PERVIOUS CONCRETE SYSTEM AND WATER QUALITY EXPERIMENTATION WITHIN A SOCIOLOGICAL CONTEXT

by

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(Under the Direction of Stephan A. Durham)

ABSTRACT

Sustainable Best Management Practices provide a means for contractors, engineers, municipalities and others to better deal with ecological changes resulting from urban developments. Two phases of research were established to assess both the sociological and technical aspects of pervious concrete. In Phase 1 a survey was created and distributed to determine the perception respondents harbored for pervious concretes. In Phase 2 laboratory testing explored the effects of two different layer configurations on filtration capability and change in pH. Water quality testing determined that 3-layer systems filtered more effectively than 2-layer systems. Additionally, this research confirmed that barriers do exist for the use of pervious concrete in Georgia and confirmed the need for targeted educational programs on pervious concrete.

INDEX WORDS: Pervious concrete, Pervious concrete pavements, Water quality, pH, Layer configuration, Sociological context, Green infrastructure, Synthetic stormwater

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DEDICATION

I dedicate this work and all work after to my current and future family. While my education has been a struggle from its humble beginnings until now I know for certain that I could not have come this far without my father and mother. I know now that my own children cannot excel beyond my capability without my own diligent guidance. Without my parents as patient fervent stars in my sky and younger siblings reminding me of my path and example to set I would never have pushed when it counted most.

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1. INTRODUCTION

Sustainable Best Management Practices provide a means for contractors, engineers, municipalities and others to better deal with ecological changes resulting from urban developments. Originally developed in 1850 pervious concrete pavements (PCP) have experienced slow growth and limited usage in the United States; however, they have proven to provide a multitude of solutions to common urban development problems (Mulligan, 2005). These problems include but are not limited to the heat island effect, contaminants, excessive stormwater runoff, and prevention of groundwater recharge. With that in mind this thesis seeks to evaluate the hydrologic and filtration performance of PCP systems and explore the barriers preventing widespread use of pervious concrete pavements within Georgia.

1.1 Objective

This thesis examines two aspects of PCP. The first aspect is an assessment of the sociological barriers influencing the use of PCP in Georgia. The second aspect is the water quality performance of PCP. Specifically the change in pH levels in the effluent after a number of storm events and the capability to filter contaminants from synthetic stormwater passing through the PCP system.

For the purposes of examining the sociological and water quality aspects of PCP this study was designed to be accomplished in two phases. Phase 1 examines the sociological aspect of PCP usage and includes both surveys and stakeholder comments. Phase 2 evaluates the hydrological and water quality performance of PCP mock ups with varying material constituents and quantities.

During the Phase 1 study a survey was created for the purposes of gathering information on why PCP is not as widely used within Georgia and how that can be overcome. The survey was distributed to a variety of professionals across the state of Georgia. These professionals included educators, architects, engineers, ready-mix suppliers, contractors, municipalities, and others. Additionally, this phase included both individual discussions and interviews with stakeholders.

In the Phase 2 study a variety of PCP properties were examined and tested. The primary objective for this phase was testing water quality, pH and filtration capability. Normal concrete and pervious concrete both use portland cement and within these cements are compounds that raise the pH of water that make contact with concrete material (Setunge 2009). PCP in particular has a much larger exposed surface area and as a result has a higher potential to influence pH levels (Thomle 2012). In addition, PCPs are capable of filtering water and the Phase 2 study involved the construction of multiple mock PCP systems designed to measure filtration capability. The results of filtration testing were compared to EPA standards.

1.2 Hypotheses

The hypotheses for this research are as follows:

1. PCPs are not widely used in Athens, GA
2. An increase in cement content leads to an increase in pH of stormwater.
3. A three layer PCP system containing a free drain rock layer for water storage and sand layer for additional filtration provides greater pollutant filtration than a two layer system without a sand layer.

1.3 Scope

A brief background on all PCP sites located in Athens, GA is provided in Chapter 2. The chapter includes commentary on the condition and specific location of each site, pictures for scale and illustration and the methodology and results for field flow condition tests.

Chapter 3 provides a thorough literature review summarizing studies on water quality with regards to PCP, the current specifications for the design and placement of PCP and relevant testing methods for the assessing the various properties of PCP.

Chapter 4 covers the significance and premise for this thesis in addition to briefly outlining the overall goals and direction of the research study.

Chapter 5 outlines the experimental plan for this study. The plan covers each phase of study and provides details such as survey methodology, mixture design, layer design, the number of mock PCP systems to be constructed, and sampling methodologies.

Chapter 6 covers the results of both the laboratory study and the sociological study. These results were analyzed from a statistical perspective which is detailed in the following chapter.

Chapter 7 covers the detailed statistical analysis of both the contaminant removal findings and pH change.

Chapter 8 discusses all findings within the laboratory and survey sections. This chapter also comments on improvements and recommendations deemed necessary post experimental phase.

2. BACKGROUND

2.1 Introduction

Porous concrete pavements have been used in the United States since the 1970s when they were first used by the State of Florida to meet stormwater retention requirements without the use of auxiliary detention systems (Ferguson, 2005). Pervious concrete first came to Georgia in 1992 and has since grown in use (Ferguson, 2005). Georgia's experience with the material continues; however, implementation has yielded varying levels of success. This varying level of success is apparent in the Athens, GA, area installations. The first PCP installations in Athens were placed in 2003 (Ferguson, 2007).

There are over ten PCP installations located around the UGA campus and Athens area that vary in both quality and effectiveness. The majority of these installations are parking lots; however, some are simply pedestrian areas meant for recreational use. The following sections provide information on the known applications of PCP in Athens along with selected photographs and brief commentary on the condition and success of the sites.

Each site in the Athens area was evaluated via two methods. The first method involved a visual inspection of the PCP surfaces to observe possible clogging and surface wear such as raveling. The second method of evaluation was a drain time test that aided in observing the internal state of specific sites. Both methods were key to determining the overall state of PCP usage within Athens. The overall success of current installations has the potential to influence public opinion and reflect the past and present experience of contractors.

The drain test by Delatte (2007) was used to determine the internal condition of the eight PCP sites within Athens. This simple test involved draining a specified volume of water into a sample site and measuring the time required for the vessel to empty (Delatte, 2007). The apparatus consists of three main elements. The first is a 4x8 inch cylindrical concrete mold with a 7/8-inch hole drilled into the bottom to allow water to drain out. The second is a removable stopper coupled with a sealant that allow for the release of water from the vessel. The final element is a stopwatch used to time the experiment. A picture of the apparatus is displayed in Figure 2.1.

Figure 2.1 – Delatte Drain Test Apparatus

2.2 Field Flow Condition Test Methodology and Results (Athens Sites)

There were five trials for each site. The average results for these trials are shown in Table 2.1 and 2.2. All times have been averaged and were compared to findings in the Delatte paper. Delatte's results show that a drain time of less than 60 seconds indicates acceptable infiltration capacity. A drain time of greater than 60 seconds indicated that the pavement was severely clogged (Delatte, 2007).

Procedure for assembly of apparatus:

The Delatte drain test apparatus requires the following materials:

- (1) 4x8 concrete cylinder mold with a 7/8 hole drilled in the bottom (at the center)
- (1) 7/8" rubber stopper with a string or rod attached to facilitate easy removal
- A rubber ring gasket
- A small 6x6" sheet of rubber foam or neoprene material
- A stopwatch
- Water

To perform the test the apparatus must be assembled as shown above in Figure 2.1. To assemble follow these instructions:

1. Drill a 7/8" hole into the bottom of the 4x8" concrete mold
2. Attach rubber ring gasket to the bottom of the mold using high strength glue
3. Attach foam rubber material to the bottom of the rubber ring gasket
4. Attach string or rod to stopper and ensure the stopper fits into the bottom hole such that no water leaks when the apparatus is left at rest.

Procedure for drain test:

1. Plug hole with stopper
2. Fill concrete mold with water until the mold is completely full
3. Place apparatus in desired sample area
4. Apply pressure to the top of the apparatus
5. Have an assistant pull plug and start stop watch
6. Record the time it takes for all water to drain from the apparatus
7. Repeat at least 5 times to produce 5 trials

2.3 Sample PCP Locations in Athens, GA

The UGA Transit Facility located at 2505 Riverbend Rd is shown in Figure 2.2. Placement of this parking lot was managed by the UGA Office of University Architects. The site is in good condition but has experienced some raveling wear since construction. The site is subjected to regular traffic from employee and visitor vehicles. In addition there are sections of the parking lot that appear clogged and ineffective.

Figure 2.2 – UGA Transit Facility Parking Lot

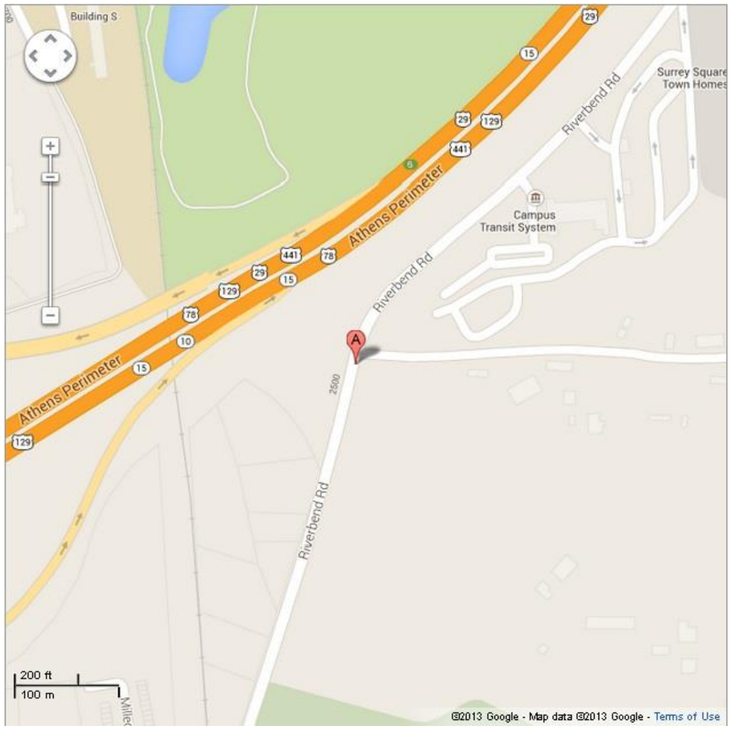

Figure 2.3 – UGA Transit Facility Parking Lot Map (Google Maps, 2013)

The UGA Governmental Relations Building parking lot is shown in Figure 2.4. This small parking lot is located at 198 Waddell Street. It is situated on the north side of UGA Government Relations was one of the first installations of PCP at UGA placed in 2003 (Ferguson, 2007). The site itself is in poor condition with clogging, prevalent raveling and surface irregularities. This lot experiences regular UGA employee and visitor vehicle traffic.

Figure 2.4 – UGA Government Relations Building Parking Lot

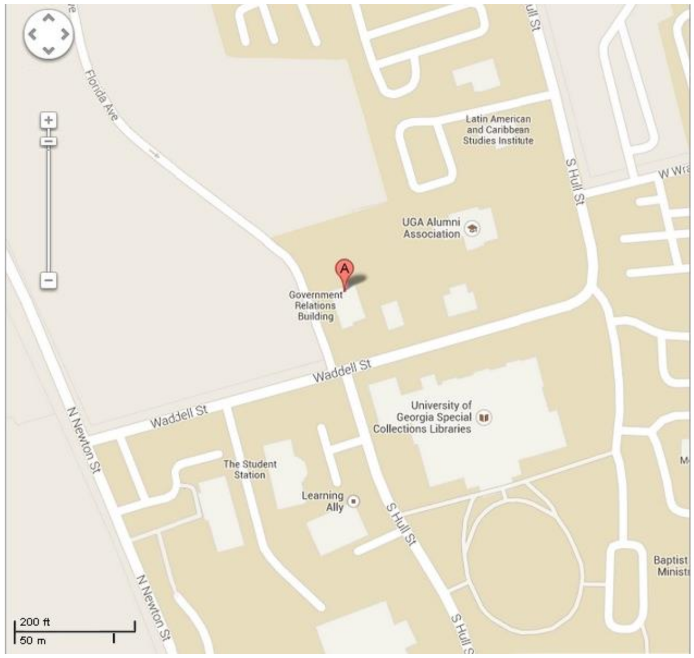

Figure 2.5 – UGA Government Relations Building Parking Lot Map (Google Maps, 2013)

The UGA College of Environment and Design pedestrian area is shown in Figure 2.6. This site located at 285 S Jackson St behind the College of Environment and Design building is a pedestrian area and is less than one year old. This site is a success so far and is currently in very good condition.

Figure 2.6 – UGA College of Environment and Design Pedestrian Areas

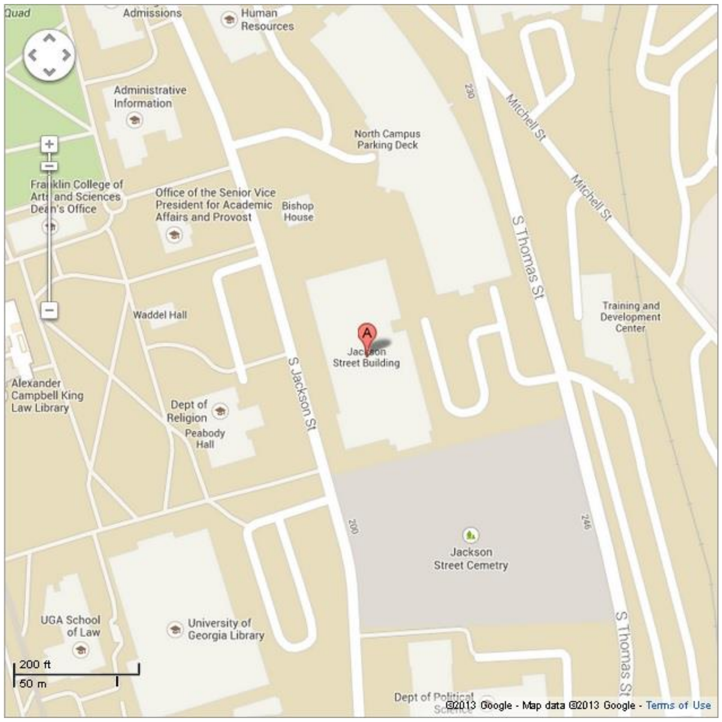

Figure 2.7 – UGA College of Environment and Design Map (Google Maps, 2013)

The Athens Transit Multi Modal Transfer Center parking lot is shown in Figure 2.8. The site is located at 775 East Broad Street adjacent to the main bus transfer platform and serves as a parking lot for passengers and staff. The site is a success thus far and is currently in very good condition.

Figure 2.8 – Athens Transit Multi Modal Transfer Center Parking Lot

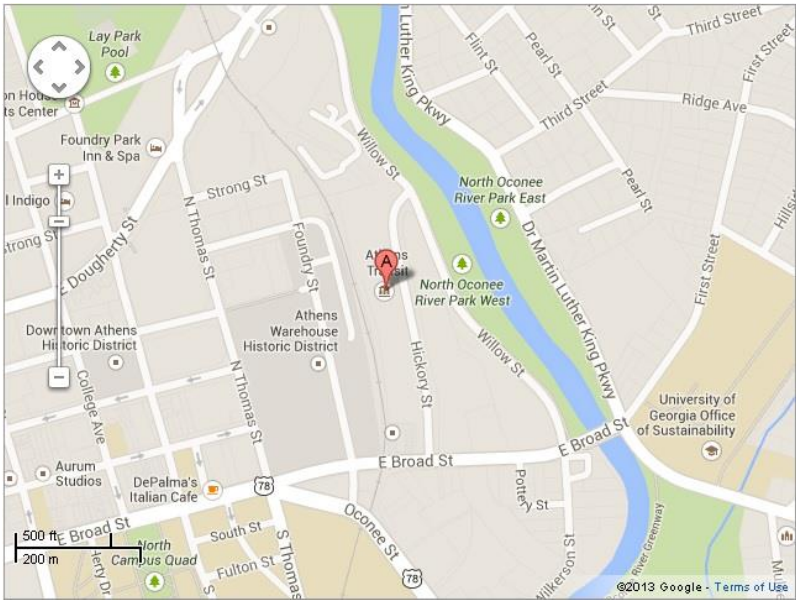

Figure 2.9 – Athens Transit Multi Modal Transfer Center Parking (Google Maps, 2013)

The St. James United Methodist Church parking lot is shown in Figure 2.10. The site is located at 111 West Lake Drive adjacent to the older parking lot near the main church building. This site shows multiple signs of wear with obvious raveling, clogging, and degradation of the PCP surface. The site is used by the members of the church and experiences regular light vehicular traffic. It is not in very good condition.

Figure 2.10 – St. James United Methodist Church Parking Lot

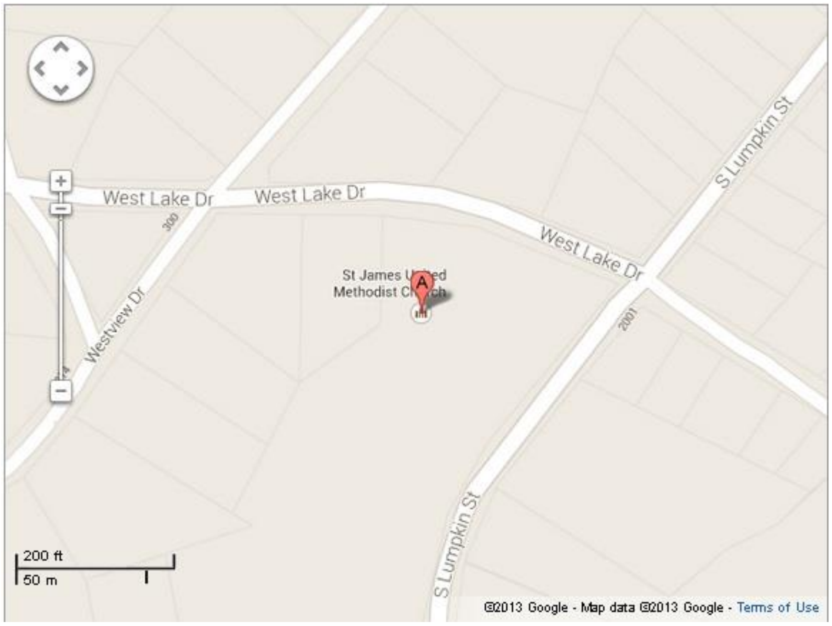

Figure 2.11 – St. James United Methodist Church Parking Lot (Google Maps, 2013)

The Athens Clarke County Community Protection and Public Works department is located at the corner of North Lumpkin and W Dougherty St. Its back parking lot consists of asphalt and pervious concrete parking spaces. The site experiences regular employee and visitor vehicle traffic and has minimal visible wear. The surface, however, is visibly clogged.

Figure 2.12 – Athens Clark County Community Protection and Public Works Parking Lot

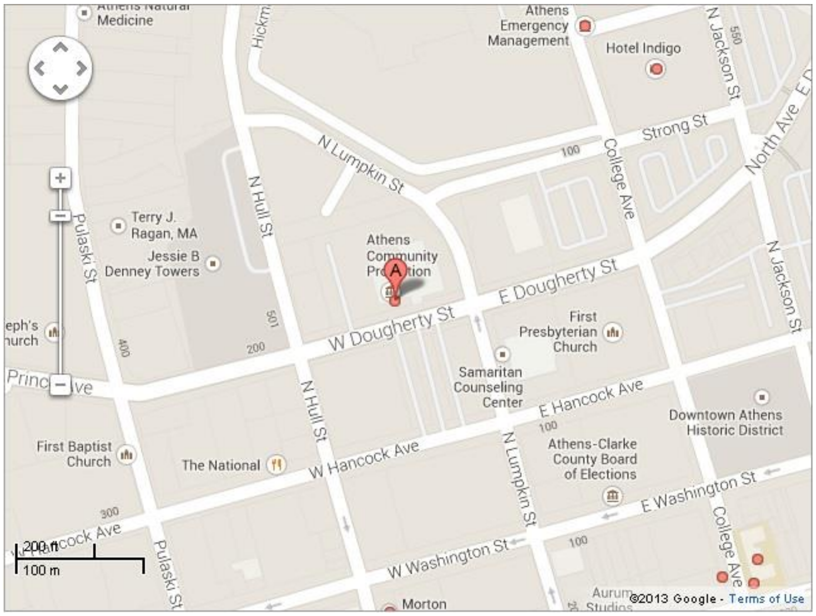

Figure 2.13 – Athens Clark County Public Works Parking Lot Map (Google Maps 2013)

The UGA Rutherford Hall dorm is located at the corner of Cedar St. and Stanford Dr. The parking lot located adjacent to the building is relatively new and contains both asphalt and pervious concrete parking spaces. The site experiences regular student vehicle traffic and is showing visible wear with apparent raveling at its joints.

Figure 2.14 – Rutherford Hall Parking Lot

Figure 2.15 – Rutherford Hall Parking Lot Map (Google Maps 2013)

The Athens Transit commuter parking lot is located near the Lexington Highway adjacent to the Athens Perimeter highway exit in the cloverleaf. This site is relatively new and contains both asphalt and pervious concrete parking spaces. The PCP displays very apparent wear with severe raveling at its joints and uneven surfaces at high traffic areas. The site experiences regular commuter vehicle traffic.

Figure 2.16 – Athens Transit Commuter Parking Lot

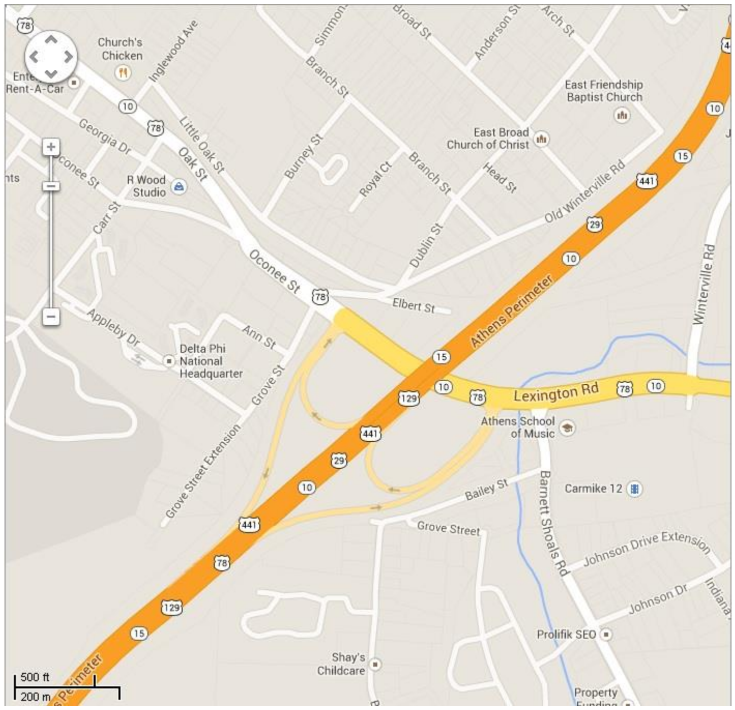

Figure 2.17 – Athens Transit Commuter Parking Lot Map (Google Maps 2013)

2.4 Drain Test Results:

The results for the drain test for June 2013 and 2014 are displayed in Table 2.1. The values reflect the amount of time water took to drain out of the apparatus into the concrete. A second test was conducted one year later to examine the hydrologic performance of these area PCP with use and time.

The drain times for each site corresponded to a hydraulic conductivity for the pavement (Delatte, 2007). Hydraulic conductivity is defined as the ease with which a fluid is able to pass through the pores of a material such as PCP in this case (Serrano, 1997). This hydraulic conductivity was found using Equation 2.1 wherein hydraulic conductivity k, in inches per hour, is estimated using the drain time, measured in seconds (Hager, 2009).

$$k = 2533e^{-.062t} \qquad \text{Equation 2.1}$$

The above drain times produced the following hydraulic index scores. These scores are found in Table 2.2 and compare findings from 2013 and 2014.

Table 2.1 – Field Drain Time Test Results (All Sites 2013 and 2014)

Location	Average Drain Time June Seconds (2013)	Average Drain Time June Seconds (2014)
UGA Transit Facility	19.92	22.56
Athens Transit Multi Modal Transfer Center	12.66	13.87
St. James United Methodist Church	142	151
UGA College of Environment and Design	9.8	11.6
UGA Government Relations	110.6	115.9
Athens Clarke County Public Works	59.5	61.67
Rutherford Hall	10.3	13.46
Athens Transit Commuter Parking lot	9.01	12.78

Table 2.2 – Hydraulic Conductivity (All Sites 2013 and 2014)

Location	Hydraulic Conductivity (k) (in/hr) 2013	Hydraulic Conductivity (k) (in/hr) 2014
UGA Transit Facility	736.65	625.43
Athens Transit Multi Modal Transfer Center	1155.44	1071.93
St. James United Methodist Church	0.38	0.22
UGA College of Environment and Design	1379.61	1233.93
UGA Government Relations	2.66	1.92
Athens Clarke County Public Works	63.32	55.35
Rutherford Hall	1337.50	1099.53
Athens Transit Commuter Parking lot	1448.87	1146.88

The hydraulic conductivity values above translate to the following conclusions. The condition of a PCP system is determined through comparison with criteria established by Delatte. These criteria designate conditions into three groups. A PCP system is in good condition if drain times are less than 20 seconds. PCP systems are moderately clogged if drain times stand between 20 and 60 seconds. Any drain times that exceed 60 seconds are classified as a severely clogged PCP system (Dellate, 2009). Conclusions based on the drain test results indicate the following for the field sites investigated in this study.

- *UGA Transit Facility* – This site was classified as being in good to moderate condition by Delatte test criteria throughout the two year period. Visual inspection yielded a few areas along the surface that showed signs of clogging but results were otherwise consistent with these conclusions.
- *Athens Transit Multi Modal Transfer Center* – This site was classified as being in good condition by Delatte test criteria. Visual inspection supports these conclusions as no signs of wear or clogging were found on site.
- *St. James United Methodist Church* – This site was classified as being in very poor condition by Delatte test criteria. Visual inspection found many signs of wear including excessive raveling and obvious signs of clogging.
- *UGA College of Environment and Design* – This site was classified as being in good condition by Delatte test criteria. The site itself is new and shows no signs of raveling or obvious signs of clogging.
- *UGA Government Relations* – This site was classified as being very poor condition by Delatte test criteria. The site shows obvious signs of degradation and raveling. The surface provides near to no infiltration and has a very uneven surface.

- *Athens Clarke County Public Works* – This site was classified as being in moderate to poor condition by Delatte test criteria throughout the two year period. There is visible wear and clogging. The site provides very little infiltration.
- *Rutherford Hall* – This site was classified as in good condition by Delatte test criteria. The site shows visible wear such as extensive raveling but provided sufficient infiltration.
- *Athens Transit Commuter Parking Lot* – This site is classified as being in good condition by Delatte test criteria. There is visible wear, despite the site being relatively new, with raveling and surface wear across the entire surface.

The majority of the local pervious concrete installations were in good condition with three out of the eight tested receiving a poor condition rating. All sites that obtained a poor rating were older PCP sites and had experienced the most wear and clogging. The hydraulic conductivity of all sites decreased from 2013 to 2014. This decrease is likely the result of incrased clogging of the PCP system. Clogging occurs when maintenance is lacking and results in the failure of a PCP system. Although many of the sites examined in this study were in good condition, a continued lack of maintenance will result in those sites becoming increasingly clogged with extensive wear and raveling.

3. LITERATURE REVIEW

3.1 Overview

Urban developments greatly alter the natural environment and as such provide distinct problems such as the heat island effect, increases in stormwater runoff, limited groundwater recharge, the introduction of contaminants, increased need for and placement of drainage accessories such as detention ponds, and safety issues such as ponding on impervious surfaces with poor drainage systems. Pervious concrete pavements have multiple proven benefits but studies on its layer configuration, practical pH experimentation and the sociological barriers to its use are lacking. Areas of study include but are not limited to water quality, field placement guidelines, mixture design, strength and durability and social outreach for the sake of educating the public about the technology.

Pervious concrete is a manufactured material that allows for deep customization ranging from determining aggregate size to placement and bonding formula. This flexibility provides for a green technology that can be placed and applied to a multitude of situations and climates. In heavily urbanized regions pervious concrete reduces the heat island effect. The heat island effect occurs when urban areas develop significantly higher temperatures than adjacent rural areas (EPA, 2012). Most surfaces in an urban environment are impervious and as such water cannot reach the subgrade (Ghaly et al, 2010). Heat islands cause several problems ranging from vastly increased energy costs to the increased production of smog (EPA, 2012). Pervious concrete remedies this problem, despite its lower solar reflective index, by providing greater surface area for cooling through its pores and voids (Haselbach et al, 2011). Now, aside from dealing with heat, pervious concrete has the ability to capture up to 100% of runoff water while having the ability to filter stormwater before it reaches groundwater, streams or other bodies of water (Kuennen, 2003). This key ability to filter stormwater is a feature applicable to any region and several cities are beginning to adopt PCPs into environmental policy (Kuennen, 2003). Additionally PCPs provide a safer driving surface for lower traffic roadways (Kuennen, 2003). By absorbing both rainwater and oil, pervious concrete has the benefit of drastically reducing tire spray and hydroplaning (Kuennen, 2003).

The sparse literature surrounding the topic of pervious concrete illustrates a green technology hindered by limited public knowledge and a lack of support. The technology itself is not new and has many proven benefits, as seen above, that only enhance the potential for better applications given proper attention. Preliminary sociological study indicates that one major concern for the use of porous concrete is durability. Pervious concrete has the potential to degrade through a process called raveling. Raveling is the wearing away of a pavement surface due to dislodgement of aggregate particles (ASTM C1747, 2011). Raveling occurs with any type of concrete but occurs with greater potential in pervious concrete as a result of poor bonding or increased voids at the surface between aggregate particles. Poor bonding may result from a poor binder paste or from poor contact between aggregate particles during the compaction process. Bonding is critical in determining how a pervious concrete system will be used. Typically, permeable concrete is applied as parking lot pavement or as recreational walk way pavement because the general perception of pervious concrete is that it cannot support greater volumes or loads of traffic. These permeable surfaces certainly provide drainage, circulation, filtration and safety to low traffic areas but could possibly be applied to areas such as low to medium traffic road ways. Bonding mixtures vary by situation but the stronger the bond between aggregate particles the less likely a surface is to ravel or fall apart.

The aim of this study is to expand the use of pervious concrete and an improved understanding of PCP system configurations, material properties and pH variation would increase applicability and in turn provide a case study to display to the public for support. It is already known that polymer binders exist that improve the durability of pervious concrete but additionally known that ravel testing is still required (Sung, 2012). This is where tests such as torsion tests or pull tests are conducted and enable proper bond experimentation (Gunasekaran, 2011). Pull tests involve casting a sample of concrete around a rod or ring and applying a tension force that increases until failure (Gunasekaran, 2011). These experiments would help garner an understanding of where pervious concrete mixtures might be going wrong. With the advent of standards such as the American Society for Testing and Materials (ASTM) C1747 there are now ways to determine adequacy compared to known acceptable strength and standards (ASTM C1747, 2011). Abiding by these standards and working to improve upon them are imperative to the success and eventual widespread adoption of PCPs.

3.2 Sociological Aspects of Green Technology

This thesis will explore the sociological side of PCP usage in Athens, Georgia. Pervious concrete is an old technology and has proven capability which warrants study into the reasons why PCPs are relatively rare in Athens, GA. As mentioned in the Background section of this thesis, there are total of eight PCP surfaces in Athens and each varied in level of success and effectiveness. A basic understanding of industry perceptions would aid in the targeted improvement of PCP and is the basis for sociological research in this thesis. PCP usage is growing in North America and industry questions must be addressed.

One effort to address industry questions was created by Dr. Ferguson at the University of Georgia. The paper, which compiles answers to relevant questions regarding PCPs, is the result of 4 years of data collection and 12 years of experience. The answers address concerns regarding cost, performance, misconceptions of common technical requirements and usage. Some questions are basic and cover technical concepts such as the fact that PCPs do not have a runoff coefficient and others address ways to encourage use. When questioned about usage and widespread adoption the author states that usage is currently limited and still significantly less than conventional pavements (Ferguson, 2009). Additionally, Ferguson comments on the need for municipalities to ensure they are not unnecessary impediments to the use of PCPs (Ferguson, 2009). The paper illustrates the effectiveness of providing basic educational material as well as providing evidence to the existence of a knowledge deficiency.

A dissertation by Keith Poole at Clemson University covers the perceptions of storm water management professionals with regard to permeable interlocking concrete pavements (PICP). The study conducted a survey and chose a group of 300 individuals from which to gather data. The principle investigator concluded that a lack of education on the technology did not prevent individuals from knowing the benefits of that technology over more conventional concretes. In addition the study concluded that the lack of use of PICP was the result of a perceived cost factor (Poole 2009). The principle investigator recommended that more education be provided for their technology with a major focus of that education to be on cost and maintenance.

A paper by the American Society of Civil Engineers (ASCE) identified and discussed ten grand challenges facing civil engineering in the next decade. The principal investigators took a report produced by the ASCE Technical Council and built upon it with a focus on enhancing the use of data sensing and analysis (DSA). Expert opinions were solicited via the use of a survey and used to build a review of both the challenges and their possible solutions (ASCE 2014). The challenges included: High building energy consumption, crude estimation of sea level, increased soil and coastal erosion, inadequate water quality, untapped and depleted groundwater, increased traffic congestion, poor infrastructure resilience to disasters, poor and degrading infrastructure, need for better mining and coal ash waste disposal, and low construction site safety (ASCE 2014).

This literature review will focus on the challenge of inadequate water quality. The principal investigators state that, from an economic perspective, inadequacies in water quality in the U.S. would cost $202.5 billion to fix (ASCE 2014). Additionally, the authors state that inadequate water quality impacts both the environment and society in a significant way. Large and small mouth bass in the Potomac River, for example, harbored reproductive defects (ASCE 2014). In addition, human beings are at constant risk of developing cancer from over 229 million lbs of toxins released into water ways (ASCE 2014). The paper evaluates the economic, environmental, and societal impacts of this challenge in a similar fashion to how this research was conducted. The multidisciplinary focus is not only important but key to enhancing the use of DSA as scope and data sources are identified. This research sought to use multidisciplinary analysis for the purposes of enhancing PCP use through the interaction of societal input and laboratory research. The paper concludes by acknowledging the benefits of identifying challenges and using collaboration to address them. Data collection was paramount and illustrated the need for additional multidisciplinary research efforts in engineering.

3.3 Water Quality Performance

3.3.1 Water Quality Overview

Stormwater runoff is produced when storm events deposit rainwater that washes over impervious surfaces created through urban development. As water travels over parking lots and other impervious concrete surfaces it collects pollutants and flows into stormwater management systems. Most storm drains lead to lakes and streams. It is during these storm events that the pH of runoff must be monitored. pH levels may rise becoming too basic or fall becoming too acidic depending on what materials or pollutants the runoff comes in contact with. At either pH point, runoff begins to harm infrastructure and aquatic life. Many aspects of PCP systems have been studied but there is a general lack of literature on the subject of pH and filtration relationships. Concrete generally has a high pH and the goal of this study is to observe its effect on runoff from first flush onwards. The following sections relate relevant studies on pH and the filtration capabilities of PCP.

3.3.1.1 Water Quality Testing

Water quality testing generally centers on finding the concentrations of key elements within a water sample and determining if such concentrations are acceptable against current environmental standards. The EPA regulates a set of over 85 contaminants with additional lists and regulations still in development. pH, as mentioned before will be one major focus of this research and will accompany other key contaminants during this study. A complete list of all contaminants regulated by the EPA is located in Appendix A Table A.1 (EPA, 2009). A list of contaminants commonly tested for as of 2012 in Athens Clark County is displayed in Table 3.1 (ACC, 2012). These criteria reflect drinking water standards for Athens Clarke County.

Table 3.1 – Common Contaminants Tested for in Athens Clarke County (ACC, 2012)

Contaminant	Typical Source	EPA Ideal Goal	Highest Allowed Level	Detected Levels
Copper	Corrosion of household plumbing systems	1.3 ppm	AL 1.3 ppm	0.074 ppm
Flouride	Water additive that promotes strong teeth	4.0 ppm	4.0 ppm	0.88 ppm
Lead	Corrosion of household plumbing systems	0.0 ppb	AL 15.0 ppb	2.5 ppb
Nitrate	Runoff from fertilizer use	10.0 ppm	10.0 ppm	0.62 ppm
Total Trihalomethanes	By-product of drinking water chlorination	0.0 ppb	80 ppb	39.33 ppb
Turidity	Soil runoff	0.0	TT = 1 NTU	0.46
Total Organic Compounds	Naturally present in environment	N/A	TT (>35% removal required)	44.3%
Chlorine	Water additive for disinfection	4.0 ppm	4.0 ppm	1.91 ppm

Athens Clarke County Term Definitions (ACC, 2012):

- AL (Action Level) – The concentration of a contaminant, which if exceeded, triggers treatment or other requirements which a water system must follow.
- ppm (parts per million) – The equivalent of one drop of water in 42 gallons.
- ppb (parts per billion) – The equivalent of one drop of water in 14,000 gallons.
- MCLG (Maximum Contaminant Level Goal) – The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety.

- MCL (Maximum Contaminant Level) – The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to the MCLGs as feasible using the best available treatment technology.
- TT (Treatment Technique) – A required process intended to reduce the level of a contaminant in drinking water.
- Turbidity – A measure of the cloudiness of water. Monitored because turbidity is a good indicator of the effectiveness of our filtration system. NTU (Nephelometric Turbidity Unit) is a measurement of the clarity of the water

Pervious concrete systems, as mentioned earlier, are capable of addressing water quality concerns. A study on the effectiveness of addressing stormwater management problems in Rajkot, India, evaluates material properties in addition to filtration capabilities. The tests included the construction of demonstration units, a test section, and the filtration of local storm and stream water. Solis et al. sought to demonstrate that PCPs produced using local Rajkot materials could properly handle the city's stormwater management needs as well as mitigate increasing health risks in the area that would arise from excessive flooding while retaining acceptable strength (Solis et al., 2012). The PCP systems succeeded in mitigating some health and water management concerns such as high nitrogen levels but failed in others due to uncontrollable circumstances such as contaminant leaching and the presence of chemicals such as pesticides (Solis et al., 2012).

The paper concluded with recommendations to retest the same stream waters and the use of other mixture designs (Solis et al., 2012). The authors concluded that some interest in the use of PCP had been generated through the demonstrations but that proper training of personnel would be required for success.

A study from Ball State University evaluated the influence of various urban pavement types on water quality. The principal investigators sought to determine if the release of contaminants from pavements could negatively affect water quality (Bernot et al, 2011). They tested sealed and unsealed asphalt concrete pavement, recycled asphalt concrete pavement, Portland cement concrete, Portland cement concrete with fly ash, Portland cement concrete with ground-granulated blast furnace slag, and porous Portland cement concrete (Bernot et al, 2011). Similar to this research the principal investigators tested pH and the concentrations of contaminants such as heavy metals and phosphates (Bernot et al, 2011). Contaminant release is a concern for municipalities as it affects both environmental and public health. This research focuses on the influence of layer configuration on contaminant removal under 100% runoff capture conditions. The data suggested that concrete pavements can act as a source of contaminants as well as a conduit for receiving waters (Bernot et al, 2011). The paper illustrates the need to determine whether or not contaminant release can be buffered by filtration through additional layers.

3.3.1.2 pH and Pervious Concrete

A study at Washington State University on the relationship between pervious concrete and pH in terms of variables such as ambient air exposure, temperature, water carbonate levels and the age of the PCP concluded that pH levels had a tendency to drop as those variables were manipulated (Thomle, 2012). The principle investigators used two types of water for these tests: deionized water and tap water but did not use any type of authentic or simulated stormwater whether real or synthetic. Additionally, specimens were tested through total submersion rather than through other more realistic methods that would represent real world conditions. During specimen age tests, Thomle concluded that older samples tended to have lower pH levels. In addition, a decrease in pH of the concrete over time was observed (Thomle, 2012). Thomle then looked at the effect of ambient air on the pH of the PCP itself. Pervious concrete has an increased amount of surface area when compared to impervious concrete and as a result, water increases in pH as it infiltrates the PCP system. The ambient air exposure tests concluded that the pH of the concrete itself tended to decrease with sufficient exposure to air but that declines were restricted by level of exposure (Thomle, 2012). Finally, concrete undergoes a chemical process called carbonation. The process is slow but acts as a capture system for CO_2 (Thomle, 2012). With this in mind, the principal investigators tested different methods for accelerating the carbonation process (Thomle, 2012). The tests concluded with the observation that one could rapidly decrease pH levels in addition to sufficiently accelerating the carbonation process (Thomle, 2012). This acceleration could turn concrete into a CO_2 sink (Thomle, 2012).

Thomle had performed the study with the intention of providing designers with a means to prevent the damage of sensitive waters through the exfiltration of runoff that has made contact with PCP. Tests showed a significant decrease in pH but more notably with tap water. Tap water as well as storm water runoff contain minerals that accelerate the decrease in pH over time the principle investigators felt the use of such water simulated possible pH values for in place PCP installations more accurately (Thomle, 2012).

Another study on the "Multiyear Performance of a Pervious Concrete Infiltration Basin" took a broad look at the overall capabilities of PCP (Horst 2011). Testing was conducted over a 2 year period. The principle investigators tested a broad range of variables ranging from infiltration capability and permeability to pH levels and filtration capability. Referring to their PCP as a best management practice, Horst created a basin capable of catching runoff from the surrounding watershed. Tests were conducted after storm events and at different soil depths. The variation in soil depth sampling allowed Horst to observe changes in pH, infiltration rate, and contaminant accumulation.

The study concluded with positive results. Horst logged high infiltration rates, high runoff capture rates, and decreases in contaminant concentrations between inlet and outlet. pH levels within the soil experienced a decrease over time but Horst elaborated very little on the consequences of such a decrease. The lack of further recommendation implies the need for further research but their preliminary results do point in a positive direction.

A similar study on the water purification properties of porous concrete investigated the compressive strength and water purification properties of porous concrete using two different aggregate sizes. Water purification capability was measured by recording the quantity of phosphorus and nitrogen removed from sample water. Sung-Bum et al. tested pH changes over time as a part of these water purification tests.

During the Sung-Bum et al. (2003) pH study, it was observed that specimens submerged in water for a set number of days yielded an increase in pH. These levels peaked at a pH of approximately 11.17 (Sung-Bum et al, 2003). The pH, however, dropped to a low of approximately 9 within 90 days which Sung-Bum et al. deemed suitable for aquatic life (Sung-Bum et al, 2003).

Upon competition of the study, Sung-Bum et al. concluded that pervious concrete pavements are able to effectively purify water (Sung-Bum et al, 2003). Purifications tests showed a steady decrease in phosphorus and nitrogen levels as a result of attached microorganisms. This study is supported by findings in a study from the University of Kentucky.

A study at the University of Kentucky explored the consequences of filtering manure through a PCP system. The principle investigators used simulated rainfall events and a number of mixture designs during their tests. The total number of specimens was 48 and those specimens were created using hand forms (Higgins, 2013). The rainfall was calibrated to simulate a 25 year, 1-hr storm. Higgins tested variables such as ammonia and carbon dioxide emissions, fecal coliform populations, and analyte concentrations within the effluent.

Analyte concentrations varied from week to week with peak concentrations occurring during the initial flush (Higgins, 2013). Additionally, there were decreases in some analyte concentrations during subsequent simulated rainfall events (Higgins, 2013). CO_2 emissions from the PCP system showed evidence of respiration and the decomposition of manure. Additionally fecal coliform populations dropped after one week.

Finally, a study at the University of Colorado explored the sustainable design of pervious concrete. The authors address the use of several different recycled aggregates, the construction of a large test section, and the water quality improvement capability of that test section relative to EPA standards. Water quality tests utilized real stormwater samples and observed the change in pH among other variables. Stormwater were incorrectly gathered and did not reflect first flush conditions. Variations in pH were observed with some increases in pH exceeding 11.78 (Hager, 2009). Those levels were significantly higher than control samples and EPA standards (Hager, 2009). The author, however, attributed these higher than normal increases to the type of recycled aggregate used in each sample (Hager, 2009). Hager commented that higher pH levels could serve as a buffer against acidic solutions and acid rain. That observation is supported by Solis et al..

The findings in the Hager study warrant the need for additional pH study under normal conditions using common PCP mixture design. The findings support the need for study on long term pH behavior as water percolates through a PCP system over time.

3.4 Field Placement

3.4.1 Pervious Concrete Mixture Recommendations

There are a variety of cement types and additives that are recommended for pervious concrete. Aggregate type and size as well as water-to-cement ratios (w/cm) and fine aggregate content are variable and depend on the climate and available materials. In addition, mixtures employ a variety of additives that tend to improve performance of pervious concrete. Performance improvements range from increased durability to increased strength and permeability.

In pervious concrete, carefully controlled amounts of water and cementitious materials (typically very low) are mixed to create a paste that coats the aggregate particles. A pervious concrete mixture contains little-to-no fine aggregate (sand), thus creating a substantial void content of approximately 15-25% voids (Tennis, et al., 2004). Because pervious concrete is generally a specialty mixture (not all concrete designers and producers are knowledgeable on the material), care must be taken when designing, mixing, placing, and curing the pervious concrete. Numerous state and national organizations provide recommendations for the design of pervious concrete mixtures and subsequent sections review these recommendations in greater detail.

3.4.1.1 Current Mixture Design Specifications

The following bullets describe the current mixture design specifications and guides used for this thesis.

- *Georgia Concrete Products Association Specifications (GCPA)* – The GCPA Specifications make recommendations on a number of aspects of PCP construction. These aspects include but are not limited to contractor qualifications, panel testing, mixture design and materials, proportions, subgrade preparation, placement, and testing.
    - Category: Specification
    - Year: 2006

- Version: Revision of August 2006

- *Specifier's Guide to Pervious Concrete Pavement Design* – This guide was created for Colorado land development and addresses specific climatic conditions when designing PCP systems (CRMCA, 2009). The guide, sanctioned by the Colorado Ready Mixed Concrete Association, addresses freeze thaw cycles, seasonal temperature variations and other environmental factors that affect the construction of PCPs and provides detailed instructions for constructing a PCP system (CRMCA, 2009). These instructions are found in subsequent sections and tables located in Section 3.4.1.2.
  - Category: Guideline
  - Year: 2009
  - Version: 1.2
- *Concrete in Practice (National Ready Mix Concrete Association)* – This short guide published by the National Ready-Mixed Concrete Association (NRMCA) quickly outlines general guidelines for installing and designing pervious concrete pavements. These general guidelines include recommended w/cm, acceptable compaction densities, acceptable porosities, and general methods for placing PCPs such as subgrade preparation.
  - Category: Guideline
  - Year: 2004
  - Version: 1
- *Pervious Concrete Pavements (National Ready-Mixed Concrete Association)* – This guide provides a more detailed account of how to design and place PCP systems. The authors provide instructions and background information on PCP design considerations, performance, behavior and engineering properties.
  - Category: Guideline

- Year: 2004
- Version: 2

- *Construction and Maintenance Assessment of Pervious Concrete Pavements* – This report is an assessment of maintenance methods used to clean PCP sites in three different states. This assessment was conducted by the Florida Department of Transportation in conjunction with the University of Florida. The paper covers 2 sites in Georgia and several others in both Florida and South Carolina. Testing included the use of two cleaning methods: vacuum sweeping and pressure washing individually or in combination. Both methods resulted in around a 200% increase in infiltration rates.
  - Category: Guideline/Report
  - Year: 2007
  - Version: 1
- *Sustainable Design of Pervious Concrete Pavements* – This dissertation produced by Dr. Hager of the University of Colorado Denver covers the sustainable design and construction of PCP in the unique Colorado climate. It explores specific mixture design recommendations, the use of various admixtures and the use of a variety of aggregate types.
  - Category: Dissertation
  - Year: 2009
  - Version: 1
- *American Society of Testing and Materials Standards (ASTM)* – Six ASTM standards will be used to assist with design within this project. These standards are ASTM C666A Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM C944 Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method, ASTM C1747 Standard Test Method for Determining

Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion, ASTM C1701 Standard Test Method for Infiltration Rate of In Place Pervious Concrete, ASTM C1754 Standard Test Method for Density and Void Content of Hardened Pervious Concrete, ASTM C33 Standard Specification for Concrete Aggregates, ASTM C150 Standard Specification for Portland Cement, ASTM C1157 Standard Test Method for Hydraulic Cement and ASTM C1688 Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete. Version and year was not available.

  - Category: Specification
  - Year: N/A

- *American Concrete Institute Standards (ACI)* – The ACI 522.1-13 Specification was created specifically for use with pervious concrete. The guide covers mixture design, placement recommendations, and other design details. Version was not available.
  - Category: Specification
  - Year: 2013

3.4.1.2 Specification Comparison

Comparisons of all mixture design specifications or guidelines are summarized in Table 3.2.

Table 3.2 – Mixture Design Specification Comparison

Design Spec	Source	Recommendation
Aggregate Size	GCPA	Well graded. Follow ASTM C 33
	NRMCA 1	No Requirement
	NRMCA 2	Follow ASTM C 33
	CRMCA	Follow ASTM C 29
	Hager	Follow ASTM C 33
	FDOT	Follow ASTM C 33
	ASTM	Follow ASTM C 33
	ACI	Shall not exceed 1 in.
Cementitious Material	GCPA	Portland Type I or II. 600 lbs/ yd^3 for vehicular traffic.
	NRMCA 1	No Requirement
	NRMCA 2	450 – 700 lbs/yd^3
	CRMCA	450 – 550 lbs/yd^3
	Hager	525 lbs/yd^3
	FDOT	No Requirement
	ASTM	No Requirement
	ACI	No Requirement
Water to Cement Ratio	GCPA	No Requirement
	NRMCA 1	0.35 to 0.45
	NRMCA 2	0.27 to 0.34 with admixtures
	CRMCA	0.26 to 0.35
	Hager	0.30
	FDOT	No Requirement
	ASTM	No Requirement
	ACI	No Requirement

Table 3.2 – Mixture Design Specification Comparison Continued

Design Spec	Source	Recommendation
Aggregate Content	GCPA	No Requirement
	NRMCA 1	No Requirement
	NRMCA 2	2000 to 2500 lbs/yd^3
	CRMCA	The bulk volume of aggregate per cubic yard shall be equal to 27 ft^3 when calculated from the density determined in accordance with ASTM C29 Jiggling Procedure
	Hager	No Requirement
	FDOT	No Requirement
	ASTM	Follow ASTM C29
	ACI	Follow ASTM C29

3.4.2 Placement

3.4.2.1 Layering

Pervious concrete systems generally contain two or three layers. These layers then contain a variety of materials depending on application, climate, subgrade and need. The first layer, consists of a pervious concrete slab, resides at the top with subsequent layers containing materials such as gravel or free drain rock or sand. In addition some layers may be lined with geotextile fabrics or impervious polymers depending on need. At this moment no specifications provide recommendations on layering. Many specifications provide design specs that cater to two layer configurations but do not emphasis specific layering arrangements. An example of the difference between layers is displayed in Figures 3.1 and 3.2 (Hager, 2009).

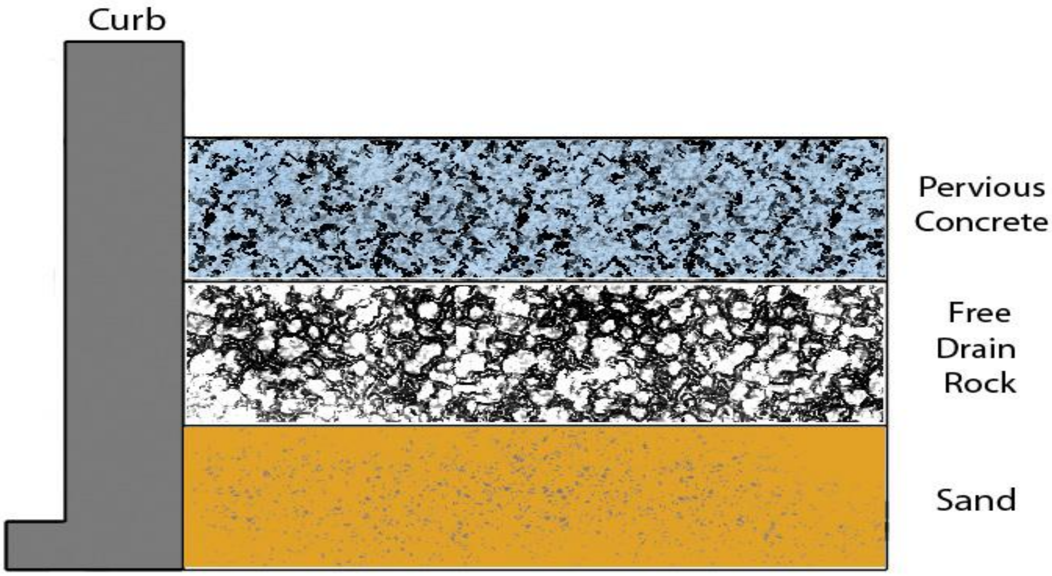

Figure 3.1 – Example 3 layer PCP system (Hager, 2009)

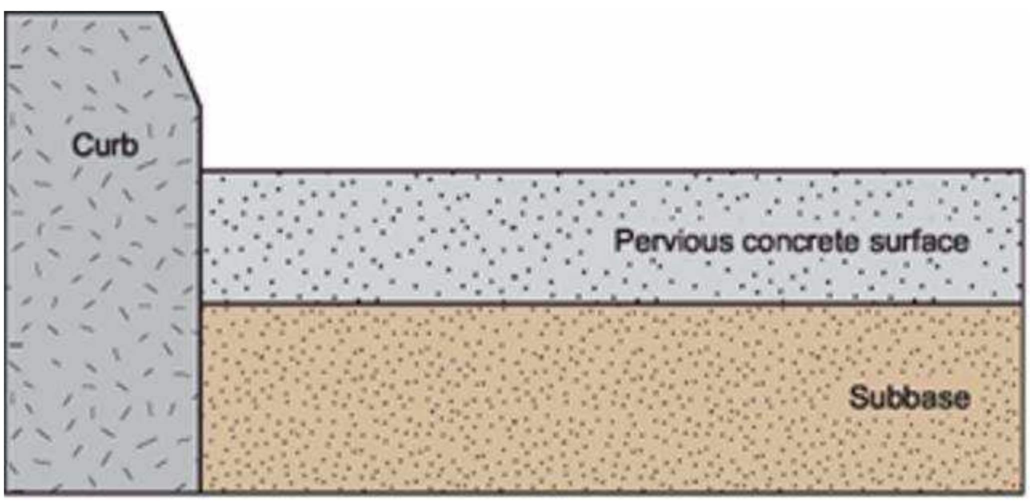

Figure 3.2 – Example of 2 layer PCP system (Tennis et al, 2004)

3.4.2.2 Subgrade Preparation

A comparison of specifications for subgrade preparation is summarized in Table 3.3.

Table 3.3 - Subgrade Design Specification Comparison Table

Design Spec	**Source**	**Recommendation**
Subgrade Prep	GCPA	Top layer must contain 6 in free drain rock or non-woven geotextile fabric. Must compact to min density of 95%.
	NRMCA 1	Compact to between 92 and 96%. Free drain rock layer. Moisten subgrade prior to placement.
	NRMCA 2	Compact to between 90 and 95%. Moisten subgrade.
	CRMCA	Moisten subgrade.
	Hager	No Requirement
	FDOT	Top layer must contain 6 in free drain rock or non-woven geotextile fabric.
	ASTM	No Requirement

3.4.2.3 Construction

Visual inspection of all elements prior to field placement of PCP is imperative to successful construction. Mixture consistency should reflect acceptable standards and carry a wet-metallic sheen when visually inspected. If a mixture fails to meet these standards or contains too much water, it should be rejected (Hager, 2009). Construction of PCP involves five basic steps. These steps are as follows (Hager, 2009):

- *Placement of concrete* – The sub-base of a PCP site must be moistened prior to placing the concrete (Hager, 2009). This ensures that the coarse aggregate does not absorb water from the PCP mixture and ensures proper hydration occurs from the beginning. Additional moisture is applied to the surface of a PCP bed following successful placement. For smaller sites hand tools are required to aid the movement of pervious concrete mixtures out of the concrete truck and into the area to be constructed.

- *Screeding* – A screed is a tool used to smooth concrete after it has been placed (Hager, 2009). This tool allows for screeding or the process of removing excess wet concrete and smoothing the surface of the pavement (Hager, 2009). The process brings the surface to proper grading and provides a safe uniform means for compaction. The screed to be used in this case is a steel roller screed.
- *Compaction* – Pervious concrete requires careful control of compaction. Too much compaction will result in reduced void space and too little will give the PCP more potential for degradation as well as less strength and smoothness (Hager, 2009). A reduction in void space results in reduced porosity. Compaction may result in smaller void ratios at the surface of a PCP section than at the lower regions of the system as well (Hager, 2009). Care should be taken to ensure consistency throughout the PCP layer. Compaction is usually achieved during the screeding process using rollers to complete the process.
- *Jointing and Edging* – The drying process for standard concrete and PCP has the potential to cause cracks. Those placing PCP control these cracks by installing joints. Joints are not always needed but are recommended when PCP dimensions exceed 20 feet (Hager, 2009). The edges of a PCP slab are the weakest part of the pavement. As such, extra material and compaction should be administered at those locations during the finishing process (Hager, 2009).
- *Curing* – Concrete requires controlled curing to gain strength and hydrate properly. This requires proper regulation of moisture and temperature. Curing is facilitated through the

application of water to the surface of the PCP and through the placement of sheathing, often made of plastic, over the top of the site. These plastic sheaths must be placed no later than 20 minutes after pervious concrete is placed and should be secured properly to ensure minimal evaporation occurs (Hager, 2009). Curing should be facilitated for no less than 14 days (Hager, 2009).

Additional provisions include:

- Contractor qualifications: This provision will follow GCPA and NRMCA standards. GCPA guidelines for Georgia state that all technicians must pass the NRMCA Pervious Concrete Technician Exam and attend training classes. All installers must also pass an NRMCA Performance Test in addition to all Technician requirements.
- Diversion of sediment: The Florida Department of Transportation briefly discusses the diversion of runoff from unfinished areas around a PCP site to ensure no clogging occurs. The GCPA, CRMCA and NRMCA provide no specific guidelines for sediment diversion but mention that clogging will occur over time if not maintained and prevented.

4. PROBLEM STATEMENT

Urban developments greatly alter the natural environment and as such afford distinct problems such as the heat island effect, increases in stormwater runoff, limited groundwater recharge, the introduction of contaminants, increased use of drainage accessories such as detention ponds, and safety issues such as ponding on impervious surfaces with poor drainage systems. Municipalities look to multiple solutions to help remedy such situations and many turn to pervious concrete pavements (PCP). Pervious concrete is an old technology but remains relatively underutilized. There are many proven benefits with known actual and perceived hazards to using the technology but the sparse literature surrounding the subject warrants additional research. This thesis seeks to expand on existing research and explore the sociological barriers that hinder the use of PCP in Georgia. This study will occur in two phases and each phase will inform the design and implementation of subsequent phases.

The first of two phases will involve a sociological study via survey and interview and will gather data on why pervious concrete is not as widely utilized within Georgia. The second phase will involve exhaustive technical laboratory testing. Experimentation will include hydrologic and water quality testing. The main objective of Phase 2 is to study PCP technically and follow up with community initiatives that enhance and expand proper and successful PCP use within UGA and Athens. In addition, laboratory testing will include the fabrication of demonstration units that will remain available to the civil engineering department for educational purposes.

The sociological side of a technology is rarely explored and such studies have rarely been performed with regard to pervious concrete pavements. Additionally, very few studies have explored the changes in pH levels and contaminant removal under realistic circumstances and practical conditions.

5. EXPERIMENTAL PLAN

5.1 Introduction

Each phase of this project is designed to build upon information gathered in previous phases. In Phase 1, a preliminary sociological study was conducted to inform the actions and designs of Phase 2 laboratory testing. Demonstration units varied in both layer design and cement content.

A flow chart showing the progression of the experimental plan is displayed below in Figure 5.1.

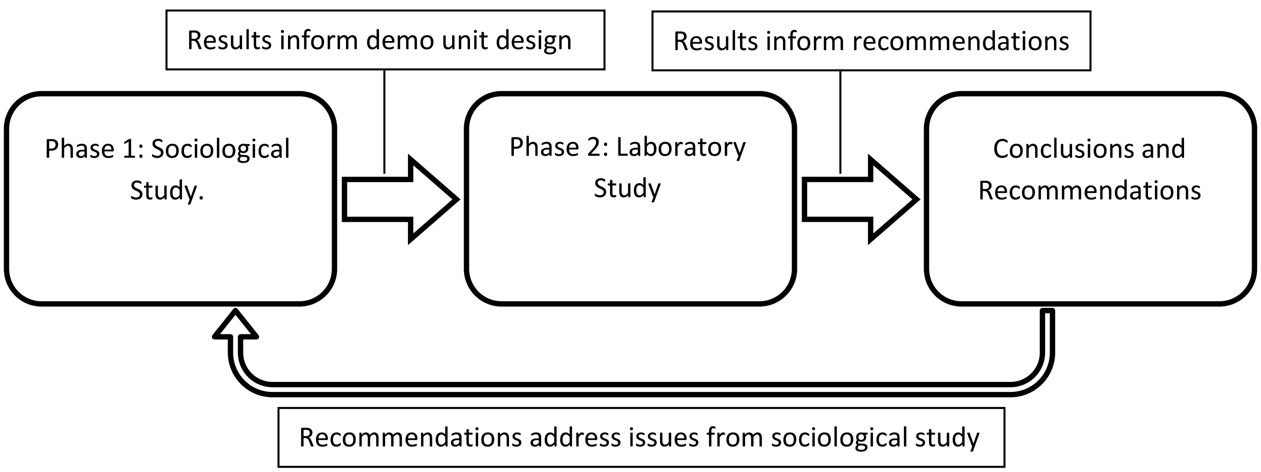

Figure 5.1 – Experimental Plan Flow Chart

5.2 Phase 1 Study: Sociological Survey

The phase 1 study focused on determining a basic understanding of sociological barriers that may limit the use of PCP in Athens, GA. A survey comprised of 6 questions was designed to gather information on experience level with PCP, what perceived barriers individuals believed stand in the way of PCP use and willingness to participate in educational workshops. The survey was built using Survey Monkey online tools and was distributed to ready-mixed concrete companies, architect firms, engineers, municipalities, landscaping companies, and university faculty. In addition to the survey, a number of individual interviews were conducted via telephone and email. A copy of the questions posed in the survey is displayed in Appendix A. The same survey questions were used to gather information through interviews. Interviews were conducted primarily via phone calls.

5.3 Phase 2 Study: Laboratory Testing

5.3.1 Overview:

The phase 2 study involved the development of 10 demonstration units which contained small scale representative PCP systems. The PCP demonstration units consisted of 2 to 3 layers. The two-layer system contained an 8 in (20.4 cm) pervious concrete and 8 in (20.3 cm) free drain rock layer. The three-layer system contained the same pervious concrete and free drain rock layers with an 8 in (20.3 cm) underlying sand layer. The focus of Phase 2 was water quality testing and the optimization of material properties. Water quality testing included the observation of pH variation with changes in cement content and the PCP layer configuration.

The demonstration units contained concrete mixtures varying in cement content from 450 to 650 lbs/ yd^3 (267 to 386 kg/m^3) and were tested using synthetic stormwater. Water quality testing was performed on filtered exfiltrated or outlet water, and all results were compared to EPA standards. Filtration capability was measured by determining how much pollutant was removed from samples.

Each demonstration was comprised of three basic elements: the container, the underdrain system, and the PCP system. For this study, the container was made out of a plastic 32 gallon bin akin to the one displayed in Figure 5.2. The underdrain system was comprised of a simple valve and is pictured in Figure 5.3. An internal schematic view of a demonstration unit is displayed in Figure 5.4. Each layer within the pictured systems had a thickness of 8 in (20.3 cm). This thickness was chosen based on the Hager study and to ensure the layers were above the 6 in minimum thickness recommended by the GCPA for free drain rock.

Figure 5.2 – Example Demonstration Unit

Figure 5.3 – Under-Drain Valve

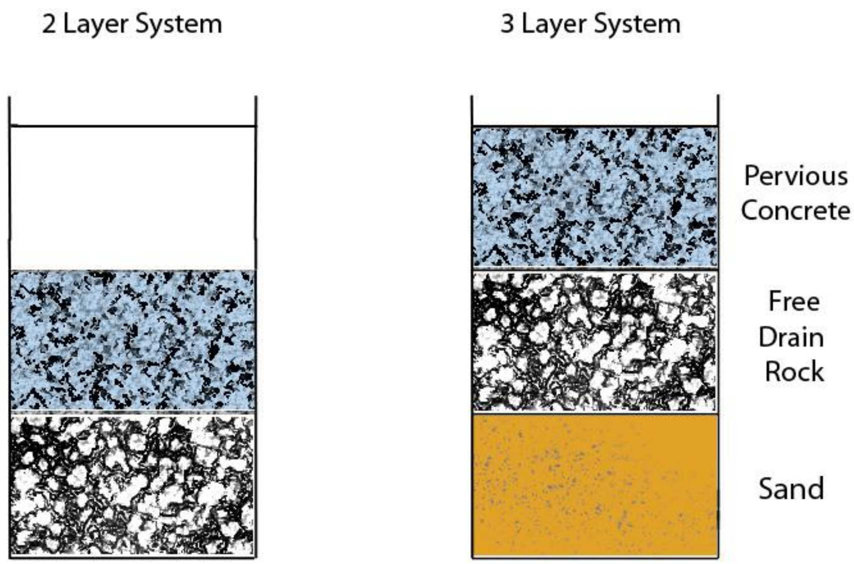

Figure 5.4 – Internal View of Example 3-Layer and 2-Layer Demo Unit

There were a total of ten demonstration units constructed for this experiment. Those ten units were divided into two groups of five (3-layer and 2-layer groups) to be tested individually. The overall goal of this study was to observe the effectiveness of different layer designs and cement contents as well as observe the effect of these systems on the pH of water passing through the system. The PCP system and concrete mixture details are presented in Table 5.1.

Table 5.1 – Testing Matrix

Demo Unit	Cement Content (lbs/ yd^3)	Water to Cement Ratio	Admixtures	Concrete Aggregate Size	Layers	Cement Type
Group 1	3-Layer PCP Systems					
DU – 1	650	0.30	VMA, HCA	<1 in	PC, FDR, Sand	Type II
DU – 2	600	0.30	VMA, HCA	<1 in	PC, FDR, Sand	Type II
DU – 3	550	0.30	VMA, HCA	<1 in	PC, FDR, Sand	Type II
DU – 4	500	0.30	VMA, HCA	<1 in	PC, FDR, Sand	Type II
DU – 5	450	0.30	VMA, HCA	<1 in	PC, FDR, Sand	Type II
Group 2	2-Layer PCP Systems					
DU – 6	650	0.30	VMA, HCA	<1 in	PC, FDR	Type II
DU – 7	600	0.30	VMA, HCA	<1 in	PC, FDR	Type II
DU – 8	550	0.30	VMA, HCA	<1 in	PC, FDR	Type II
DU – 9	500	0.30	VMA, HCA	<1 in	PC, FDR	Type II
DU – 10	450	0.30	VMA, HCA	<1 in	PC, FDR	Type II

Table Terms

- DU – Demonstration Unit
- VMA – Viscosity Modifying Admixtures
- PC – Pervious Concrete
- FDR – Free Drain Rock
- HCA – Hydration Controlling Admixture

The cement content, w/cm, admixtures, aggregate size, and cement type were all chosen based on industry standards and the recommendations of past studies and current specifications from the NRMCA, ACI, and ASTM previously discussed in section 3.4.1.1. The cementitious materials content for pervious concrete mixtures ranged from a lower limit 450 lbs/yd^3 (NRMCA 2 and CRMCA) to an upper limit of 700 lbs/yd^3 (NRMCA 2). For the purposes of this research and based on previous literature a cementitious materials content range of 450 to 650 lbs/yd^3 (267 to 386 kg/m^3) was chosen. Refer to Table 3.2 of the literature review. Specifically, cementitious materials contents that were evaluated in this study are 450, 500, 550, 600, and 650 lbs/yd^3. Mixtures with higher cementitious contents were expected to increase the pH of effluent water as a direct result of increased levels of calcium hydroxide formed during the reaction between portland cement and water (Thomle, 2012). A w/cm ratio of 0.30 was chosen based on the Hager study. See Table 3.2. This w/cm ratio provides sufficient water to the cementitious content reactions while ensuring a compressive strength above 2000 psi given proper placement and curing procedure (Hager, 2009). Admixtures were chosen as necessary to place PCP in the local climate and to preserve workability. The use of VMAs or viscosity modifying admixtures results in better flow, quicker discharge from concrete truck, and easier placement and compaction (Majdoub, 2011). The use of hydration control admixtures or HCAs slows the rate of hydration and extends the life of fresh pervious concrete. Both HCAs and VMAs were not necessary to the construction of the demonstration units but apply more to field placement.

Aggregate size was uniform and did not exceed 1 inch as recommended by ACI. Layer configurations were chosen based on the Hager study and NRMCA recommendations. The NRMCA PCP guidelines show a two layer configuration and the Hager study makes use of a three layer configuration. It is expected that the three layer configuration yields greater benefits as it contains both a detention layer of free drain rock and a filtration layer of sand. Refer to Figure 3.1 as an example. The NRMCA configuration makes use of only a free drain rock layer for detention purposes. Please refer to Figure 3.2 as an example.

Upon completion of all demonstration units, a series of trials were conducted to determine the change in pH over several storm events when utilizing collected or synthetic stormwater in addition to the filtration capability of each unit according to their layer configuration and design.

5.3.2 Pervious Concrete Mixing and Placement

Mixture portioning was determined via the use of concrete mixture design spreadsheets developed by the UGA concrete materials research group. These spreadsheets provided the values for aggregate content, water content, and cement content in lb/yd^3 and provided additional tools for portioning out individual batches. The values for each of the five mixtures are displayed below in Table 5.2.

Table 5.2 – Mix Design Values

Mixture	Cement Content (lb/yd^3)	Aggregate Content (lb/yd^3)	Water Content (lb/yd^3)	Water to Cement Ratio (w/cm)
Mixture 1	450	2889	135	0.30
Mixture 2	500	2806	150	0.30
Mixture 3	550	2722	165	0.30
Mixture 4	600	2639	180	0.30
Mixture 5	650	2555	195	0.30

The values in Table 5.2 were calculated after setting the water to cement ratio to 0.30, the sand content to 0 lb/yd^3, the specific gravity (S.G.) of the concrete aggregate to a value of 2.70, the absorption coefficient (A.C.) of the concrete aggregate to 1.15 and the desired air void content to 0.20 which was the optimum air void content determined by the Hager study (Hager 2009). The S.G. and A.C. values were provided by the quarry who provided the aggregate. The aggregate used for mixing was No. 89 rock. This aggregate was recommended for use by a local ready-mix company and contained enough fines to remove sand from the design calculations. It was believed that this aggregate gradation would provide the necessary strength for the pervious concrete while maintaining adequate hydrologic capabilities.

Additionally, values were adjusted according to the moisture content of the aggregate for the day concrete mixtures were produced. Mixing did not occur until the exact weight of each element was determined accurately. Once acquired each material was measured out using a table and floor scale. Each sub-layer (free drain rock and sand) required installation prior to pervious concrete mixture placement. Sub-layers were separated via the use of geotextile sheets. The geotextile used for this application was chosen for its resistance to pH change and for its ability to separate layers but not filter. In this case, the geotextile used was a woven TenCate Mirafi X-Series fabric. The geotextile sheets were located below the sand layer to stop sand from entering the underdrain system and located below the free drain rock layer which prevented layer mixing.

The bottommost layer within each 3-layer system was comprised of Georgia Department of Transportation approved sand. This sand was made from crushed granite. The free drain rock layer within both the 3-layer and 2-layer systems were comprised of No.57 aggregate. As mentioned earlier each layer within a system was designated as 8 inches (20.3 cm) in thickness. Each layer was compacted using hydro compaction and light tapping on the bin surface. Water was poured over each layer upon completion and left to sit as compaction occurred and air pockets were removed. The water compaction also helped with subgrade preparation as the lower layers required hydration before pervious concrete placement.

Pervious concrete mixing was conducted using a 12.5 cu ft electric concrete mixer and each of the five mixtures were portioned such that both the two layer and three layer systems could be placed in one batch. The process for mixing requires that close attention be paid to the pervious concrete mixture as materials are slowly added. The materials in this case were added in small portions and mixed together until all materials were deposited into the mixer. The aggregate, cement and water were then mixed until the pervious concrete took on a metallic shine as per the recommendation of the Hager study. Each of the five different pervious concrete mixtures were placed into their respective demonstration unit upon completion of each batch.

This ensured optimum workability and time for molding and placement. Shovels were used to transport fresh concrete into each demonstration unit and then worked into place and proper thickness by hand.

Once placed the pervious concrete layers were then compacted using a wooden compaction tool built specifically for these specimens. This compaction tool is displayed in Figure 5.5. After achieving the desired thickness and properly compacting each unit, a sheet of plastic was placed over the unit and sealed using duct tape.

Figure 5.5 – Picture of Compaction Tool used on demo units

Each demonstration unit underwent seven days of intensive curing where the tops of each unit were covered and sealed with plastic sheeting. The seals were intended to capture and contain moisture within the demonstration unit. This containment of moisture ensured that the concrete was supplied with enough water to maintain the curing process. In addition, the curing process was supplemented by water misting each demonstration unit every day during the 7 day intensive curing period.

5.3.3 Synthetic Stormwater and Storm Event Simulation:

The experimental plan originally included the use of local street sweeper waste to make contaminant rich synthetic storm water solutions that reflected what could be found as pollutants in Athens. This plan, however, was rejected when consistency and steady supply could not be effectively achieved. The street sweeper waste either did not contain a high enough concentration of any one contaminant or would have been inconsistent from batch to batch.

Synthetic stormwater solutions contained contaminants commonly tested for in the Athens area and abroad. The contaminants tested for in this phase are listed in Table 5.3. Those contaminants were chosen based on multiple sources and were considered as representative of the more important contaminants to observe. Values for pH were tested for and obtained before and after passing through each demonstration unit. Water quality testing involved the production and use of synthetic stormwater. This synthetic stormwater was comprised of five elements that were obtained through additional research closer to the conduction of Phase 2 testing. The five elements and their concentrations are displayed below in Table 5.3.The concentrated solution was created at a local water quality testing lab using stock solutions for each heavy metal and element. These elements were found in urban stormwater here in Georgia and in other states (A.J. Erickson et al 2013). Additionally, a local water quality laboratory collaborated with this research to create both the test concentrations and desired element composition selected for Phase 2.

Table 5.3 – Contaminant List and Concentrations

Contaminant	Desired Concentration (ppm)
Cadmium	0.005
Copper	0.40
Phosphorus	2.00
Lead	0.50
Zinc	1.00

The concentrations in Table 5.3 were formulated with aid from the local water testing lab after several preliminary batches were created to ensure the desired concentrations were achieved. Final concentrations reflected the maximum found in A.J. Erickson et al (2013) and the decision of the water testing lab to increase some initial concentrations even further. The increased concentrations ensured that detectable change would be found during testing and dilution. The concentrated synthetic stormwater solution was poured directly into a tank containing 50 gals of normal tap water and mixed thoroughly and constantly using a drill and paddle mixer for 5 minutes. All contaminants were dissolved.

Once mixed the release valve at the bottom of the tank was opened to allow any residual water to evacuate the drain pipe. An initial sample was taken and stored after ensuring excess water had left the pipe and that the synthetic stormwater had gotten a chance to reach the outlet. An example of how each synthetic stormwater batch was mixed is shown in Figure 5.6. A picture of the tank and valve mentioned earlier is shown in Figure 5.7 and Figure 5.8.

Figure 5.6 – Mixing Synthetic Stormwater using drill and paddle

Figure 5.7 – Picture of 50 gal tank and valve

Figure 5.8 – Picture of 50 gal tank and valve

5.3.4 Contaminant Removal Trials:

A total of 7 trials were conducted over a two month period to measure the contaminant removal capability of each of PCP system. Trials were conducted at intervals during the experimental phase. These trials tested contaminant removal over a set number of simulated storm events. The interval for the trials was 5 storm events. After thirty one storm events a total of 7 trials were conducted. One storm even occurred per day. Storm event simulations did not occurred on consecutive days.

The first trial occurred on the first day of testing and occurred under first flush conditions. During each trial, initial samples were taken directly from the mixing tank. These samples were gathered to test contaminant concentrations before the synthetic stormwater passed through each system. Effluent samples were taken after 2.5 gals (9.5 L) passed through each system. These samples were gathered to test the concentration of contaminants after passing through the PCP system. These samples were then taken to a water quality laboratory within 48 hours for testing. Forty-eight hours represented an optimum holding time as designated by the water testing lab.

During each trial a set and consistent volume of water was carefully poured into each system. A volume of 5 gallons (19 L) was chosen as a practical and consistent measurement that could be applied to each unit. During preliminary research a several volumes were considered but rejected as a result of being too impractical. Average rainfall amounts in inches for the local area along with storm event types used in other studies were either requiring too much water or providing too little for the purposes of testing.

Measures needed to be taken to prevent cross contamination and provide consistent representative samples during testing. To ensure optimum representation the previous days water was drained until no water dripped out of the system. When running both contaminant removal trials and off day water pH testing 2.5 gals (9.5 L) were then allowed to drain out of each system of the total 5 gals after pouring. This allowed for any residual water from previous trial or non-trial runs to drain out and for the trial solution to properly run through the system. Outlet samples were taken and stored for testing once sufficient water had pass through the system. Trail runs were conducted every five days for 31 days. This allowed for a total of 7 total contaminant trial runs and 24 off days. During these off days 5 gallons of water were poured through each simulated pervious concrete system to represent a storm event. Before and after measurements of pH were taken during these off days and recorded to determine how much the pH would be drawn down over time.

5.3.5 pH Testing:

Water pH testing was conducted using a pH meter and a set of sample bottles that were rinsed before each sampling. Water samples were gathered before and after each simulated storm event and trial for each demonstration unit. A picture of the pH meter used in these experiments is displayed in Figure 5.10.

Figure 5.10 – Picture of pH meter used for measurements

125 ml sample bottles were used for pH testing and were filled with effluent water to ensure maximum submersion of the pH meter probe. pH measurements were not recorded until the pH reading was completely stable. Stability ensured an accurate reading each time. The pH meter probe was thoroughly rinsed after each reading to ensure no cross contamination or inaccurate readings occurred from sample to sample. A picture of how the pH meter probe was used to measure pH is displayed in Figure 5.11.

Figure 5.11 – Picture of pH testing

Each demonstration unit underwent full draining after each trial and off day simulated storm event. Full drainage allowed for excess test water to be removed from the PCP systems. Drainage time varied from unit to unit, and water was collected using wide pans or hoses attached to demo unit outlets. An example of the drainage conducted for each trial is shown in Figure 5.12.

Figure 5.12 – PCP Demo Unit Drainage

5.3.6 Void Content Testing:

The void content test followed the procedure provided by the Hager study. The procedure is listed below (Hager 2009):

Procedure:

1. Obtain a container that can completely contain the concrete specimen (it is preferable, if possible, to use a container with the same dimensions as the concrete specimen, i.e., for concrete cylinder specimens use an empty cylinder mold). Measure the inside dimensions of the container (if not readily available).
2. Measure the diameter and length of the pervious concrete.
3. Place the pervious concrete specimen into the container.
4. Slowly pour water into the container until it is filled. As the water nears the capacity of the container, the flow should be limited to a trickle. Once the water over-flows the container, the water flow should be limited to a drip. Continue to drip water for an additional approximate 15 seconds after over-flowing the container.

5. Pour the water from the container into a graduated cylinder, and measure the amount of water. The container should be allowed to drain until no water drips from the container for a period of at least 15 seconds. *Note: The longer that the sample is submerged in the water filled container, more of the smaller inner voids of the pervious concrete will become saturated, thus increasing the percentage of porous void space calculated and providing a more accurate measurement of the porosity.*
6. Calculate the percent porous void space as:

$$\%\,Void\ Space = \frac{Volume\ of\ Water}{Volume\ of\ Concrete\ Specimen} \qquad \text{Equation (5.1)}$$

5.3.7 Compressive Strength Testing:

The compressive strength test was conducted using an automated compressive strength testing machine. For this laboratory study five test cylinders were created to represent the five mixtures used for the PCP demonstration units. Upon completion of the void content test listed earlier each cylinder was tested using the same preloading and ramp up. The preloading used in this case was 1000 lbf (4.45 kN). That ramp up, which controlled how much loading the cylinder received per second was 35 psi/s (241 kPa/s).

All void content tests were conducted before compressive strength tests. Each cylinder was tested individually and tested until complete failure was achieved. Instructions for compressive strength testing are listed below:

1. Remove test cylinder from any molds or containers
2. Complete all void content tests
3. Ensure excess water is removed
4. Center cylinder within testing machine

5. Jog compression arm down until slight contact is made with cylinder holder surface
6. Tare/zero machine so no initial stress or load is recorded
7. Begin test and continue until cylinder failure and machine stop
8. Clear debris and repeat for all test cylinders

6. EXPERIMENTAL RESULTS

The research for this thesis was split into two phases. The first phase involved a cursory sociological study with the goal of determining whether or not there were barriers limiting the use of pervious concrete and whether or not individuals were willing to learn more about the technology. This sociological study involved the use of surveys and interviews. The second phase of research involved extensive laboratory testing and explored the changes in pH over thirty-one storm events within ten PCP systems and the contaminant removal capability for both two and three layer systems. Thirty-one simulated storm events were conducted with 7 of these simulated storm events being contaminant removal trials.

6.1 Sociological Study

The purpose of the sociological study was originally to determine why pervious concrete was not used more extensively in the Athens area. Initial research found as few as five total sites in and around Athens but quickly increased as more sites were identified. The field sites surveyed for the background section of this thesis were found to be in generally poor condition when it came to wear and raveling problems. Five of eight sites managed to yield reasonable drain times but may not be receiving adequate maintenance.

Each site was tested twice but at different times. The first round of tests were conducted in June 2013 and yielded the conclusion and results found in the Background section of this thesis. The second round of tests were conducted in June 2014. The sociological study benefited from this background research as it correlated with survey responses and perception.

The data showed a slight increase in drain times for each site. Some increase more than others but overall the change is not significant. The change in drain times could be attributed to clogging and poor maintenance or the location of the test within the site. Some areas of a sight may be in poorer condition than others and as a result yield slightly varied results.

As it stands, the results support previous conclusions drawn for each sight regarding their condition and maintenance levels. A majority still retains their infiltration capability but there has been no change in wear or maintenance. For comparison purposes the Dellate test was conducted on the lab specimens constructed for Phase 2 of this study as well. Those results are displayed below in Table 6.1.

Table 6.1 – Demo unit Dellate drain times

Cement Content (lb/yd^3)	**Drain Time (sec)**
450	7.52
500	8.03
550	8.06
600	11.24
650	15.76

The drain times listed above show drain times below 20 seconds. These values mean that all specimens are in good condition. A rating of good condition is supported, moreover, by the hydraulic conductivities displayed in Table 6.2.

Table 6.2 – Demo unit hydraulic conductivity

Cement Content (lb/yd^3)	Hydraulic Conductivity (k) (in/hr)
450	1589.09
500	1539.63
550	1536.77
600	1261.78
650	953.40

The pervious concrete created for laboratory testing underwent proper placement, proper mixing and proper compaction and curing before undergoing both simulated storm event testing and the aforementioned Dellate test.

The results show a decrease in hydraulic conductivity as cement content increases. This could be attributed to un-hydrated cement within the specimens, the existence of more fines within each specimen, or a higher density as a result of cement hydration.

6.1.1 Sociological Survey:

The purpose of the sociological survey was to gain insight into why pervious concrete was not as widely used within Athens. A survey was created to ask individuals a short set of questions that would provide at least a cursory understanding of what barriers are perceived to stand in the way of pervious concrete use.

A list of survey questions along with other accompanying text can be found in Appendix A of this thesis. The survey was sent to as many ready-mixed concrete companies, architect firms, engineers, municipalities, landscaping companies, and university faculty as possible. The questions used for the survey are shown below.

1. Your input is extremely valuable. Please input your contact information. Thank you. (Optional).
2. Which of the following best describes the field in which you work?
3. How would you describe the usage level of PCPs in Georgia?
4. On a scale from 1 to 5 how would you rate your experience level with PCPs?
5. Please take a moment to describe your experiences with PCP (If no experiences enter "N/A" into the space provided).
6. In your opinion what are the barriers/limitations facing the use/acceptance of PCPs in your field?
7. What would you like to learn more about with regards to PCP?
8. Would you attend a workshop or a series of workshops designed to educate about the benefits of PCP as well as how to design and construct PCP systems?

Forty-two individuals received the survey. In the end the survey yielded 12 responses for a response rate of about 29% and provided at least some understanding of how pervious concrete pavements are perceived in Athens. Three of the 12 responses were collected via phone interview.

Each question gathered information that would either inform the work to be done in Phase 2 or inform on barriers facing the use of pervious concrete. Question 1 of the survey asked the user what they perceived as the usage level of PCPs in Georgia. The results are displayed below in Figure 6.1. A rating of 1 represented a low usage level, a rating of 3 represented a moderate usage level and a rating of 5 represented a high usage level.

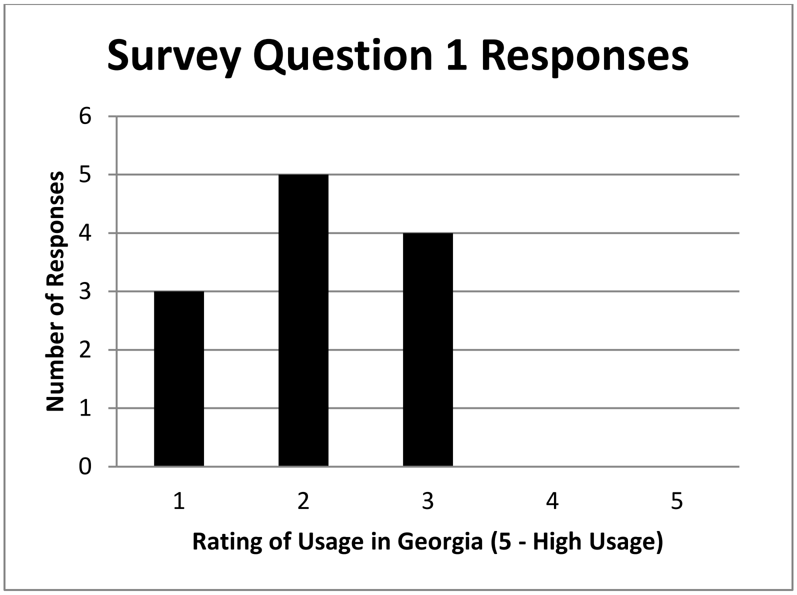

Figure 6.1 – Survey Question 1 Responses

Responses pointed to moderate or below usage here in Georgia. These responses represent the perception of individuals both experienced and inexperienced in pervious concrete. Question 2 of the survey requested that users input their experience level. These responses are displayed in Figure 6.2. A rating of 1 represents a low level of experience, a rating of 3 represents a moderate level of experience and a rating of 5 represents a high level of experience.

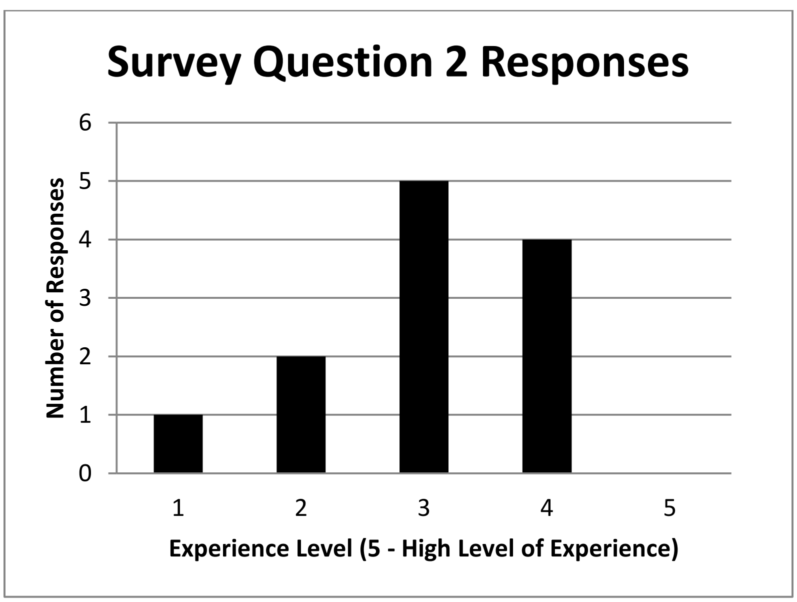

Figure 6.2 – Survey Question 2 Responses

A majority of respondents had an experience level at 3 and 4 with a rating of 3 moderate experience having the most responses. Understanding the experience level of respondents allows insight into how much stock can be put into their perception of PCP usage and the barriers facing the product. Experience level, however, does not discount the understanding gained from the responses of inexperienced individuals. The general public may not have a positive perception of PCPs and may in turn influence which products are invested in within the commercial and industrial sector.

Survey question 3 gave respondents a chance to comment on their experience level with pervious concrete. The purpose of question 3 was to understand where experience is coming from for each individual and see if it might influence their perception of PCP. Respondents gave many examples of experience. Responses are displayed in Table 6.3.

Table 6.3 – Question 3 Responses and Comments

Responses
St. James Methodist Church PCP parking lot addition (Athens, GA)
Instructional based experience for the design and application of PCP; literature review, and installed condition observations.
Used as development of specification. Witnessed placement in crosswalks
Installation of PCPs for various applications on UGA campus.
We have used PCPs as effective stormwater management tools in parking bays in the downtown area and in a collegiate setting.
I have observed several hundred installations in all parts of North America, given continuing education courses on the subject to specifiers and installers, and published several research publications.
Pedestrian area at UGA College of Environment and Design

Some respondents refused to comment as the question was optional. The seven responses above speak of local and national experience with PCP but many of those same respondents reported a perception of moderate to low PCP usage in Georgia. Additionally, many additional comments for other questions called for more education and knowledge in general regarding pervious concrete. These responses regarding education and topics of interest informed the focus of Phase 2 research. While Phase 2 did not directly answer each concern found in Phase 1 there was still research in water quality, hydrological perfomrnace, and structural performance.

Survey question 4 requested that respondents choose which barriers best represent the ones facing the use of pervious concrete in Georgia. The responses are displayed in Figure 6.3. A set of eight possible barriers were chosen for the question to cover different aspects as broadly as possible. These barriers include: costs, construction time, strength, durability, clogging, availability, public acceptance, and contractor experience. Cost and Contractor experience were selected as the greatest concerns regarding PCPs usage. Installation and materials costs drive whether many products succeed or fail. Costs may go up if contractor experience is lacking. A lack of knowledge and experience may result in poor placement and poor maintenance. Additionally, poor placement and maintenance would result in a lack of strength and durability as is evident in local Athens area installations.

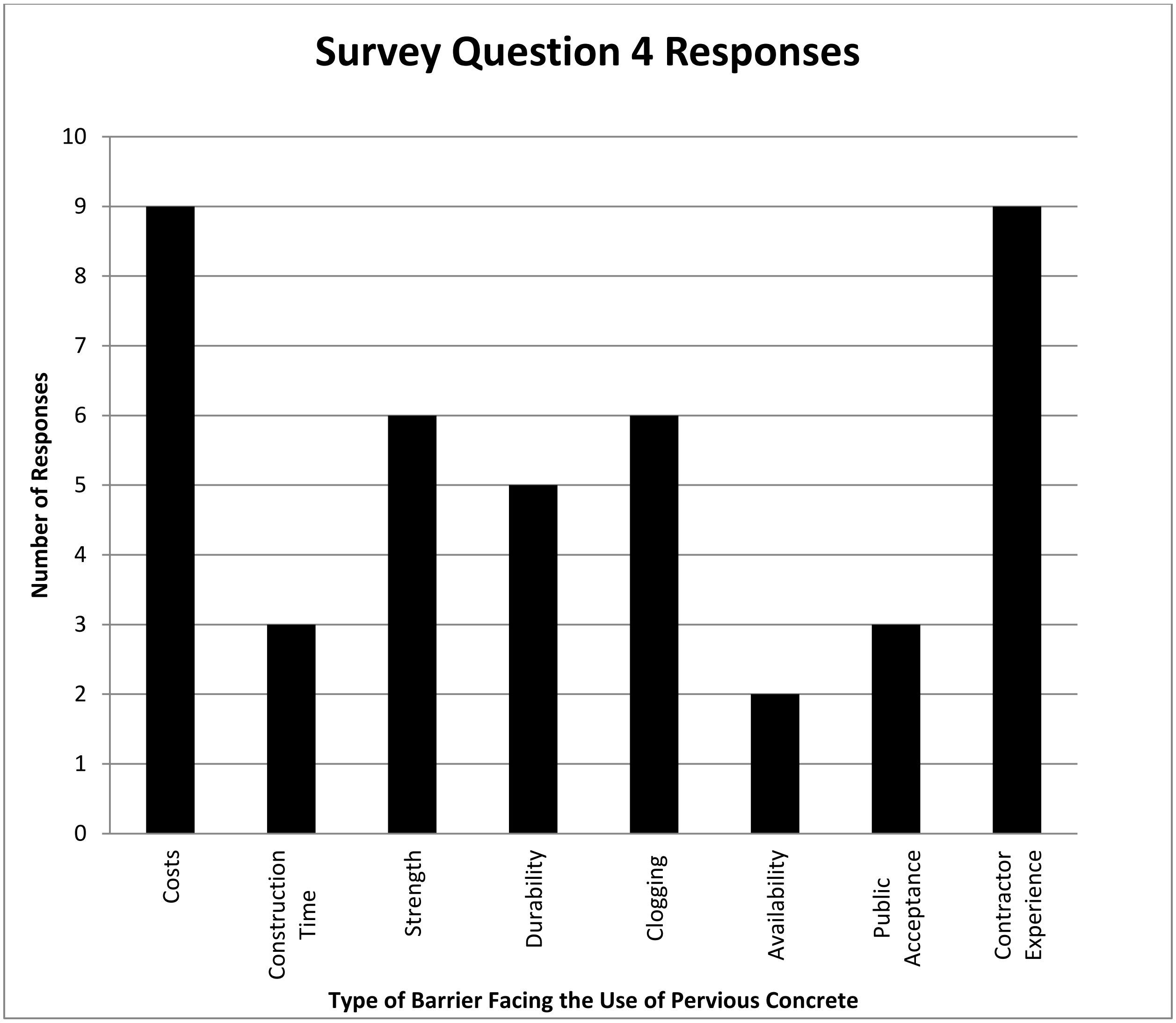

Figure 6.3 – Survey Question 4 Responses

Question 5 asked respondents about what they would be most interested in being educated about. Topics included: design of PCP, construction of PCP, water quality, hydrological performance, and structural performance. Responses are illustrated in Figure 6.4.

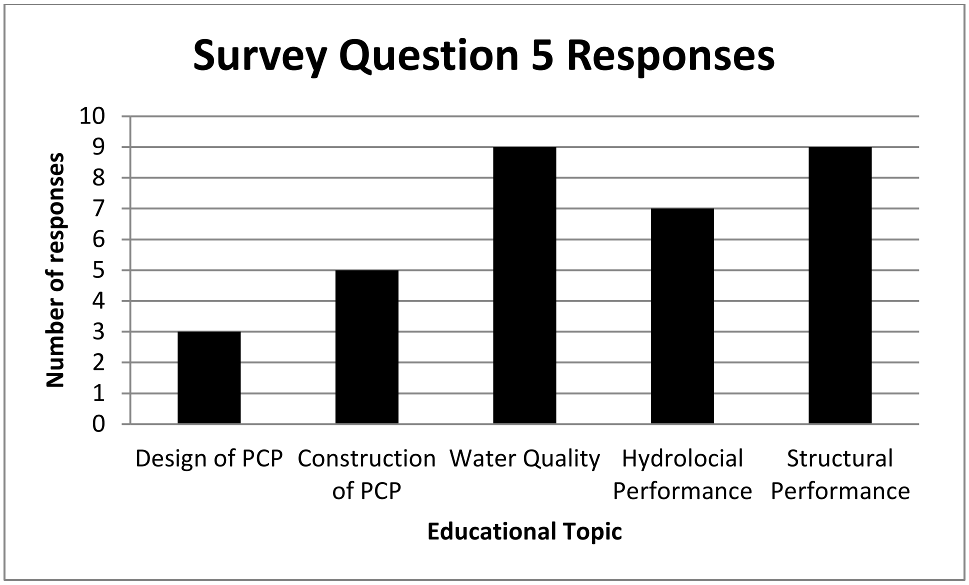

Figure 6.4 – Survey Question 5 Responses

As mentioned earlier, the responses found in Phase 1 were meant to gain insight while also informing the decisions made in Phase 2. Question 5 influenced and validated the focus of Phase 2 pH and water quality testing. Respondents showed most interest in water quality and structural performance with hydrological performance following close behind. In Phase 2 water quality testing was conducted along with minor compressive strength, void, and hydraulic conductivity testing.

The final question in the survey, question 6, evaluated how willing a respondent would be to attend an education workshop on pervious concrete. Eleven respondents replied with interest in attending educational workshops with one respondent not willing to attend. This response confirms the need for periodic workshops to inform and promote PCP design, construction, and maintenance in the Athens, GA area.

6.2 Laboratory Study

The purpose of the laboratory study on the PCP demonstration units was to determine:

1. the contaminant removal capability of a two layer PCP system versus a three layer system
2. the pH change over time for each unit.

The pH of effluent typically tends to rise at first with newer concrete installations. The expectation was that the pH would decrease with time as water passed through the system.

As mentioned before, two groups of five PCP systems were constructed for laboratory testing. The first group was comprised of five 3-layer systems and the second group was comprised of five 2-layer systems. Within each group, there was a variation of cement content. This variation was the same for each group. The five mixtures varied in cement content from 450 lb/yd^3 to 650 lb/yd^3 in 50 lb/yd^3 increments.

6.2.1 Contaminant Removal Test Results

Contaminant removal testing was conducted over 31 simulated storm events. Seven of those simulated storm events were contaminant removal trials. Each group was subjected to the same amount of water, the same synthetic storm water solution and sampled at the same time. All raw data is presented in Appendix A.

The synthetic storm water solution contained five elements: cadmium, copper, phosphorus, lead and zinc. Samples of each synthetic stormwater batch were taken before and after each trial and tested with limitations in lab equipment detection thresholds in mind. Each synthetic stormwater batch contained varying concentrations of each element post dilution and mixing. Concentrations did not always reach desired levels. Some concentrations even dipped to half the desired concentration.

A statistical analysis of each trial as well as the interaction between variables was conducted and is included in Chapter 7. An average of each trial was taken and used to illustrate the removal of each contaminant between each group. The average values for all 7 trials and each demonstration unit is shown in Table 6.4.

Table 6.4 – Average of Concentrations for All Elements and Demo Units Post Trial

Sample	Cadmium (Cd) (ppm)	Copper (Cu) (ppm)	Phosphorus (P) (ppm)	Lead (Pb) (ppm)	Zinc (Zn) (ppm)
EPA Cutoff	0.005	1.30	0.01 to 0.04	0.00	5.00
B	0.01	0.20	2.14	0.20	0.81
Group 1					
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.16	0.03	0.01
A5	0.01	0.01	0.06	0.03	0.01
Group 2					
A6	0.01	0.08	1.19	0.09	0.21
A7	0.01	0.11	1.33	0.10	0.20
A8	0.01	0.07	0.87	0.06	0.16
A9	0.01	0.13	1.26	0.09	0.28
A10	0.01	0.11	1.30	0.07	0.25

The symbol ‘B’ represents the concentrations before a trial run. Symbols A1 to A5 represent Group 1 and the group of five 3-layer systems. Symbols A6 to A10 represent Group 2 and the group of five 2-layer systems.

Contaminant removal data was broken up to represent the performance of each group for each element. Each column graph illustrates the concentrations before and after for each group. Removal performance for cadmium is displayed in Figure 6.5, removal performance for copper is displayed in Figure 6.6, removal performance for phosphorus is displayed in Figure 6.7, removal performance for lead is displayed in Figure 6.8 and removal performance for zinc is displayed in Figure 6.9. Cadmium removal was the same across the board. This was mainly because all readings were below laboratory equipment detectable thresholds.

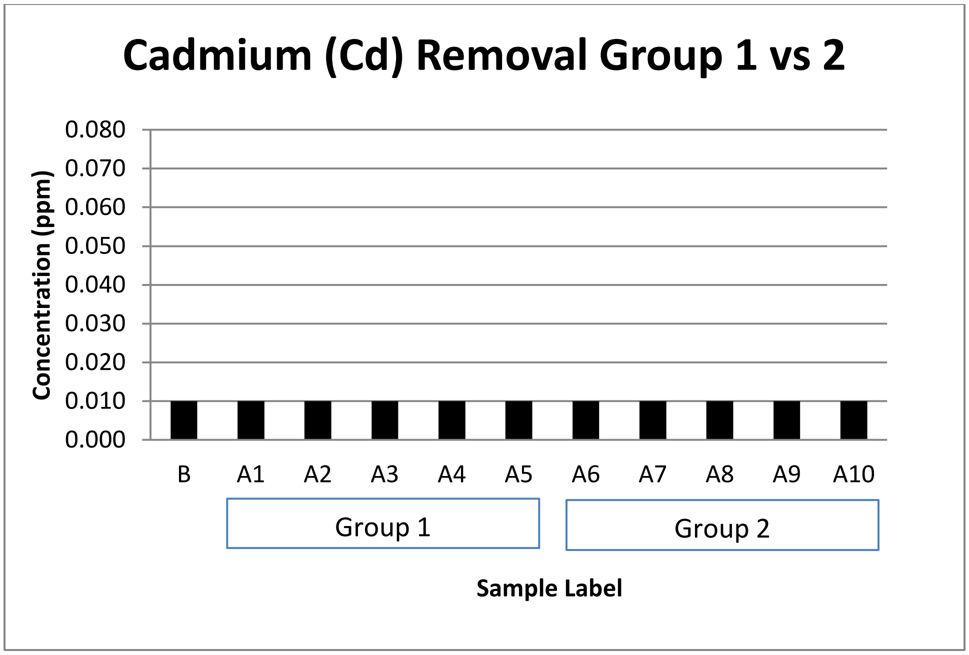

Figure 6.5 – Contaminant Removal Comparison for Cadmium

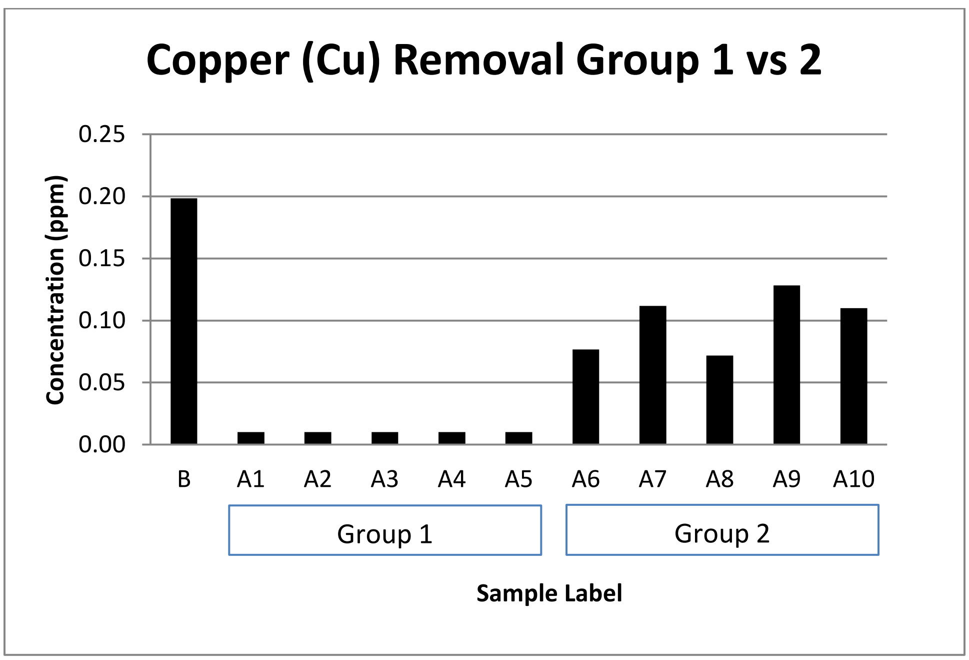

Figure 6.6 – Contaminant Removal Comparison for Copper

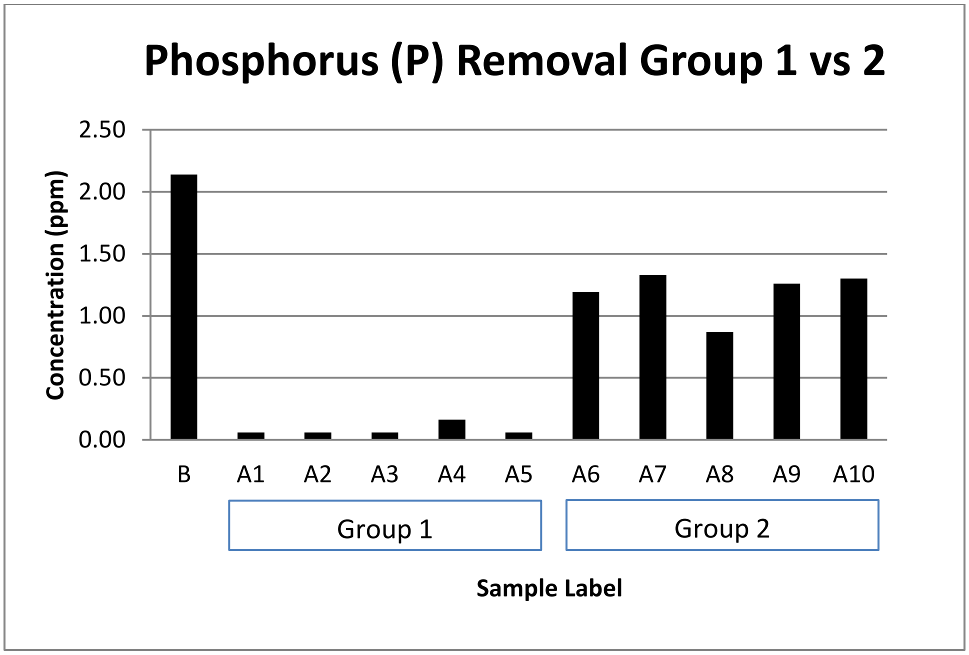

Figure 6.7 – Contaminant Removal Comparison for Phosphorus

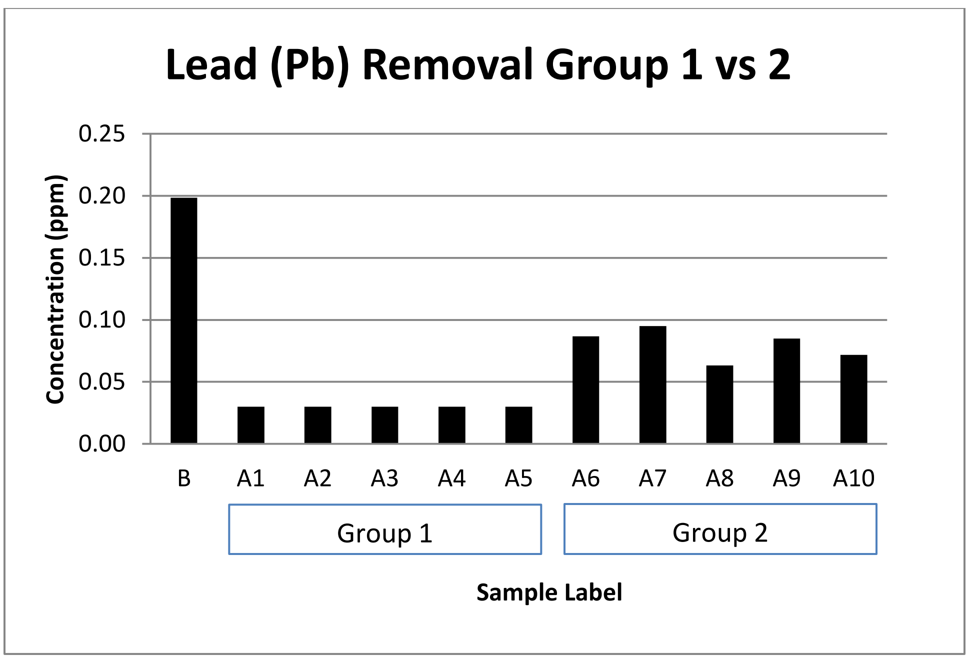

Figure 6.8 – Contaminant Removal Comparison for Lead

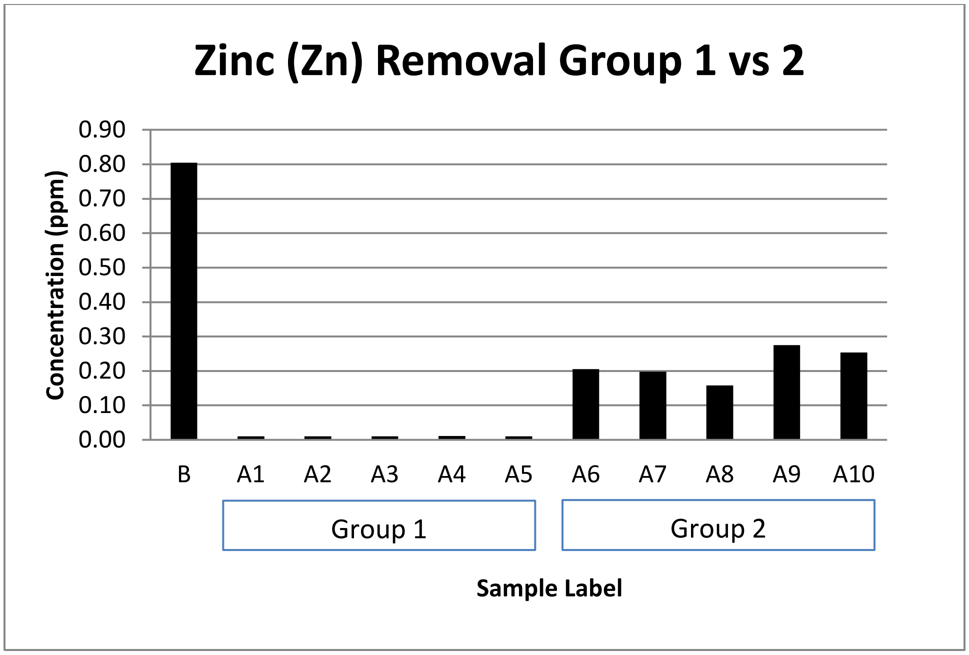

Figure 6.9 – Contaminant Removal Comparison for Zinc

There is a clear distinction, even before statistical analysis, between the performances of Group 1 versus Group 2. The 3-layer systems in Group 1 nearly completely remove all traces of each contaminant. It is worth noting that laboratory equipment limitations affected how data values were reported. In the case of cadmium and Group 1 most values were reported as being below or less than the detection threshold of the given lab equipment. To allow for proper analysis all values that were reported as below equipment thresholds were conservatively assigned the value of the threshold. In the case of cadmium, the desired concentration was 0.005 ppm. When designing initial concentrations 0.005 was deemed above detection thresholds by the water testing lab staff. This, however, was not the case and resulted in a flat value before and after contaminant removal trials. As shown from Figure 6.5, all values had to be assigned the threshold value of 0.01 ppm in order for analysis to continue forward.

Other elements were more responsive and showed distinct change in concentrations. Group 1 showed an approximately 95% reduction in contaminant concentration when it came to filtering copper. In the case of Phosphorus, the reduction was nearly 97%. For Group 2, the reductions in concentrations were apparent but not as significant as those from Group 1. As mentioned before, a statistical analysis was performed and found no apparent significance in the variation of cement content. This allows for the groups to be considered and compared as a unit. These results therefore show 3-layer systems as more effective. The distinct change in concentration is believed to be a direct result of the sand layer within the 3-layer system.

When compared to EPA standards lead, phosphorus, and cadmium were above or at EPA regulations for both groups. The EPA calls for a maximum of 0.005 ppm for cadmium, a maximum of 0 for lead and between 0.01 and 0.04 ppm for phosphorus. During laboratory testing lead concentrations were designed to reach detectable levels for testing purposes. The data shows that lead will be filtered by a pervious concrete system if present in runoff. According to Figure 6.8 the three layer system is far more effective in filtering lead. The same situation applied to phosphorus. As mentioned before, many Group 1 values were assigned the value of equipment thresholds for the purposes of analysis and as a result true effectiveness, informed by actual values, cannot be calculated. The EPA calls for the maximum values found in Table 6.4 (EPA, 2009).

The values in Table 6.4 represent EPA cutoffs for contaminant concentrations. The pervious concrete systems in this study were tested using concentrations either above or below these cutoffs to ensure that concentrations remain within detectable range and to ensure safe disposal when draining each system.

6.2.2 pH Test Results

Testing for pH was conducted over 31 simulated storm events with pH measurements taken before and after each simulated event. Water passed through each system without stopping or being left to sit and measured immediately after leaving the PCP system. The purpose of collecting samples immediately after infiltration was to create a realistic and representative environment to study changes in pH and the effect of different layer configurations on pH.

Statistical analysis deemed cement content insignificant to the change in pH and as such an average of pH change for all units in each group was calculated and used to create a plot of pH change over 31 storm events. This plot is illustrated in Figure 6.10. During simulated storm event 1 and trial 1 Group 1 displays a small initial rise in pH. This small change, however, does not remain and in subsequent days the PCP systems behave as expected with pH rising above 12 in both groups. It is believed that the small initial change in pH for Group 1 is a result of the sand within the 3-layer system which happens to produce a lower pH when mixed with normal tap water. Additionally, it is possible that residual water from the intensive curing process may have influenced the starting pH of water passing through the system.

Initial pH values consistently fluctuate between 6 and 9.5 throughout the 31 storm event experiment with the deepest fluctuations occurring during contaminant removal trials. This fluctuation did not seem to significantly affect the change in pH at first but the pH was consistently lower when measured during a contaminant removal trial. This is a direct result of the higher concentration of heavy metals within the solution at the time of testing.

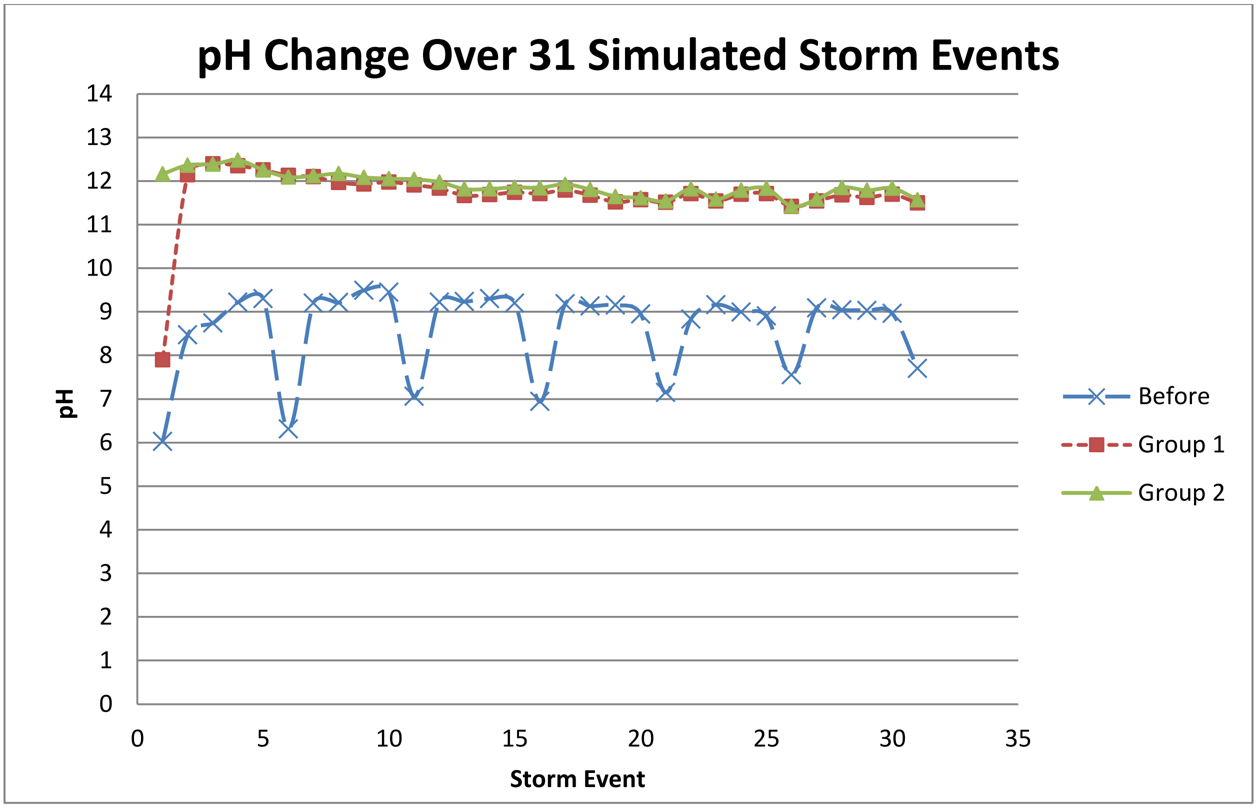

Figure 6.10 – pH change over 31 storm events.

By the end of Trial 7, all pH values had dropped below 12 to an average of about 11.5 pH. A full table containing the raw pH measurements is located in Appendix A. More discussion on pH and the effect of layer configurations will be conducted in Chapter 7 of this thesis. pH change seems to be very gradual in pervious concrete.

6.2.3 Void Content Test Results

Five test cylinders were tested for void content with each representing one of the five different mixture designs used for laboratory testing. The procedure for void content testing followed the Hager study. The full procedure is listed in Chapter 5 of this thesis. Two trials were conducted to ensure void content values were consistent and averaged to give the values in Table 6.5. A void content target of 20% was chosen for this experiment per recommendation of the Hager study.

Table 6.5 – Void Content Test Results

Cement Content (lb/yd^3)	Void Content (%)
450	24.28
500	30.14
550	22.15
600	18.58
650	18.13

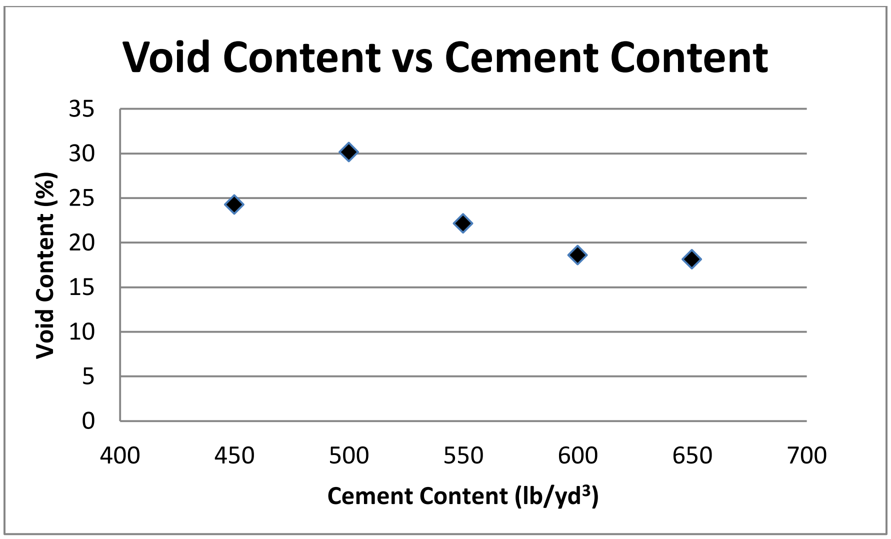

Figure 6.11 – Void Content vs Cement Content

Void content trended lower as cement content increased with an anomaly in the trend at 500 lb/yd^3 (297 kg/m^3). This may be a result of poor consolidation during construction and an inadequate curing process.

6.2.4 Compressive Strength Test Results

One concrete cylinder was made for each mixture used for the PCP demonstration units for a total of five test cylinders. These cylinders were made by gathering excess mixture material and compacting it into 4x8 in concrete cylinder molds. Upon completion of the void content test the cylinders were loaded into the compressive strength testing machine to be subjected to a 1000 lbf preloading and a 35 psi/s ramp which signified the amount of loading the specimen would experience per second.

Each specimen was subjected to loading until the maximum possible stress was achieved. The maximum stress for each specimen is displayed below in Table 6.6.

Table 6.6 – Compressive Strength Test Results

Cement Content (lb/yd^3)	Maximum Stress (psi)
450	616
500	356
550	987
600	1590
650	1392

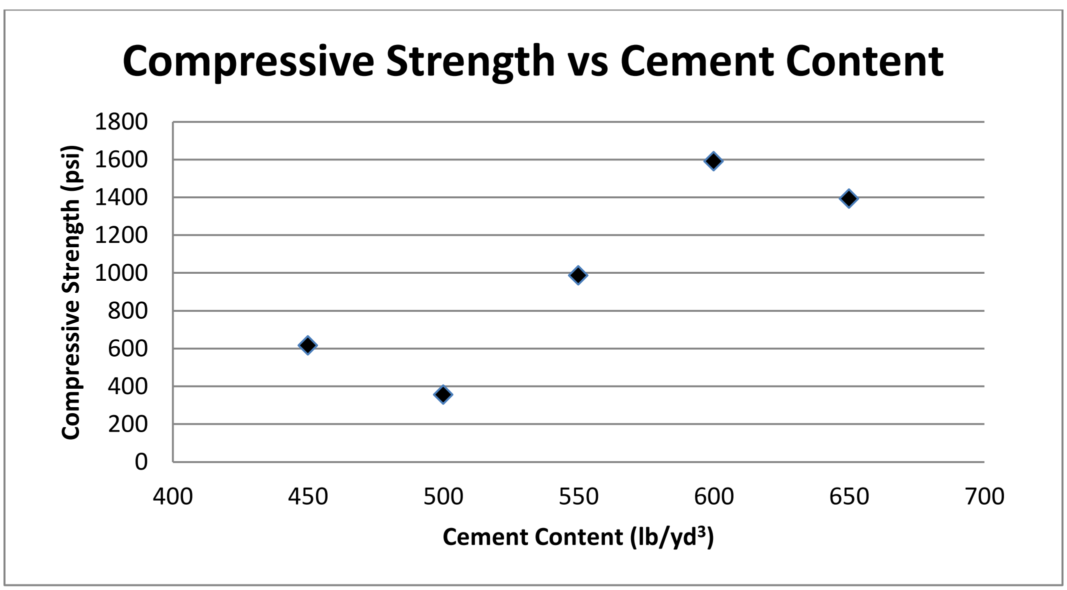

Figure 6.12 – Compressive Strength vs Cement Content

The compressive strength of the test cylinders did trend upward with increasing cement content but as mentioned before the test cylinder containing 500 lb/yd^3 (297 kg/m^3) cement content may not have been consolidated adequately to reach full potential. Figure 6.13 shows the compressive strength with respect to void content.

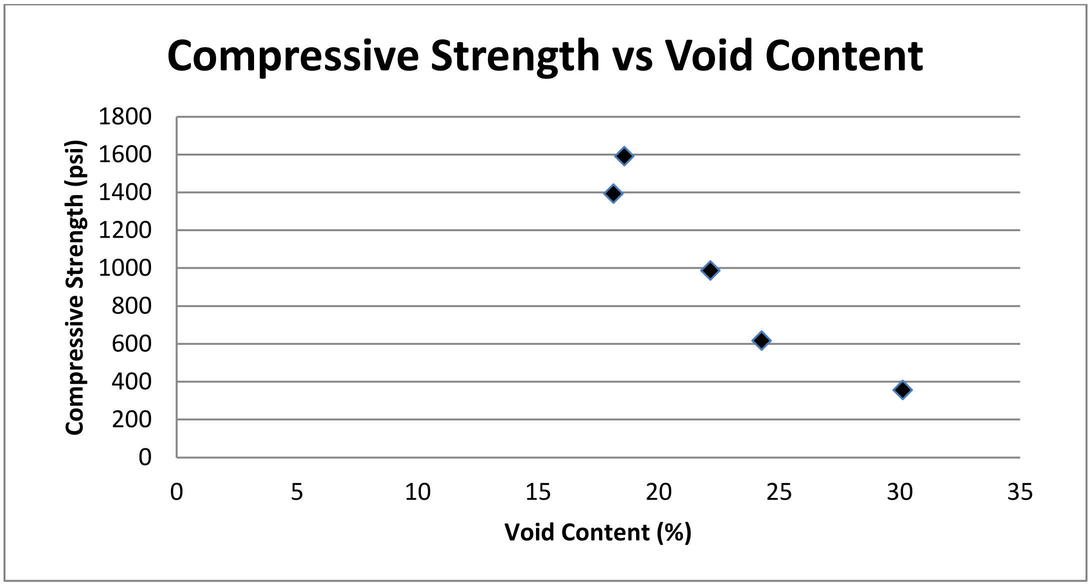

Figure 6.13 – Compressive Strength vs Void Content

The graph in Figure 6.13 illustrates the relationship between void content and compressive strength. Compressive strength decreases with increasing void content. If void content goes down and consolidation is increased along with cement content, the compressive strength of the pervious concrete goes up substantially.

Note that the PCP testing cylinders were not tested at either 28 day or 56 day strengths but rather over 120 days after being made. Additionally more cylinders should have been created for the purposes of void content and compressive strength testing at the time of demonstration unit construction. A total of 6 cylinders would be adequate with 3 tested at both the 28 and 56 day strengths.

7. STATISTICAL ANALYSIS

7.1 Overview

An Analysis of Variance (ANOVA) is a statistical test that compares the difference between the means of two or more groups. This test is a generalization of the t-test which is used to find the difference between two groups at a time. This statistical analysis was conducted to determine whether or not the data obtained during laboratory tests sufficiently provide enough evidence to keep or reject the null hypothesis H_o.

In an ANOVA, the p-value determines the significance of a variable. If a p-value is less than 0.05, then the variable significantly affects the response. If a p-value is greater than 0.05, then there is no reason to consider the variable significant. Two way and three way ANOVAs are capable of analyzing multiple variables at once. The statistical program Minitab was used to analyze both the contaminant removal data and pH change data.

7.2 Contaminant Removal Analysis

The contaminant removal trial results are discussed in Chapter 6. The main purpose of the contaminant removal trials was to determine if there is a significant different between 3-layer and 2-layer PCP systems.

The ANOVA for this section tested two variables. The first variable was cement content, and the second variable was the trial. The objective with the ANOVA was to first determine whether or not the variation in cement content had any significant effect on filtration and the second objective was to determine if there was any significant difference going from trial to trial.

The results show that both have no significant effect on filtration. P-values for each variable are displayed in Table 7.1.

Table 7.1 – P-values for Contaminant Removal Variables

Variable	p-value
Cement Content	0.934
Trial	0.935

Minitab has the capability to determine the interaction between variables as well and when tested there was no significance to the interaction between the trials and cement content. The p-value was 1.00.

The next test required for the contaminant removal trials was to determine whether or not there was a significant difference between the two and three layer PC systems. Without the need to take either cement content or trials into account, the ANOVA level reduces to a one-way ANOVA. Here the response is the difference between the initial concentration and the averaged concentration for each contaminant within each group tested during the trial and the layer configuration. The p-value results for the one-way ANOVA are displayed in Table 7.2.

Table 7.2 – P-value for Significance of Layer Configuration

Variable	p-value
Layer Configuration	0.046

This p-value confirms the earlier assumption in Chapter 6 that the layer configuration does influence the amount of contaminant removal. The p-value is just under 0.05 but with additional trials and more experimentation the value would become lower and significance greater.

Additionally, this p-value signifies that the null hypothesis that a 3-layer system would be more effective than a 2-layer system should not be rejected.

7.3 pH Change Analysis

pH testing sought to observe two aspects of pervious concrete. The first aspect was the change in pH over several simulated storm events and the second was the effect of layer configuration on the change in pH. The expectation was for each PCP system to raise the pH level of all water that makes contact with the system.

As with the contaminant removal analysis, multiple variables required consideration in order to conduct a thorough analysis. Here the variables of cement content, layer configuration, and water type were chosen to gain a full understanding of what factors affected the change in pH. The p-values for the variables stated above are listed in Table 7.3.

Table 7.3 – P-values for pH Change Analysis

Variable	p-value
Cement Content	0.999
Layer Configuration	0.000
Water Type	0.000

The p-values above show that the variation in cement content did not significantly affect the change in pH over 31 simulated storm events. The p-values for layer configuration and water type show that they did in fact have a significant effect on the change in pH. Overall Group 1 yielded lower pH values than Group 2. This adds additional evidence to support the hypothesis that 3-layer systems are more effective than 2-layer systems. It is worth noting that during Trial 1 there were 5 anomalous pH values. These pH values were much lower than expected and as a result had the potential to skew the analysis. The analysis was run again without the anomalous values. This resulted in p-values nearly identical to the ones shown in Table 7.3 and confirmed that the anomalies were not significant. The p-values in Table 7.3 provide enough evidence to reject the hypothesis that a variation in cement content would affect the change in pH for the PCP systems.

The significant effect of water type on the change of pH is likely a direct result of the heavy metals that were mixed into the synthetic storm water solution during each contaminant removal trial. This effect, however, may not alter the overall change in pH as additional storm events could yield the same apparent gradual change in pH.

8. DISCUSSION AND CONCLUSION

8.1 Summary of Work

The purpose of this research was to study the sociological side of pervious concrete use, the effects of layer configuration on filtration, and the effects of layer configuration on pH change. Two phases of research were conducted to determine the perception of pervious concrete and the difference between 3-layer and 2-layer PCP systems. In Phase 1, a sociological survey gathered insight on what barriers lay in the way of more pervious concrete use in Georgia while additionally assessing the state of pervious concrete in Athens. In Phase 2, two sets of experiments determined filtration performance for two groups of pervious concrete demonstration systems. Synthetic storm water was produced, filtered and tested and pH change was recorded for each storm event.

8.2 Sociological Study Conclusions

The sociological study produced several insights into how pervious concrete is perceived around Athens, GA. First and foremost, there is a general perception that there is moderate to low pervious concrete usage in Georgia. Second, respondents cited both cost and contractor experience as the two most concerning issues surrounding the use of pervious concrete. Third, respondents expressed a desire for education on pervious concrete. Namely, there was a greater desire to learn more about water quality aspects and structural performance aspects of pervious concrete. Experience with pervious concrete was not as lacking as previously expected and correlated to both perception of PCP usage and the desire for programs and industry standards to educate others on pervious concrete.

In Chapter 3, a paper by ASCE discusses the importance of collaboration in solving civil engineering grand challenges. This research sought to increase collaboration on a local level by surveying the local populous and using their input to inform the experimental phase. The ASCE sees the importance in studies such as this and similar efforts should be encouraged in the future.

8.3 Sociological Study Recommendations

Contractor experience may be the deciding factor in how effective pervious concrete is in the field. Poor installations and maintenance will result in strength and durability issues for PCP sites and ultimately increasing costs. Such a situation is evident in Athens area installations that have attained poor condition ratings as a result of Dellate flow tests. Additionally, low effectiveness could produce a negative perception of pervious concrete as strength and durability problems were the second most selected aspects of pervious concrete respondents cited as barriers.

8.4 Laboratory Study Conclusions

Three-layer systems contain an additional sand layer that, when placed, cannot be serviced or cleaned upon completion of the full PCP system. The only layer that is serviceable is the pervious concrete layer. As mentioned in Chapter 3, maintenance methods include both pressure washing and vacuuming but such methods are limited to the surface and PCP layer. Within a two-layer system, there is no sand layer and as a result there is less filtration. The inability to service a sand layer poses a disadvantage in the long run but balanced by the proven increase in filtration.

The laboratory study produced two sets of data. The first concerned the removal of contaminants from a synthetic stormwater solution, and the second concerned the change in pH for each storm event over 31 separate simulated storm events. Two overall trends formed as a result of both data. In the case of contaminant, removal 3-layer pervious concrete systems performed significantly better than 2-layer systems. This conclusion was confirmed by the statistical analysis of contaminant removal and by the statistical analysis of pH change over those 31 storm events. 3-layer systems contain a sand layer, and it is believed that this layer provides both additional filtration capability as well as pH balancing properties that make 3-layer systems more effective in lowering the pH.

When compared to EPA cutoffs, three of the five contaminants tested had concentrations above or at EPA standards. This, however, was not due to the ineffectiveness of the PCP systems but rather to the fact that test concentrations were designed to enable detection during water quality testing. Three-layer systems effectively filtered lead and phosphorus and confirmed that three-layer PCP systems are capable of filtering key contaminants if present in runoff. The two-layer systems were also capable of filtering contaminants but could not match the more than 95% reduction found in three-layer systems.

8.5 Laboratory Study Recommendations

3-layer pervious concrete systems were capable of filtering out contaminants to the point where concentrations were below lab equipment thresholds. P-values may have been lower and thus more significant for layer configuration and pH change had true values been available. The hypothesis regarding the effectiveness of 3-layer system was not rejected and as such this research supports the use of 3-layer pervious concrete systems over 2-layer systems. The benefits to water quality are substantial and would only serve to develop a more positive perception for the green technology as water quality was cited as a main concern during the sociological study.

pH change is gradual and would need to be observed over additional simulated storm events. Other studies have proven that pH dissipation to acceptable levels is possible with time and the gradual trend downward of the pH measurements of this study supports that assumption. The hypothesis that cement content would have an effect on pH was rejected as a result of the statistical analysis.

8.6 Recommendations for Future Research

During the sociological study, several issues arose that require attention. First, the sample size was less than the statistical standard (30 samples or responses required) to deem the sample size as large. Future surveys should include a greater number of respondents. In addition, future research should focus solely on the sociological aspect of green technology so as to ensure proper attention is rendered for all aspects of the study. This thesis has identified several aspects of pervious concrete that concern individuals as barriers to PCP use. Future research should include efforts to identify solutions to the given problems from a sociological and education perspective. Additionally, separate future work should include field and laboratory studies that address the structural performance concerns identified in the sociological study.

Laboratory testing involved the creation of a synthetic stormwater solution, the testing of pH, the collection of samples, the creation of test cylinders, and creation of mock pervious concrete systems also known as demonstration units. Synthetic stormwater creation went through several delays before reaching its final form. The original objective was to create synthetic stormwater by mixing local street sweeper waste into normal tap water to ensure that local contaminants were contained and filtered during contaminant removal testing. This, however, was not possible as consistency could not be achieved. To achieve consistency future research should adopt the methods used in this thesis while increasing concentrations to ensure detectable levels and concentration changes at all times.

Synthetic stormwater solution mixing and dilution was achieved via the use of a heavy duty drill and paddle. Future research should include the use of more effective methods of mixture. Wider paddles or additional mixing time would likely generate more consistent concentration levels for contaminants. Better mixing methods along with higher initial contaminant concentrations should garner more effective stormwater solutions.

Future laboratory testing should occur in a fully climate controlled environment to ensure all pH measurements are consistent throughout testing. Climate controlled environments would provide an environment more conducive to a successful curing process. Covering each specimen with plastic sheeting and providing additional water through misting is effective for curing but would benefit greatly from limited evaporation and temperature change.

Demonstration units are effective when built using simple trash bins and form well when performing compaction and curing action but future research could improve on the design by including strong and more mobile containers for each unit. Attaching wheels and utilizing different materials such as wood or thicker plastics could provide for more versatile demonstration units.

Lastly, more test cylinders created from the pervious concrete mixtures used for laboratory testing should have been created for both void content and compressive strength testing. Future research should produce enough pervious concrete mixture at the time of placement to produce an adequate number of cylinders for testing purposes.

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APPENDIX A

Table A.1 – EPA Contaminants:

Microorganisms	**MCLG (mg/L)**	**MCL or TT1 (mg/L)**	**Potential Health Effects from Ingestion of Water**	**Sources of Contaminant in Drinking Water**
Cryptosporidium	as of 01/01/02: zero	as of 01/01/02: TT	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste
Giardia lamblia	zero	TT	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste
Heterotrophic plate count	n/a	TT	HPC has no health effects, but can indicate how effective treatment is at controlling microorganisms.	HPC measures a range of bacteria that are naturally present in the environment
Legionella	zero	TT	Legionnaire's Disease, commonly known as pneumonia	Found naturally in water; multiplies in heating systems
Total Coliforms (including fecal coliform and E. Coli)	zero	5.0%	Used as an indicator that other potentially harmful bacteria may be present	Coliforms are naturally present in the environment; fecal coliforms and E. coli come from human and animal fecal waste.
Turbidity	n/a	TT	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (e.g., whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff
Viruses (enteric)	zero	TT	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste

Disinfectants & Disinfection Byproducts	MCLG (mg/L)	MCL or TT (mg/L)	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Bromate	as of 01/01/02: zero	as of 01/01/02: 0.010	Increased risk of cancer	Byproduct of drinking water disinfection
Chloramines (as Cl2)	as of 01/01/02: MRDLG=4	as of 01/01/02: MRDL=4.0	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes
Chlorine (as Cl2)	as of 01/01/02: MRDLG=4	as of 01/01/02: MRDL=4.0	Eye/nose irritation; stomach discomfort	Water additive used to control microbes
Chlorine dioxide (as ClO2)	as of 01/01/02: MRDLG=0.8	as of 01/01/02: MRDL=0.8	Anemia; infants & young children: nervous system effects	Water additive used to control microbes
Chlorite	as of 01/01/02: 0.8	as of 01/01/02: 1.0	Anemia; infants & young children: nervous system effects	Byproduct of drinking water disinfection
Haloacetic acids (HAA5)	as of 01/01/02: n/a	as of 01/01/02: 0.060	Increased risk of cancer	Byproduct of drinking water disinfection
Total Trihalomethanes (TTHMs)	none ---------- as of 01/01/02: n/a	0.10 ---------- as of 01/01/02: 0.080	Liver, kidney or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection

Inorganic Chemicals	MCLG (mg/L)	MCL or TT (mg/L)	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Antimony	0.006	0.006	Increase in blood cholesterol; decrease in blood glucose	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder
Arsenic	none	0.05	Skin damage; circulatory system problems; increased risk of cancer	Erosion of natural deposits; runoff from glass & electronics production wastes
Asbestos (fiber >10 micrometers)	7 million fibers per liter	7 MFL	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Barium	2	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits
Beryllium	0.004	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries
Cadmium	0.005	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints
Chromium (total)	0.1	0.1	Some people who use water containing chromium well in excess of the MCL over many years could experience allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits
Copper	1.3	TT; Action Level=1.3	Short term exposure: Gastrointestinal distress. Long term exposure: Liver or kidney damage. People with Wilson's Disease should consult their personal doctor if their water systems exceed the copper action level.	Corrosion of household plumbing systems; erosion of natural deposits
Cyanide (as free cyanide)	0.2	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories
Fluoride	4.0	4.0	Bone disease (pain and	Water additive which

			tenderness of the bones); Children may get mottled teeth.	promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories
Lead	zero	TT; Action Level=0.015	Infants and children: Delays in physical or mental development. Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits
Mercury (inorganic)	0.002	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and cropland
Nitrate (measured as Nitrogen)	10	10	"Blue baby syndrome" in infants under six months - life threatening without immediate medical attention. Symptoms: Infant looks blue and has shortness of breath.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits
Nitrite (measured as Nitrogen)	1	1	"Blue baby syndrome" in infants under six months - life threatening without immediate medical attention. Symptoms: Infant looks blue and has shortness of breath.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits
Selenium	0.05	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines
Thallium	0.0005	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and pharmaceutical companies

Organic Chemicals	MCLG (mg/L)	MCL or TT (mg/L)	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Acrylamide	zero	TT	Nervous system or blood problems; increased risk of cancer	Added to water during sewage/wastewater treatment
Alachlor	zero	0.002	Eye, liver, kidney or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	0.003	0.003	Cardiovascular system problems; reproductive difficulties	Runoff from herbicide used on row crops
Benzene	zero	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills
Benzo(a)pyrene (PAHs)	zero	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines
Carbofuran	0.04	0.04	Problems with blood or nervous system; reproductive difficulties.	Leaching of soil fumigant used on rice and alfalfa
Carbon tetrachloride	zero	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities
Chlordane	zero	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide
Chlorobenzene	0.1	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories
2,4-D	0.07	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Dalapon	0.2	0.2	Minor kidney changes	Runoff from herbicide used on rights of way
1,2-Dibromo-3-chloropropane (DBCP)	zero	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards

o-Dichlorobenzene	0.6	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories
p-Dichlorobenzene	0.075	0.075	Anemia; liver, kidney or spleen damage; changes in blood	Discharge from industrial chemical factories
1,2-Dichloroethane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
1,1-Dichloroethylene	0.007	0.007	Liver problems	Discharge from industrial chemical factories
cis-1,2-Dichloroethylene	0.07	0.07	Liver problems	Discharge from industrial chemical factories
trans-1,2-Dichloroethylene	0.1	0.1	Liver problems	Discharge from industrial chemical factories
Dichloromethane	zero	0.005	Liver problems; increased risk of cancer	Discharge from pharmaceutical and chemical factories
1,2-Dichloropropane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
Di(2-ethylhexyl) adipate	0.4	0.4	General toxic effects or reproductive difficulties	Leaching from PVC plumbing systems; discharge from chemical factories
Di(2-ethylhexyl) phthalate	zero	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories
Dinoseb	0.007	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables
Dioxin (2,3,7,8-TCDD)	zero	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories
Diquat	0.02	0.02	Cataracts	Runoff from herbicide use
Endothall	0.1	0.1	Stomach and intestinal problems	Runoff from herbicide use
Endrin	0.002	0.002	Nervous system effects	Residue of banned insecticide
Epichlorohydrin	zero	TT	Stomach problems; reproductive difficulties; increased risk of	Discharge from industrial chemical factories; added to water during treatment

			cancer	process
Ethylbenzene	0.7	0.7	Liver or kidney problems	Discharge from petroleum refineries
Ethelyne dibromide	zero	0.00005	Stomach problems; reproductive difficulties; increased risk of cancer	Discharge from petroleum refineries
Glyphosate	0.7	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use
Heptachlor	zero	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide
Heptachlor epoxide	zero	0.0002	Liver damage; increased risk of cancer	Breakdown of hepatachlor
Hexachlorobenzene	zero	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories
Hexachlorocyclopentadiene	0.05	0.05	Kidney or stomach problems	Discharge from chemical factories
Lindane	0.0002	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on catttle, lumber, gardens
Methoxychlor	0.04	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock
Oxamyl (Vydate)	0.2	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes
Polychlorinated biphenyls (PCBs)	zero	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfils; discharge of waste chemicals
Pentachlorophenol	zero	0.001	Liver or kidney problems; increased risk of cancer	Discharge from wood preserving factories
Picloram	0.5	0.5	Liver problems	Herbicide runoff

Simazine	0.004	0.004	Problems with blood	Herbicide runoff
Styrene	0.1	0.1	Liver, kidney, and circulatory problems	Discharge from rubber and plastic factories; leaching from landfills
Tetrachloroethylene	zero	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners
Toluene	1	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories
Toxaphene	zero	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle
2,4,5-TP (Silvex)	0.05	0.05	Liver problems	Residue of banned herbicide
1,2,4-Trichlorobenzene	0.07	0.07	Changes in adrenal glands	Discharge from textile finishing factories
1,1,1-Trichloroethane	0.20	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories
1,1,2-Trichloroethane	0.003	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories
Trichloroethylene	zero	0.005	Liver problems; increased risk of cancer	Discharge from petroleum refineries
Vinyl chloride	zero	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories
Xylenes (total)	10	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories

Radionuclides	MCLG (mg/L)	MCL or TT (mg/L)	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Alpha particles	none ---------- as of 12/08/03: zero	15 picocuries per Liter (pCi/L)	Increased risk of cancer	Erosion of natural deposits
Beta particles and photon emitters	none ---------- as of 12/08/03: zero	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits
Radium 226 and Radium 228 (combined)	none ---------- as of 12/08/03: zero	5 pCi/L	Increased risk of cancer	Erosion of natural deposits
Uranium	as of 12/08/03: zero	as of 12/08/03: 30 ug/L	Increased risk of cancer, kidney toxicity	Erosion of natural deposits

EPA Contaminants List Table Definition list

- Maximum Contaminant Level (MCL) - The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards (EPA, 2009).
- Maximum Contaminant Level Goal (MCLG) - The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals (EPA, 2009).
- Maximum Residual Disinfectant Level (MRDL) - The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants (EPA, 2009).
- Maximum Residual Disinfectant Level Goal (MRDLG) - The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not

reflect the benefits of the use of disinfectants to control microbial contaminants (EPA, 2009).

- Treatment Technique (TT) - A required process intended to reduce the level of a contaminant in drinking water (EPA, 2009).

Survey:

Introduction:

The objective of this survey is to explore the reasons why pervious concrete pavements, PCPs, are not widely used within Georgia. This survey includes a series of eight multiple choice and open-ended questions regarding your experiences with PCPs. No previous experience is required. This research is currently being funded by the UGA Office of Sustainability Grant and your responses will be used to inform the development and design of PCPs as a green building technology. We estimate that this survey will take about 10 minutes to complete. We truly appreciate your input. Thank you.

Background Information on PCPs:

Similar to conventional concrete, pervious concrete consists of portland cement, water, and aggregates; however, the voids within pervious concrete is produced by significantly reducing or eliminating the amount of fine aggregate (sand) in the mixture. Benefits of pervious concrete include: (1) reduction in untreated runoff discharging into stormwater systems, (2) recharging groundwater tables, (3) channeling more water and air to tree roots (can pave PCP right up to trees and shrubs), (4) eliminate hydrocarbon pollution, (5) decreasing the dependency on detention ponds, and (6) reducing heat island effect. PCPs are considered a stormwater Best Management Practice.

Privacy:

Your contact information will NOT be shared. If you choose to provide your information we will only contact you for the purposes of expanding on your responses.

Questions:

1. Your input is extremely valuable. Please input your contact information. Thank you. (Optional).
2. Which of the following best describes the field in which you work?
3. How would you describe the usage level of PCPs in Georgia?
4. On a scale from 1 to 5 how would you rate your experience level with PCPs?
5. Please take a moment to describe your experiences with PCP (If no experiences enter "N/A" into the space provided).
6. In your opinion what are the barriers/limitations facing the use/acceptance of PCPs in your field?
7. What would you like to learn more about with regards to PCP?
8. Would you attend a workshop or a series of workshops designed to educate about the benefits of PCP as well as how to design and construct PCP systems?

Contaminant Removal Trial Data:

Trial 1

Sample	ppm (parts per million)				
	Cd cadmium	Cu copper	P phosphorus	Pb lead	Zn zinc
B	0.01	0.21	2.10	0.23	0.79
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.06	0.03	0.01
A5	0.01	0.01	0.06	0.03	0.01
A6	0.01	0.07	1.11	0.08	0.23
A7	0.01	0.14	1.34	0.10	0.14
A8	0.01	0.09	1.03	0.06	0.22
A9	0.01	0.09	1.17	0.05	0.27
A10	0.01	0.13	1.31	0.03	0.34

Trial 2

Sample	ppm (parts per million)				
	Cd cadmium	Cu copper	P phosphorus	Pb lead	Zn zinc
B	0.01	0.11	2.14	0.19	0.78
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.67	0.03	0.02
A5	0.01	0.01	0.06	0.03	0.01
A6	0.01	0.01	1.14	0.09	0.16
A7	0.01	0.01	1.38	0.07	0.13
A8	0.01	0.01	0.97	0.10	0.09
A9	0.01	0.04	1.24	0.05	0.24
A10	0.01	0.04	1.70	0.06	0.19

Trial 3

Sample	ppm (parts per million)				
	Cd cadmium	Cu copper	P phosphorus	Pb lead	Zn zinc
B	0.01	0.24	2.18	0.27	0.75
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.06	0.03	0.01
A5	0.01	0.01	0.06	0.03	0.01
A6	0.01	0.12	1.51	0.18	0.22
A7	0.01	0.14	1.00	0.13	0.10
A8	0.01	0.11	0.47	0.09	0.08
A9	0.01	0.19	1.00	0.14	0.14
A10	0.01	0.10	0.94	0.11	0.15

Trial 4

Sample	ppm (parts per million)				
	Cd cadmium	Cu copper	P phosphorus	Pb lead	Zn zinc
B	0.01	0.20	2.18	0.10	0.90
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.06	0.03	0.01
A5	0.01	0.01	0.06	0.03	0.01
A6	0.01	0.12	1.30	0.04	0.23
A7	0.01	0.16	1.46	0.07	0.27
A8	0.01	0.09	0.97	0.03	0.19
A9	0.01	0.20	1.56	0.08	0.34
A10	0.01	0.19	1.47	0.09	0.32

Trial 5

Sample	ppm (parts per million)				
	Cd cadmium	Cu copper	P phosphorus	Pb lead	Zn zinc
B	0.01	0.22	2.22	0.15	0.84
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.06	0.03	0.01
A5	0.01	0.01	0.06	0.03	0.01
A6	0.01	0.13	0.89	0.08	0.20
A7	0.01	0.18	1.38	0.12	0.31
A8	0.01	0.10	0.62	0.07	0.16
A9	0.01	0.17	1.21	0.13	0.33
A10	0.01	0.15	0.98	0.10	0.22

Trial 6

Sample	ppm (parts per million)				
	Cd cadmium	Cu copper	P phosphorus	Pb lead	Zn zinc
B	0.01	0.21	2.01	0.25	0.77
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.06	0.03	0.01
A5	0.01	0.01	0.06	0.03	0.01
A6	0.01	0.01	1.21	0.05	0.19
A7	0.01	0.04	1.42	0.08	0.24
A8	0.01	0.03	1.16	0.03	0.21
A9	0.01	0.08	1.37	0.06	0.33
A10	0.01	0.05	1.41	0.04	0.30

Trial 7

	ppm (parts per million)				
Sample	Cd cadmium	Cu copper	P phosphorus	Pb lead	Zn zinc
B	0.01	0.01	1.98	0.03	0.47
A1	0.01	0.01	0.06	0.03	0.01
A2	0.01	0.01	0.06	0.03	0.01
A3	0.01	0.01	0.06	0.03	0.01
A4	0.01	0.01	0.06	0.03	0.01
A5	0.01	0.01	0.06	0.03	0.01
A6	0.01	0.01	0.35	0.03	0.01
A7	0.01	0.01	0.48	0.03	0.01
A8	0.01	0.01	0.10	0.03	0.01
A9	0.01	0.01	0.84	0.03	0.08
A10	0.01	0.01	0.84	0.03	0.08

pH Data:

pH

pH Per Day

	B	A1	A2	A3	A4	A5
1	6.02	7.89	7.67	7.48	8.58	7.87
2	8.47	12.21	12.18	12.22	12.10	12.01
3	8.74	12.36	12.40	12.45	12.36	12.37
4	9.22	12.34	12.35	12.34	12.36	12.36
5	9.30	12.24	12.23	12.28	12.27	12.25
6	6.31	12.05	12.14	12.15	12.14	12.14
7	9.20	11.96	12.15	12.15	12.11	12.11
8	9.21	11.93	11.93	11.96	12.03	11.97
9	9.49	11.79	11.96	11.95	12.05	11.88
10	9.45	11.90	12.04	12.05	11.89	12.00
11	7.06	11.87	11.98	11.99	11.70	11.99
12	9.22	11.82	11.82	11.87	11.76	11.89
13	9.23	11.54	11.65	11.65	11.80	11.70
14	9.30	11.62	11.70	11.74	11.76	11.60
15	9.20	11.63	11.75	11.77	11.80	11.75
16	6.94	11.68	11.69	11.71	11.76	11.72
17	9.18	11.68	11.83	11.83	11.80	11.80
18	9.13	11.61	11.76	11.69	11.68	11.63
19	9.15	11.52	11.54	11.51	11.48	11.53
20	8.95	11.62	11.59	11.59	11.54	11.51
21	7.15	11.50	11.55	11.49	11.50	11.51
22	8.83	11.66	11.71	11.77	11.76	11.63
23	9.16	11.55	11.59	11.59	11.58	11.40
24	8.99	11.60	11.70	11.74	11.73	11.70
25	8.90	11.67	11.73	11.74	11.73	11.68
26	7.55	11.39	11.40	11.42	11.44	11.41
27	9.09	11.48	11.56	11.57	11.58	11.51
28	9.04	11.60	11.72	11.67	11.72	11.67
29	9.03	11.64	11.69	11.64	11.55	11.59
30	8.96	11.65	11.67	11.70	11.72	11.72
31	7.70	11.45	11.46	11.52	11.53	11.52

pH

pH Per Day

	B	A6	A7	A8	A9	A10
1	6.02	12.22	12.26	12.08	12.16	12.09
2	8.47	12.36	12.38	12.35	12.36	12.37
3	8.74	12.40	12.47	12.30	12.30	12.45
4	9.22	12.42	12.45	12.50	12.48	12.55
5	9.30	12.24	12.15	12.20	12.31	12.36
6	6.31	11.99	12.12	12.13	12.10	12.11
7	9.20	12.02	12.11	12.16	12.13	12.17
8	9.21	12.12	12.13	12.18	12.10	12.31
9	9.49	12.02	12.16	12.02	12.03	12.19
10	9.45	12.08	12.13	12.06	11.98	12.02
11	7.06	11.97	12.17	12.05	11.96	12.04
12	9.22	11.89	11.93	12.07	11.98	12.01
13	9.23	11.80	11.79	11.88	11.82	11.79
14	9.30	11.86	11.92	11.86	11.74	11.70
15	9.20	11.81	11.77	11.90	11.85	11.95
16	6.94	11.85	11.83	11.88	11.80	11.86
17	9.18	11.85	11.93	11.97	11.89	11.98
18	9.13	11.92	11.94	11.78	11.70	11.69
19	9.15	11.63	11.61	11.63	11.66	11.70
20	8.95	11.57	11.65	11.59	11.60	11.66
21	7.15	11.59	11.62	11.57	11.49	11.42
22	8.83	11.85	11.88	11.82	11.78	11.78
23	9.16	11.65	11.60	11.52	11.65	11.50
24	8.99	11.73	11.76	11.84	11.77	11.83
25	8.90	11.82	11.89	11.86	11.78	11.80
26	7.55	11.43	11.33	11.40	11.40	11.55
27	9.09	11.64	11.47	11.59	11.57	11.64
28	9.04	11.84	11.87	11.85	11.84	11.85
29	9.03	11.80	11.78	11.80	11.71	11.84
30	8.96	11.81	11.82	11.83	11.86	11.85
31	7.70	11.57	11.61	11.57	11.55	11.56