved.

# Candidate Solutions

The candidate solutions to the problem of nonpoint-source pollution in streams are different types of permeable pavement. Permeable pavement is an accepted Best Management Practice (BMP) for pollution control due to runoff. It allows water to infiltrate naturally to soil underneath the pavement, while still providing a surface with the potential for vehicular traffic. To date, permeable pavement is commonly used for sidewalks and parking lots, but it also has limited use in roads and highways.

## Scope of solutions considered

The three permeable pavement designs: porous asphalt, porous concrete, and permeable interlocking concrete pavers were chosen because they are the most widely used and researched designs available at this time.

There are many other BMPs to consider when looking to improve stream health in a watershed. Included here are some other engineering solutions: dry ponds, infiltration and filtration basins, and constructed wetlands. None of these were considered due to the project restraints. These solutions require large amounts of land, which make them unrealistic for reducing runoff in urban areas (U.S. Environmental Protection Agency, 1993).

Vegetative practices such as grass swales, green roofs, and filter strips are not suggested here. These practices are often combined with other BMPs. It is also generally accepted that there is very little downside to planting native grasses and foliage as filtration for runoff (U.S. EPA, 1993). Therefore, it is assumed that vegetative practices will likely be used alongside a larger design project, such permeable pavement.

A study by Huang, Wang, and Zhang compared permeable pavement to green roofs and rain-water gardens (2017). The study conducted in Guangzhou City and Chicago found that permeable pavement had the most runoff reduction out of all the BMPs used individually and had a cheaper entire cost at 1309.7 x $10^4$ Yuan when compared to the entire cost for a combination of the three types at 1859.0 x $10^4$ Yuan (Huang et al., 2017). Using the current exchange rate (1.00 CNY = .151110 US Dollars[1]) the price of the permeable pavement is $830,050.00 cheaper. Permeable pavement is an efficient and cost-effective BMP. Therefore, the focus of this paper is to determine the best design to use when introducing permeable pavement into urban communities over other BMPs.

## Historical or current solutions no longer considered viable

As BMPs are developed specifically to each site, there is no universal failed BMP. Permeable pavements specifically are not recommended in areas where the soil has low infiltration rates, and where the slope of the ground is greater than 5% (Philadelphia Water Stormwater Plan Review (PWSR), 2014).

---

[1] found on http://www.x-rates.com/

## Non-engineering solutions

There are many ways to go about decreasing impervious land cover. On a small scale, the general public could be educated in storm water management, and encouraged to plant foliage and grass to limit runoff from their property. These practices are not a substitute for the BMPs suggested above, but are always worth promoting and implementing to help mitigate the need for BMPs.

Government regulations play a role in managing runoff as well. In 2010, the Philadelphia Water Department, for example, began to determine water bills for non-residential land based on the amount of impervious land on the property. A reward system resulting in less expensive water bills was included in this to encourage the implementation of BMPs to decrease impervious land (“Stormwater Billing & Retrofits”, n.d.). This helps incentivize industries to consider implementing storm water management practices where possible, and again supplements larger solutions.

## Explanation of candidate solutions

Permeable pavements, which allow rainwater to pass through the surface of the pavement, and stay in a storage basin until it can infiltrate the soil. In this way, the pavement acts as water infrastructure, controlling the amount of polluted runoff that finds its way to streams. Studies have shown that permeable pavement as a BMP is successful in removing pollutants. Studies conducted by Park and Tia, and Teng and Sansalone found that permeable pavement had the potential to filter up to 90% of total suspended solids, 65% of total phosphorus, and 80% of total nitrogen (Sansalone et al., 2012).

## General Design

Permeable Pavements are generally designed to supplement existing stormwater management practices, and even limit the need for water infrastructure. Many permeable pavements are designed to have storage tanks that eventually allow for rainwater to infiltrate, and replenish groundwater. In some cases, the water is instead rerouted to water treatment facilities to be treated. In either case, the runoff does not become a source of pollution to surface water. A common permeable pavement structure design is shown below. This design includes the top layer of pavement with aggregate layers underneath, a stone reservoir, and an additional geotextile layer for support between the soil of the subgrade and the pavement structure.

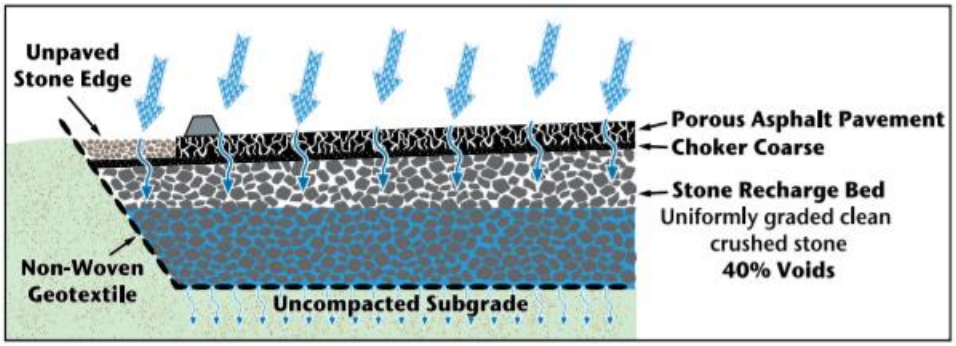

*Figure 1: Cross Section of Porous Pavement*[1]

There are many more design considerations for permeable pavements other than pavement material and structure. The specifications of the stone reservoir, the adhesive used for the pavement, and grading of the aggregate used are also important for the success of the pavement. All systems require maintenance, as debris clogging disrupts the drainage process. For comparison purposes, it is assumed that the best possible choices for other considerations are being made for all three options. In this way, the design itself is the examined variable.

## Properties Considered

Pavement flow rate, hydraulic conductivity, storage capacity, compressive strength, repair potential, longevity, cost, and aesthetic appeal are considered in this comparison.

### *Hydrological Properties*

The hydrological properties of the pavement include flow rate and hydraulic conductivity. These factors control the permeability of the pavement, and should be made as high as possible for project success.

Flow rate is the rate at which liquids can pass through the pavement. It has been given in inches per hour. The hydraulic conductivity "characterizes the flow of water through porous media" (Montes, & Haselbach, 2006, p. 961). Knowing hydraulic conductivity is useful because it allows us to determine what the porosity should be. When we relate porosity to hydraulic conductivity using Equation 2, we can find the minimum needed porosity for our desired hydraulic conductivity. The greater the hydraulic conductivity, the easier it is for water to pass through the pavement. Hydraulic conductivity is different from flow rate because it specifies water as the fluid passing through the pavement. It is also specific to the pavement because it considers surface area of the pavement, as well as porosity (Montes, & Haselbach, 2006).

### *Physical Properties*

Storage capacity is another major concern considering the functionality of porous asphalt. While the surface of the pavement may be permeable, water takes time to infiltrate the soil of the

---

[1] Hansen, K., P.E. (2008). *Porous Asphalt Pavements for Stormwater Management Design, Construction and Maintenance Guide* (Publication No. 131). National Asphalt Pavement Association. Retrieved December 5, 2017, from http://driveasphalt.org/assets/content/resources/IS-131_Porous_Asphalt_Pavements_for_Sormwater_Management-screen.pdf

subbase. Allowing for adequate storage capacity will ensure that the pavement is not flooded. While hydraulic conductivity and flow rate are important in determining permeability, the storage capacity determines if the pavement is prepared to handle the volume of rainfall it will receive from storms. While a single rain event may not bring that much water into the system, one of the main purposes of permeable pavement is to allow the water to infiltrate the soil at a natural rate. Acknowledging this, the pavement must be designed to hold water from single storm events, as well as additional rainfall that may occur before the reservoir can fully drain. The storage capacity is dependent on the thickness of the pavement and the porosity: the percentage of empty space within the pavement. The expected storage capacity has been calculated below using Equation 3. The porosity and pavement thickness used for the calculation was based off of general accepted values in permeable pavement construction manuals listed in Table 1.

Compressive strength is another important consideration when choosing a permeable pavement design. Compressive strength determines how heavy a load the pavement can handle, and the length of time it can carry this load for before it becomes damaged. This is of vital importance because ensuring a high compressive strength pavement is necessary to protect the public safety. In light of this concern, it is suggested that pervious pavements be installed in areas that will not see large amounts of traffic, or be consistently used by heavier trucks.

The pavement longevity is also important, as permeable pavement is a long-term investment that should continue to provide benefits for years after its installment. Methods for repair should be considered as well, as pervious pavement maintenance can preserve a damaged pavement system, increasing its lifetime. It should be noted that while required maintenance must be taken care of by the owners, permeable pavement cannot function when clogged with debris and trash. Keeping porous pavement free of extra debris must be a community effort.

### *Economic/Public Concerns*

Cost of the pavement is important to all investors involved in the project, and is critical in choosing which permeable pavement design is best suited to specific site needs. Cost is important to control for project feasibility.

Finally, aesthetic properties are important to consider when trying to gain public support for a permeable pavement project.

## Porous Asphalt (PA)

Source: (Eisenberg et al., 2015)

Porous asphalt is created by increasing the void space in classic asphalt mixes. Asphalt is made from aggregates held together with a bituminous binding according to the United States Army Corps of Engineers (2013). It is most commonly used in road construction.

### *Hydrological Properties*

A guide on permeable pavement construction states that "[t]he infiltration rate of porous asphalt and concrete may exceed 2,000 inches per hour" (Cahill, M. Godwin, & Sowles, 2011, p. 3). While this is much more than the average storm, it is best to ensure that the initial flow rate is as high as possible, as clogging can cause flow rate reduction down to as little as 2 inches per hour (Cahill, M. et al., 2011).

I calculated the anticipated hydraulic conductivity using typical values for porosity to see the difference in expected permeability. The U.S. Army Corps of Engineers suggests that porous asphalt should be designed to have 15-20% porosity to allow water to permeate at a reasonable rate, while the pavement maintains its structural integrity (2013). With this information, I found the hydraulic conductivity to be 0.0019-0.0051 inches per second.

### *Physical Properties*

Porous asphalt has a calculated storage capacity of 0.75-1.6 inches. This is a range of potential capacity determined using the minimum and maximum acceptable values for pavement thickness and porosity to find the extrema. The storage capacity listed here does not include the storage capacity of the reservoir.

Porous asphalt has an average compressive strength of 2,000-4,500 pounds per square inch (Tennis et al., 2004 & Interlocking Concrete Pavement Institute (ICPI), 2008).

Porous asphalt in particular is expected to last for 15-20 years (USACE, 2013). There is limited repair potential for porous asphalt. Damaged areas can be patched, but with impervious asphalt rather than porous asphalt according to the ICPI (2008).

### *Economic/Public Concerns*

The cost of the materials for porous asphalt is approximately $3.00-$4.50 per square foot (USACE, 2013).

While accompanying foliage adds an aesthetic element to all designs, the pavement itself can be designed to have aesthetic components as well. Porous asphalt aesthetic appeal is limited, as the color of the pavement cannot be modified.

## Porous Concrete (PC)

Source: (Cahill, M. et al., 2011)

Porous concrete is made from Portland cement. The cement is naturally light in color, and is made mainly from limestone.

### *Hydrological Properties*

The Federal Highway Administration cites the American Concrete Institute's data for the flow rate through porous concrete, which is approximately 1,724 inches per hour (2012). Other sources confirm this high flow rate and say, like porous asphalt, porous concrete may reach flow rates up to 2,000 inches per hour (Cahill, M. et al., 2011).

The hydraulic conductivity for porous concrete was also calculated using the method shown below. It was determined to be within the range of 0.0019-0.011 inches per second.

### *Physical Properties*

While concrete is generally known for its high compressive strength, the compressive strength of porous concrete was found to be similar to that of porous asphalt in the range of 2,000-4,500 psi (Tennis et al., 2004 & ICPI, 2008). Storage capacity was calculated using the same methods as above. Porous concrete may have a storage capacity within the range of 0.45-0.80 inches.

Porous concrete has an expected lifetime of about 20 to 30 years according to the U.S. Army Corps of Engineers (USACE, 2013). The ICPI determined that PC can be repaired by replacing a damaged portion of pavement with new porous concrete, but the new concrete must be cured before the pavement can be used (2008). While it can be replaced with the same material, it cannot be made completely identical to the original pavement.

### *Economic/Public Concerns*

The material cost of porous concrete is expected to be between \$2.00 and \$6.50 (USACE, 2013). While the minimum cost is low, the price range varies widely, showing that the cost can be hard to anticipate.

Porous concrete is described as aesthetically pleasing as it can be designed to have color. It is also naturally appealing, with a texture that "has been compared to a Rice Krispies® treat" Pervious Interlocking Concrete Pavers (Tennis et al., 2004, p.3).

## Permeable Interlocking Concrete Pavers (PICP)

Source: http://www.lakegeorgeassociation.org/protect/lake-friendly-living/permeable-pavement/

Pervious Interlocking Pavers (PICP) consist of paver blocks made from unmodified Portland cement. The pavers are connected and stabilized by a gravel structure which includes pores for water to pass through. (Philadelphia, 2015). Since standard concrete is used in PICP, the gravel structure that allows for permeability is also considered in the analysis.

### *Hydrological Properties*

The Federal Highway Administration estimates that flow rates for interlocking concrete pavers can be up to 1,000 in/hr (2015). This is confirmed in a study conducted by Belgard Commercial, which measured the infiltration rate through six different paver shape designs the company created. This study used typical concrete in all trials. Six different products had infiltration rates of 1,368 in/hr, 785 in/hr, 1,124 in/hr, 1,793 in/hr, 1,532 in/hr, and 1,512 in/hr (Belgard Commercial, 2015).

For PICP only the minimum hydraulic conductivity is calculated as there is no data available for the maximum anticipated porosity needed for the calculations. The minimum hydraulic conductivity was determined to be 0.00047 inches per second.

### *Physical Properties*

The maximum storage capacity of PICP could not be calculated due to incomplete data on porosity. More studies must be conducted before a claim can be made with regard to storage. The minimum storage capacity was calculated to be 0.30 inches.

PICP utilizes normal concrete, and therefore has a high compressive strength. The expected compressive strength for permeable interlocking pavements is around 8,000 psi (ICPI, 2008 & Eisenberg et al, 2015).

The longevity of PICP is similar to porous concrete, and is expected to last for approximately 20-30 years (USACE, 2013). Permeable interlocking concrete pavement offers simple repairs, as individual units can be replaced upon failure (ICPI, 2008).

## Economic/Public Concerns

The material cost of permeable interlocking concrete pavement can be expected between \$5.00 and \$10.00 per square foot (USACE, 2013). The prices are higher, and vary within a \$5.00 range.

PICP have many design opportunities as the color, and shape of the pavers can be varied (ICPI, 2008). This leads to increased potential for aesthetic appeal.

## Calculations

The calculations of hydraulic conductivity and storage capacity were done for a more complete comparison of the permeable pavement designs.

*Table 1: Raw Data used in Calculations*

|  | **PAP** | **PCP** | **PICP** |
|---|---|---|---|
| *Recommended Pavement Thickness (in)* | 5-8 inches<br>(USACE, 2013) | 3-4 inches<br>(USACE, 2013) | 3 inches<br>(USACE, 2013) |
| *Porosity (%)* | 15-20%<br>(USACE, 2013) | 15-25%<br>(Tennis et al., 2004) | >10%<br>(PWSR, 2015) |

## Storage Capacity

The equation used to find the storage capacity is explained on page 7. Calculations for storage capacity were done using the average range of recommended pavement thickness for each.

The storage capacity of the subbase is neglected because we assume an identical subbase for each pavement type. The calculations also use the recommended porosity, the ratio of void space to aggregate in the material given in Table 1.

PA:

$$Min.\,Storage\ Capacity = 5in * 15\% = 0.75in$$

$$Max.\,Storage\ Capacity = 8in * 20\% = 1.6in$$

PC:

$$Min.\,Storage\ Capacity = 3in * 15\% = 0.45in$$

$$Max.\,Storage\ Capacity = 4in * 20\% = 0.80in$$

PICP:

$$Min.\,Storage\ Capacity = 3in * 10\% = 0.30in$$

## Hydraulic Conductivity

Hydraulic Conductivity, denoted as $K_s$, was calculated from the porosity listed in Table 1. This data was used in the relationship Montes & Haselbach developed for porosity and hydraulic conductivity Equation 2 on page 6.

PA:

$$\boldsymbol{K_{s,min}} = 18\frac{.15^3}{(1-.15)^2} = 0.0019\ {}^{in}/_{s}, \boldsymbol{K_{s,max}} = 18\frac{.20^3}{(1-.20)^2} = 0.0051\ {}^{in}/_{s}$$

PC:

$$\boldsymbol{K_{s,min}} = 18\frac{.15^3}{(1-.15)^2} = 0.0019\ {}^{in}/_{s}\ ,\ \boldsymbol{K_{s,max}} = 18\frac{.25^3}{(1-.25)^2} = 0.011\ {}^{in}/_{s}$$

PICP:

$$\boldsymbol{K_{s,min}} = 18\frac{.10^3}{(1-.10)^2} = 0.00047\ {}^{in}/_{s}$$

## Comparative assessment of candidate solutions

*Table 2: Comparison Chart, Porous Asphalt, Porous Concrete, and Pervious Interlocking Pavers*

| | **Porous Asphalt (PA)** | **Porous Concrete (PC)** | **Pervious Interlocking Concrete Pavers (PICP)** |
|---|---|---|---|
| **Flow Rate (in/hr)** | May exceed 2,000 | Average = 1,724<br>*may exceed 2,000 | Average = 1,352[1]<br>*as high as 1,000 |
| **Hydraulic Conductivity Range (in/s)** | 0.0019-0.0051 | 0.0019-0.011 | Minimum of 0.00047 |
| **Storage Capacity for maximum and minimum recommended pavement thickness (in)** | 0.75-1.6 | 0.45-0.80 | 0.30-unknown |
| **Average Compressive Strength (psi)** | 2,500-4,000 | 2,500-4,000 | 8,000 |
| **Material Cost (price per square foot)** | $3.00–$4.50 | $2.00–$6.50 | $5.00–$10.00 |
| **Longevity (years)** | 15-20 | 20-30 | 20-30 |
| **Repair Potential** | Difficult repairs, patched with impervious asphalt | Difficult repairs, patched area must be cured after installation | Easy repairs, units can be replaced |
| **Aesthetic Factors** | No aesthetic component | Aesthetic texture<br>Can be colored | Shape and color variety |

---

[1] This is an average I calculated from 6 individual tests from the study cited.

# Project Recommendations

## Recommended solution

Based on the project goals and data from our comparison chart, porous concrete is the best permeable pavement design of the three: porous concrete, porous asphalt, and pervious interlocking concrete pavers. Overall, PC allows for the highest permeability while maintaining adequate strength. It is more economically feasible than PICP. While PA is cheaper, repairs on PA are more difficult, and can potentially compromise the functionality of the pavement. PC is also more aesthetic than PA. PICP's main benefit is its compressive strength, which can be achieved by standard pavement at a cheaper cost. PICP can also claim the most aesthetic design, but since this is not of vital importance, it was first design to be taken out of the comparison. While PA boasts the highest storage capacity and lowest cost range, it was considered more of a risk due to its repair needs and lack of longevity. Porous concrete is the best design because of its own merit, as it has the most promising permeability at a cost and compressive strength that are still reasonable, and matches PICP in its longevity and aesthetic appeal. Porous concrete is the only option that has minimal drawbacks in every category of Table 2, and for these reasons described in further detail below, PC was chosen to be the best design for attaining the project goals.

The stated goal of the project is to implement pervious pavement as a BMP to reduce the amount of pollution due to inefficient stormwater management, and an increase in impervious land cover due to urbanization. With this goal in mind, one of the most important factors to consider is design permeability. Parameters such as porosity, flow rate, and hydraulic conductivity quantify this permeability. Table 2 shows that porous concrete has the highest values for hydraulic conductivity and flow rate. Overall, porous concrete is the best design regarding permeability.

Porous asphalt had the highest storage capacity. The maximum storage capacity for porous concrete is just above the minimum storage capacity for asphalt. PICP has the lowest storage capacity, but a complete comparison cannot be made due to a lack of data. A maximum value for PICP paver thickness is not recorded, so more studies should be done on PICP before a claim can be made.

Compressive strength is an important design parameter because it determines the load the pavement can safely withstand. Since permeability and strength are inversely related, it is important to find balance between the two parameters for success. The strength for PICP is high, which we can expect because the material used in PICP is standard concrete. The strength of porous asphalt and concrete is less due to higher permeability, but still acceptable.

The anticipated cost of PA is the lowest followed by PC and finally PICP. As the comparison was done using a unit price (price per square foot), we can see that a large cost per square foot can quickly add up, and become very costly when planning for pavement of a large surface area. Therefore, cost difference cannot be discounted.

Anticipated repairs and longevity are important because they consider the quality of the pavement long term. Porous asphalt has the shortest expected lifespan and is the most difficult to repair. The pavement's permeability will even be compromised in those areas. Porous concrete has a similar repair process, but damaged pavement can be replaced with the same type of material, PC, unlike with asphalt. Repairs can be made simply for PICP because of the fact that individual pavers can be replaced.

An aesthetic design may help the project gain support, but aesthetics does not affect the functionality of the pavement. Because of this, it is not considered a top priority in this comparison. PICP has the most options aesthetically speaking, as the paver shape color and placement can be modified. Color can be added to a porous concrete mix as well. Porous asphalt was the most limited type, as it can only come in dark colors due to use of tar in asphalt.

In summary, porous concrete is not only the most successful pavement in the most important area, permeability, but also the design option with the least drawbacks. Porous concrete is a wonderful candidate to reduce pollution and runoff to streams.

## Design and implementation challenges

One of the biggest challenges to the project is finding a team to install the pavement. Porous pavement installation requires trained professionals. The process for installation is complex, as steps must be taken to minimize compaction of the subbase during installation, and the concrete must be mixed and cured properly.

The need for special technical skill is evidenced by the fact that engineers can become certified specifically to install porous concrete pavement. The National Ready Mixed Concrete Association gives three different certifications: Pervious Concrete Technician, Installer, and Craftsman (2012).

Convincing business owners to invest may also be difficult. The installation of a new pervious concrete pavement parking lot would disrupt business, as the concrete must be cured for 7 days, without traffic (ICPI, 2008 & Eisenberg et al, 2015).

Without proper funding, the project will not be implemented. This is why it is important to create a detailed plan, outlining the pavement design, and the potential benefits for possible sponsors to see. Documenting the design process properly will give investors faith in the project, and will make them more likely to become involved.

If porous concrete is installed, it must be properly maintained to ensure its longevity. Vacuuming the pavement to manage clogging is recommended twice a year (Eisenberg et al., 2015). The owners, as well as those who use the pavement should also be educated about pavement maintenance. The pavement should also be monitored overtime to ensure its continual effectiveness.

One challenge of adding porous concrete pavements is to decide where the pavement can ideally be installed. Permeable pavement does not have large space requirements, so it is specifically suitable for urban environments. (Virginia Department of Environmental Quality, 2011). It is recommended that porous concrete be installed in areas where the slope of the ground is generally uniform, and less than 5% (PWSR, 2014). It is also important that the natural soil on site be uncompacted. This is because the water must be able to percolate through the soil becoming groundwater after it passes through the pavement, and soil compaction leads to a decrease in soil infiltration rate (Cahill, T.H., 2012).

Another challenge will be to gain the community’s support. Public support could help the project gain funding. This challenge will be addressed in part by planning aesthetically pleasing colors for the porous concrete, as well as adding native vegetation to the edges of the pavement design, adding another aesthetic factor to the project. Educating the public on the benefits of porous concrete will also help with this issue.

## Conclusion

It is reasonably projected that sponsors of porous concrete projects will benefit from long-term monetary gains. Public projects installing porous concrete reduce the need for other water infrastructure to manage runoff. It is important to note that porous pavement should not be used to replace sewage and runoff management, but are meant to supplement existing structures.

If a private company takes on the project of implementing concrete porous pavement into a parking lot design, the company will gain three points towards LEED® certification for helping to reduce the heat island effect, and for stormwater quality and quantity control (Colorado Asphalt Pavement Association, n.d.). Benefits of LEED® certification include publicity, increased business, and in some states, tax cuts (U.S. Green Building Council, 2015).

There are numerous environmental benefits: reduction of volume of runoff, reduction of pollution due to runoff, improved water quality, reduced stream bank erosion, improved habitat quality in streams, and reduction of the heat island effect.

The success of porous concrete benefits the general public as well. The environmental benefits listed also lead to health benefits related to improved water quality. Installation projects would create more jobs in construction. Porous concrete can also mitigate flooding concerns, increasing public safety. The project is also an opportunity to educate the public on environmental awareness. A successful project could be used as an example of implementation of stormwater management practices. This could inspire awareness and individual responsibility.

Ultimately, projects to integrate porous concrete into communities wherever possible will benefit private companies or local governments that manage the project, the environment, and the general public.

## Glossary

**Best Management Practice (BMP)** – A structure or technique used to limit water pollution[1]

**compressive strength** – a material's ability to withstand a compressive force which pushes particles in the material closer together[2]

**geotextile** – a woven structure that provides structure and drainage[1]

**hydraulic conductivity** – measures the volume of water flowing through a surface when time and area are normalized

Since hydraulic conductivity is specific to water, it takes the specific viscosity of water into account.[3]

**porosity** – having gaps or pores

This can allow for fluids, such as water to pass through gaps in the structure. However, porosity decreases strength as the pores can lead to cracking.[5]

**porous asphalt** – standard asphalt consisting of aggregate and bituminous binding modified to have a porous structure[1]

**porous concrete** – standard concrete, Portland cement commonly made from limestone and clay, modified to have a porous structure[4]

**permeable interlocking concrete pavers** – standard concrete pavers of any shape fitted together on a porous gravel structure[4]

**subbase** – bottom layer of pavement that acts as a base or platform for the rest of the pavement, also increases strength[5]

**Portland cement** – cement made from chalk or limestone, clay, and shale, creates cement gel in a reaction with water[5]

---

[1] Author

[2] http://www.oxfordreference.com/view/10.1093/acref/9780199534463.001.0001/acref-9780199534463

[3] https://or.water.usgs.gov/projs_dir/willgw/glossary.html#P

## References

Belgard Commercial. (n.d.). *Infiltration Rate of PICP Systems*(Rep.). Retrieved December 5, 2017, from Belgard Commercial website: www.belgardcommercial.com/FILE/10282/infiltration_rate_of_picp_systems.pdf

Cahill, M., Godwin, D. C., & Sowles, M. (2011). *Porous Pavement* (Publication No. ORESU-G-11-002). Retrieved December 5, 2017, from Oregon State University website: http://seagrant.oregonstate.edu/sites/seagrant.oregonstate.edu/files/sgpubs/onlinepubs/g11002-lid-porous-pavement.pdf

Cahill, T. H. (2012). *Low impact development and sustainable stormwater management* (1st ed.). Hoboken, NJ: John Wiley. Retrieved September 5, 2017, from http://www.wiley.com/WileyCDA/WileyTitle/productCd-0470096756.html

Colorado Asphalt Pavement Association. (n.d.). Asphalt Pavements and LEED® Certification. Retrieved December 9, 2017, from http://co-asphalt.com/wp-content/uploads/2015/03/LEED-HMA_contribution_points-CAPA.pdf

Eisenberg, B., Collins Lindow, K., Smith, D. R., Permeable Pavements Task Committee, & American Society of Civil Engineers. (2015). *Permeable Pavements*. Retrieved October 15, 2017, from http://www.worldcat.org/title/permeable-pavements/oclc/906584600

Federal Highway Administration. (2012, December). *Tech brief: Pervious concrete* (Issue brief No. FHWA-HIF-13-006). Retrieved December 5, 2017, from Federal Highway Administration website: https://www.fhwa.dot.gov/pavement/pub_listing.cfm?TitleStart=T

Federal Highway Administration. (2015, January). *Tech Brief: Permeable Interlocking Concrete*

*Pavement* (Issue brief No. FHWA-HIF-15-007). Retrieved December 5, 2017, from Federal Highway Administration website: https://www.fhwa.dot.gov/pavement/pub_listing.cfm?TitleStart=T

Huang, T., Wang, Y., & Zhang, J. (2017). Simulation and Evaluation of Low Impact Development of Urban Residential District Based on SWMM and GIS. *IOP Conference Series: Earth and Environmental Science,74*. doi:10.1088/1755-1315/74/1/012009

Interlocking Concrete Pavement Institute (ICPI). (2008, Feb). [Brochure]. Author. Retrieved December 5, 2017, from http://newlinehardscapes.com/environmental/PICPComparisonBrochure.pdf

Kayhanian, M., Peter, W. T., Gulliver, J. S., & Khazanovich, L. (2015, June). *The Application of Permeable Pavement with Emphasis on Successful Design, Water Quality Benefits, and Identification of Knowledge and Data Gaps* (Publication). Retrieved October 15, 2017, from National Center for Sustainable Transportation website: https://ncst.ucdavis.edu/wp-content/uploads/2014/08/09-30-2015-NCST-SR-Permeable-Pavement-FINALv5.pdf

Kibler, D. F. (1982). *Urban Stormwater Hydrology*. doi:10.1029/WM007

Montes, F., & Haselbach, L. (2006). Measuring Hydraulic Conductivity in Pervious Concrete. *Environmental Engineering Science, 23*(6), 960-969. doi:10.1089/ees.2006.23.960

National Ready Mixed Concrete Association. (2012). Pervious concrete contractor certification program. Retrieved December 07, 2017, from https://www.nrmca.org/Education/Certifications/Pervious_Contractor.htm

Pennsylvania Department of Environmental Protection. (n.d.). Track PA's Progress. Retrieved

October 15, 2017, from http://www.dep.pa.gov/Business/Water/Pennsylvania%E2%80%99s%20Chesapeake%20Bay%20Program%20Office/Pages/Track-Pennsylvania%E2%80%99s-Progress.aspx

Philadelphia Water Stormwater Plan Review (PWSR). (2014). *Philadelphia stormwater management guidance manual, Version 2.1*. Retrieved October 21, 2017, from https://www.pwdplanreview.org/manual-info/pre-july-2015-resources

Philadelphia Water Stormwater Plan Review (PWSR). (2015). *Philadelphia stormwater management guidance manual Version 3.0*. Retrieved October 21, 2017, from https://www.pwdplanreview.org/manual-info/guidance-manual

Rasmussen, T., Johnson County Stormwater Management Program, & U.S. Geological Survey. (2008). Water quality of streams in Johnson County, Kansas, 2002-07 (Fact sheet (Geological Survey (U.S.)); 2008-3090). Reston, Va.]: U.S. Dept. of the Interior, U.S. Geological Survey.

Sansalone, J., Kuang, X., Ying, G., & Ranieri, V. (2012). Filtration and clogging of permeable pavement loaded by urban drainage. *Water Research, 46*(20), 6763-6774. doi:10.1016/j.watres.2011.10.018

Swan, D. J., & Smith, D. R. (2010). Development of Design System for Permeable Interlocking Concrete Pavement. *Green Streets and Highways 2010*. doi:10.1061/41148(389)26

Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). *Pervious concrete pavements* [2]. Retrieved October 15, 2017, from http://myscmap.sc.gov/marine/NERR/pdf/PerviousConcrete_pavements

U.S. Army Corps of Engineers, Department of the Army (USACE). (2013, October 31). *Public*

*Works Technical Bulletin 200-1-132 Guidelines for sustainable parking areas, including native vegetation considerations, in support of low impact development*. Retrieved December 3, 2017, from http://www.wbdg.org/ffc/army-coe/public-works-technical-bulletins-pwtb/pwtb-200-1-132

U.S. Environmental Protection Agency (EPA). (1993). *Urban Runoff Pollution Prevention and Control Planning*. Retrieved October 15, 2017, from https://nepis.epa.gov/Exe/ZyPDF.cgi/30004LY0.PDF?Dockey=30004LY0.PDF

U.S. Green Building Council. (2015, February 10). The Business Case for Green Building. Retrieved December 9, 2017, from https://www.usgbc.org/articles/business-case-green-building

Virginia Department of Environmental Quality. (2011). Permeable Pavement. *Virginia DEQ Stormwater Design Specification No. 7 Version 1.8*. Retrieved December 3, 2017, from http://vwrrc.vt.edu/swc/NonPBMPSpecsMarch11/VASWMBMPSpec7PERMEABLEPAVEMENT.html

## Additional sources consulted

https://www.buildings.com/article-details/articleid/18830/title/permeable-pavement-battles-stormwater-runoff

doi:10.1088/1757-899x/176/1/012025

https://www.usgbc.org/Docs/Archive/General/Docs9915.pdf