ASSESSMENT OF STORM WATER QUALITY THROUGH POROUS PAVEMENT SYSTEMS

by

Swarup Kumar Dudala

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Approved by

Clifford R. Lange, Chair, Associate Professor of Civil Engineering
Andrzej Nowak, Elton & Lois G. Huff Eminent Scholar and Professor of Civil Engineering
Mark O. Barnett, Professor of Civil Engineering, Associate Chair Department of Civil Engineering

Abstract

Stakeholders, (designers, industrial developers, governmental agencies, and private landowners) are increasingly concerned about enhancing storm water quality, reducing run off, and improving the recharge of ground water. They are increasingly turning to sustainable pavement systems to address these issues. The most widely used pervious pavements consist of porous asphalt or concrete over open graded aggregate base and are considered storm water Best Management Practice (BMP). However, without proper information pervious pavements are inapplicable. In choosing pervious pavement options valid measures such as infiltration rate, storm water quality, thermal gain, and water storage capacity are routinely considered, but environmental performance is not.

This study discusses the effects of storm water quality on porous pavements and impacts on groundwater quality of infiltrating contaminated storm water. In order to assess these impacts a bespoke field site was constructed on the Auburn university campus which provides parallel assessment of pervious and impervious, regular and experimental paving systems. These pavements tested included conventional concrete and asphalt, porous concrete and porous asphalt, photocatalytic pervious and impervious concrete. In this study, effluents from all the pavements were tested for contaminants such as Oil and grease, PAH, Heavy metals (Pb, Cu, Zn, Cd, Cr and Fe), Sediments, Nutrients, Chloride, and TDS. The results of this experiment suggest pervious pavements can effectively remove selected contaminants from storm water runoff and leachate

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Table of Contents

List of Tables

List of Figures

Chapter 1

Chapter 3

Chapter 4

List of Abbreviations

BMP	Best Management Practice
BTEX	Benzene, Toluene, Ethyl benzene, Xylene isomers
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
IC	Impervious Concrete
ICP	Inductively Coupled Plasma Spectroscopy
IPC	Impervious Photocatalytic Concrete
NO_x	Nitrogen Oxides
NPA	Non Porous Asphalt
NTU	Nephlometric Turbidity Unit
PA	Porous Asphalt
PC	Pervious Concrete
PPC	Pervious Photocatalytic Concrete
PVC	Polyvinyl Chloride
SO_x	Sulphur Oxides
TDS	Total Dissolved Solids
TiO_2	Titanium Dioxide
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids

TU	Turbidity Unit
U.S.	United States
UV	Ultraviolet
VOCs	Volatile Organic Compounds
ND	Not detected
N/A	Not applicable

Chapter 1

Introduction

Background

Water quality, particularly urban storm water is capable of washing and scouring debris and the pollutants from the landscape [1]. This has been the major focus for many researchers, municipalities, and homeowners in urban areas. It is a known fact that infiltration can only occur on vegetated or pervious surfaces. The rainfall which is not infiltrated or evaporated becomes active urban runoff which increases washing, scouring and causes flood related property damage [2]. Stormwater runoff is also the major reason for contamination of downstream water bodies. To avoid degradation of the aquatic environment, Storm-water Best Management Practices (BMP) are now being implemented [3]. This study will focus on the pervious pavements located on Samford Avenue pavement testing site, Auburn University.

Porous Pavements

A porous pavement is described as a pervious surface course underlain by a stone bed of uniformly graded and clean-washed coarse aggregate with a void space of at least 40% [4]. Following Figure 1 shows a proper representation of Porous Asphalt System[5]. Although, there are several types of porous pavements being employed, two commonly installed pavement types are porous asphalt, and pervious concrete. In addition, this study also included pervious and impervious photocatalytic concrete pavement system. The principle quality differentiating porous and traditional surfaces is that a porous surface will allow the storm-water to drain through the pavement surface directly into the underlying stone bed as the aggregate is screened in the porous surface.

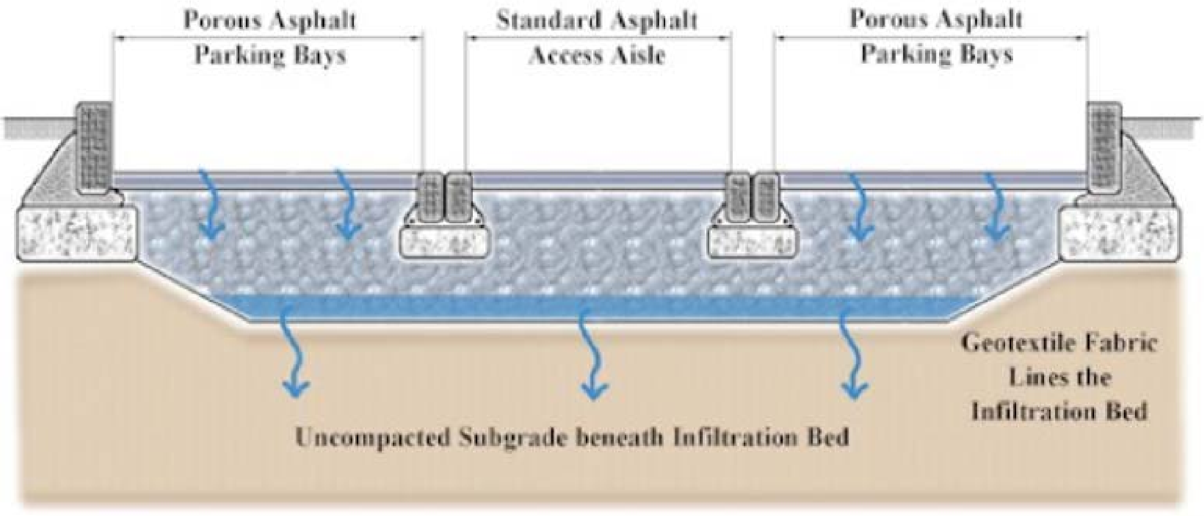

Figure 1. Porous Asphalt System (PADEP 2007)

Photocatalytic Concrete

Photocatalytic concrete is a pervious pavement enhanced with titanium dioxide to give it photocatalytic properties. Urbanization has driven many countries to seek methods to reduce air pollution especially that emitted from vehicles. However, photocatalytic concrete is new, thus it and its properties are relatively unknown. [6]. The photo catalyst, titanium dioxide (TiO_2) is the main ingredient which activates with ultraviolet (UV) radiation to oxidize air pollutants, such as nitrogen oxides (NO_x), Sulphur oxides ($SO_{x)}$ and Volatile organic compounds (VOCs)[7]. This method of applying TiO_2 photocatalytic effect onto pervious pavements seemed to be a promising environmental property [6]. Figure 2 illustrates the photocatalytic effect of TiO_2 on the pavement. The principle followed is, the pollutants from vehicle exhaust get adsorbed to the pavement surface. The TiO_2 coating on the pavement surface gets activated with the ultraviolet sunlight, and then breaks down the pollutants. The resulting products are then removed from the pavement.

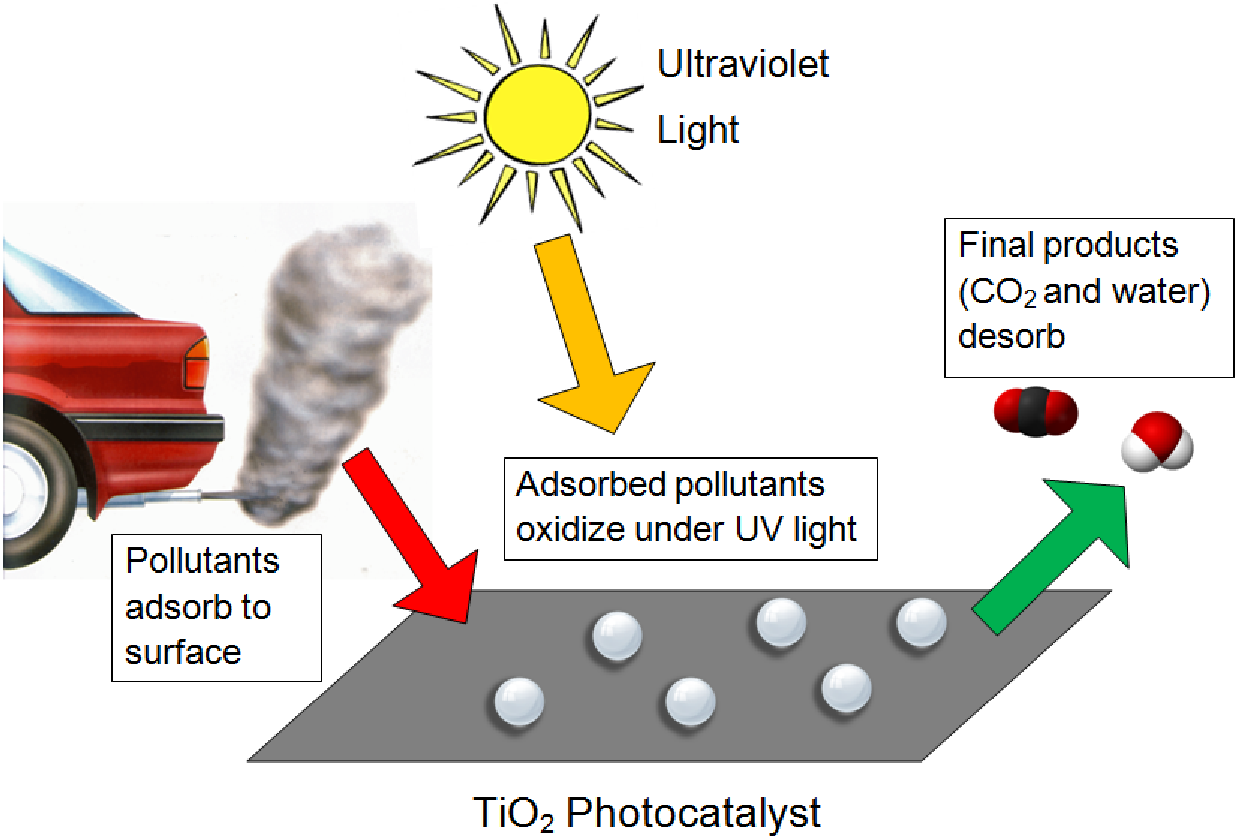

Figure 2. Photocatalytic effect of Titanium dioxide onto the pavement

In addition, it is also used to remove pollutants in water like BTEX (benzene, toluene, ethyl benzene, xylene isomers) and Total petroleum hydrocarbons (TPH). Although photocatalytic effect or organic pollutants in water treatment works, it is difficult to separate and retrieve the small TiO_2 suspended particles. This can be a major problem and hence studies suggested to incorporate TiO_2 into cementitious construction materials. This will immobilize TiO_2 and allow the photocatalytic degradation to take place.

Project Overview

This study focuses on Pervious concrete (PC), Porous asphalt (PA) and Pervious Photocatalytic Concrete (PPC) paving surfaces which are often used alongside impervious pavements. This allows to treat and reduce the peak flows, storm water runoff volumes and improves runoff quality. The pollutants included in this study are key urban pollutants such as PAHs, Heavy metals, Oil and Grease, Nutrients, Sediments, and other contaminants in the water source. A series of parallel assessments connecting storm water quality of pervious and impervious, conventional and experimental paving systems are generated. This study is therefore, necessary to get data regarding reduction of storm water contaminants thorough various pervious and impervious pavement systems. The data generated from this study will also be helpful to watershed groups, communities, and industries to protect and restore water quality.

Chapter 2

Literature Review

Introduction

Precipitation in the form of rain and sleet usually contains trace amounts of minerals, gases and other substances as it falls through the earth's atmosphere [2]. It also doesn't have any bacterial content. However, once the precipitation reaches the earth's surface it may pick up mineral and organic substances, microorganisms, particles of soil. Most of this suspended particles are filtered out when the surface water flows downward into the soil. This natural filtration is believed to be partially effective in removing contaminants [2]. Whereas groundwater contains more dissolved minerals than surface water because as surface water seeps down the water table, it dissolves the trace minerals contained in the soil and rocks. In addition, water quality can be categorized in the following four categories.

Physical

Turbidity - Water which contains suspended material is known to be turbid water. The Unit of measurement is Turbidity Unit (TU) or Nephlometric turbidity Unit (NPU). Turbidity should not be more than 5TU and are usually objectionable for aesthetic reasons. Water containing clay or other inert suspended particles may not effect health but the water should be treated before using it [2],

Color – Color in the water may result from the dissolved organic material and industrial wastes or sometimes from the presence of humus and peat materials. Its presence is objectionable and water needs appropriate treatment to be used for general and industrial applications [2, 8].

Taste and Odor – Taste and odor in water may result from the presence of foreign matter such as organic compounds, inorganic salts and dissolved gases originated from domestic and agricultural sources. Water should be treated before using it for drinking or any other general applications [2, 8].

Temperature – Most drinking waters are cool and doesn't show fluctuations of more than few degrees [2, 8]. From the studies it has been believed that water having temperature range between 10^{o}-15^{o}C is most desirable.

Chemical

Chloride – Chloride in the water may result from the presence of leaching of sedimentary deposits or by pollution from sea water, domestic and industrial wastes. It is in the form of Cl ion in wastewater and water. Chloride concentration in excess of 250 mg/L may have a detectable salty taste. The limit for domestic water is less than 100 mg/L. It has been observed that a high chloride content harms metallic pipes, structures and also plants [1].

Fluoride – In some areas, fluoride may occur naturally in water. Excessive fluoride in drinking water causes fluorosis or mottling of teeth. Acceptable levels of fluoride are usually between 0.8 mg/L and 1.3 mg/L fluoride. Fluoride concentrations sometimes may approach 10 mg/L in some waters because this is naturally occurring fluoride. Such waters should be immediately defluoridated [1, 2].

Iron – Most waters contain some amount of iron as geologic materials contain large amount of iron. The presence of iron in water is considered harmful as iron in water can cause staining of laundry and also affects the tastes of beverages. Acceptable level of iron is less than 1 mg/L [8].

Lead – Lead when exposed to a body even in small dosage can be seriously damaging to health. Natural waters rarely contain more than 20 ug/L, although high values have also been reported. Lead in the water may result from industrial, mine or dissolution of old lead plumbing. It is known to be a serious cumulative poison, hence the water should be treated before using it for drinking purposes [1, 8].

Manganese – Manganese seldom present in excess of 1 mg/l, imparts a brownish color to water and to the laundry. Also it imparts tenacious taste to coffee and tea [8].

Sodium – It is present in most of the natural waters. The presence of sodium in water can effect persons suffering from heart, kidney or circulatory ailments. Acceptable limiting concentration is 2 to 3 mg/l [1, 2, 8].

Sulfate - Water which contains sulfate is caused due to leaching of natural deposits containing magnesium or sodium sulfate. This should not be present in excess in drinking water [1].

Zinc – Previous mining operations are a principle predictor of the presence of zinc. It may also result from industrial waste pollution. Some natural waters contain zinc. It is very essential in body growth but concentrations above 5 mg/l can cause bitter astringent taste. The U.S. drinking waters have varying concentrations between 0.006 mg/l and 7.00 mg/l. Zinc is not considered harmful to health but it usually imparts bad taste to drinking water [1, 6, 8].

Arsenic – Arsenic may occur in water as a result of industrial discharge or mineral dissolution. The concentration of arsenic in most potable water rarely exceeds 10 µg/l, although sometime as high as 100 µg/l has been reported. Arsenic is known to have carcinogenic properties therefor ingestion of as little as 100 mg can cause serious chronic effects [2, 8].

Toxic Inorganic Substances – These include Nitrates, cyanides, and heavy metals. Water having high concentrations of nitrate caused blue baby syndrome in infants. Cyanide attacks hemoglobin sites in the human body that bind oxygen to red blood cells. This causes oxygen deprivation known as cyanosis. The toxic heavy metals include arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), selenium (Se), and silver (Ag). These are known to have acute poisons for example As and Cr and also chronic disease for example Pb, Cd and Hg [1, 8].

Toxic Organic Substances – The U.S. EPA has listed over 120 toxic compounds which includes pesticides, insecticides and solvents. Likewise, toxic inorganic substances these are known for the acute and chronic effects [2, 8].

Microbiological Characteristics

The organisms which cause water unfit for drinking include viruses, bacteria, protozoa, and worms. Unfortunately there is no clear idea regarding the specific disease producing organisms present in the water. The tests for determining particular organism are complex and time consuming. Hence, Total coliform test has been employed to determine the relative degree of contamination in terms of easily defined quantity [1, 2]. This test estimates the number of microorganisms of the coliform group which includes Escherichia coli and Aerobacter aerogens. This test is widely used because of the following reasons:

- Easy to culture, hence easy to perform tests without expensive equipment

- These group of organisms usually inhabit the intestinal tracts of humans and other mammals. Therefore, the presence of these organisms indicates fecal contamination of the water.
- The coliform group of organisms survive better in water than most of the pathogens and does not reproduce. Hence, presence of coliforms in water indicate fecal contamination [2].

Radiological Characteristics

Radiological contamination results from mining of radioactive materials, as wells as naturally occurring radioactive materials. Unnecessary exposure should be avoided. The areas near to the nuclear industries will have water with high radioactivity and thus precautions should be taken to avoid the exposure [1].

Chapter 3

Methods, Procedures, and Facilities

In order to conduct water quality analysis, a parallel comparison among different paving systems was proposed. These paving systems were constructed at Auburn building science field laboratory instrumented with runoff and leachate collection, as shown in Figure 1. As mentioned earlier, pervious and impervious pavements include photocatalytic concrete, traditional concrete, and asphalt.

Figure 1. Location map, Samford Avenue Pavement Testing Site.

Following are the step by step procedures employed while constructing the pavement at the facilities site.

Water Pressure determination

The first thing was to determine the sprinklers water pressure that will be used to simulate rain. From the previous studies it has been observed that a minimum water pressure of 40 psi is required for the sprinklers to function properly. The site has water pressure of about 50 psi which is more than the minimum water pressure required, as shown in Figure 2.

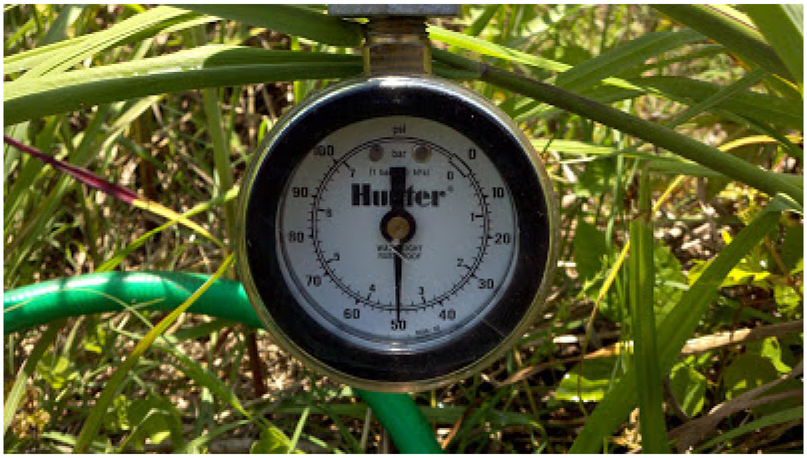

Figure 2. Site water pressure

Placement of the Project

This was the next step and this location was chosen because it is not in between other activities that will take place on the site and also this had maximum exposure to the sunlight. The location is marked with the orange flag tape where the pavements will be constructed as shown in the Figure 3.

Figure 3. Placement of the project

Formwork

This was completed and installed with the help of Facilities. The forms were placed according to the plans from the Sketch Up model and string line was used to ensure the alignment and slope of this formwork, as shown in the Figure 4.

Figure 4. Formwork Layout

Plumbing

With the help of facilities and their trencher supply-lines and the field-drain were excavated. This field-drain helped in draining the excess water from the tests. After this 3 faucets, each supplied by a ½″ PVC line were installed. One faucet (Fig. 5) was run for the job trailer, one was run for some concrete aggregate bins study, and the last was run for the Water Quality Study.

Figure 5. Plumbing in the site.

Placing # 57 Stone and Backfilling

Stones were filled into the trough boxes using backhoe (Fig. 5). Then the area between the sample panels was backfilled with the soil that was excavated earlier in the project (Fig. 6).

Figure 6. Placing of #57 Stone.

Figure 7. Backfilling in the site

Placing of regular and pervious concrete

In this process, firstly the #57 stone was flushed with water to remove the fines (Fig. 7). This helped in preventing the stone to pull out water from concrete and no interference of fines while testing. Then, the traditional concrete and pervious concrete was poured as shown in the Figure 8 and Figure 9.

Figure 8. Flushing water to remove fines

Figure 9. Pouring of traditional concrete

Figure 10. Pouring of pervious concrete

Placing of regular and pervious photocatalytic concrete

Photocatalytic concrete is a concrete which is relatively new and unknown with a very good promising environmental properties. It has a photo catalyst (titanium dioxide) that uses sun light to clean contaminated water and air by reacting with NO_x and SO_x pollutants. This basically means that it is self-cleaning and has the ability to remove certain pollutants, as mentioned earlier. Once after placing traditional photocatalytic concrete, pervious photocatalytic concrete was placed as shown in the Figure 10 and Figure 11.

Placing of regular and pervious asphalt

The procedure is same as mentioned for placing traditional concrete and photocatalytic concrete.

Figure 11. Placing of traditional photocatalytic concrete

Figure 12. Placing of pervious photocatalytic concrete

Irrigation system

After the successful placing of concrete, asphalt, and white concrete irrigation system was the next step. For this a trench was dug at -12″ and ½″ PVC irrigation piping was assembled and connected to the water supply as shown in Figure 12. One or two inches of #57 gravel was used to avoid mud on surface.

Figure 13. Irrigation system in the site

Stormwater Application

After completion of Samford Avenue pavement testing site next step was Storm Water application. A rainfall event was simulated in the pavement testing site using the water sprinklers which was installed as mentioned earlier in the irrigation system. The sprinklers were operated for 30 minutes to apply a consistent volume of water to each paving system. A water pressure meter located verified a consistent flow rate into each paving system. It showed water pressure of about 50 psi which is more than the minimum water pressure required.

Water Sample Collection

The water was turned on and the sprinklers started to rain water onto the slab. Water samples were collected by hand from each pavement slab. These were collected both during warm season (July to October) and cool season (November to February).

Water Quality Analyses

Water samples from the pavement testing site were analyzed for the concentrations of oil and grease, heavy metals (Pb, Cu, Zn, Cd, Cr, and Fe), Sediments, PAHs, Nutrients, chloride, and Total Dissolved solids (TDS). In addition to these pH, and alkalinity were also monitored. All water quality analyses in the Environmental Engineering laboratory, Ramsay hall. Metal concentrations were determined using inductively coupled plasma spectroscopy (ICP) (EPA Method 200.8). Hydrocarbons, sediments, nutrients, chloride, and Total Dissolved solids (TDS) were analyzed using EPA Methods 418.1, 160.2, 350.1, 325.1, and 160.1 respectively. In addition, pH and Alkalinity were detected using EPA methods 150.1 and 310.1 respectively.

Chapter 4

Stormwater Comparison Results and Discussion

The results of the Stormwater comparison from Porous Asphalt (PA), Pervious Concrete (PC), Pervious Photocatalytic Concrete (PPC), Non-Porous Asphalt (NPA), Impervious Concrete (IC), Impervious Photocatalytic Concrete (IPC) comparison study are discussed in this chapter.

pH

The pH value is a measure of the acidity of the water [8]. A pH value of less than 7 is defined as acidic, while a pH value of 7.1 or greater is defined as basic. [1]. Most estuarine organisms can safely inhabit an environment with a pH value from 6.5 to 8.5 [1, 8]. The pHs from the samples were found to be slightly basic. The mean pH values for different paving systems mentioned earlier are shown in Table 1.

Table 1. Descriptive pH for different paving systems

Parameter	PC	PA	IC	NPA	IPC	PPC
pH (N=3)	7.38	7.56	7.42	7.63	7.49	7.24

Figure 1 shows the graphical representation and comparison of the average pH values generated for different paving system. The graph indicates that there is not much difference between the pH of pervious and impervious surfaces. This small difference can be due the chemical composition of fresh concrete. However, porous pavements showed good performance overall.

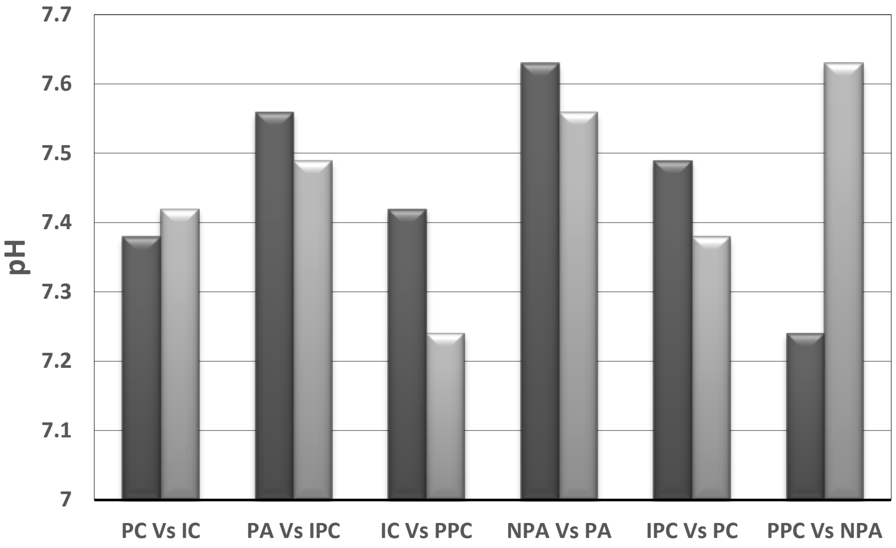

Figure 1. Graphical representation of average levels of pHs from different paving systems.

Alkalinity

The alkalinity is a measurement of the acid neutralizing capacity of water. In other words, alkalinity is the water's ability to maintain a relatively constant pH. This parameter is very important for aquatic life because it buffers against rapid pH changes. Higher alkalinity levels in surface water usually buffers acid rain and other acid wastes. In addition, prevents pH changes that are harmful to aquatic life [1, 8]. The alkalinity of stromwater sample was determined by titrating the sample with Sulphuric acid of known values of pH, volume and concentrations. The values for the alkalinity of the different pavement systems are shown in Table 2.

Table 2. Total Alkalinity for different paving systems

Parameter (N=3)	PC	PA	IC	NPA	IPC	PPC
Alkalinity (mg/L)	225.3	185.6	145	124.2	225.4	185

The average alkalinity values showed lot of variation between the pavements. The impervious concrete and Non-porous asphalt surfaces had values of 145 mg/L and 124.2 mg/L respectively which was lower than pervious and porous sections and, porous pavements have higher alkalinity, as shown in Figure 2. Presumably, this could be due to the dissolved solids from the concrete and/or the aggregate layer underlying the pavement.

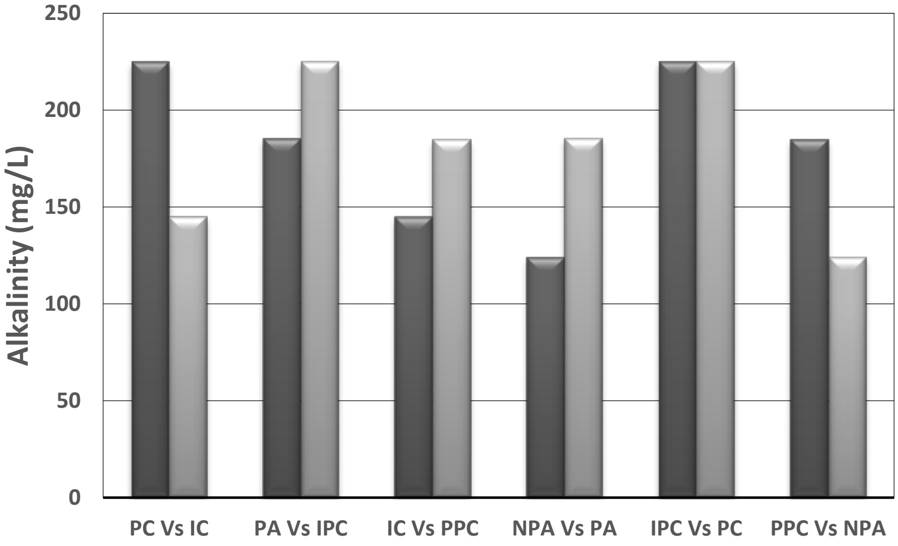

Figure 2. Graphical representation of the average levels of Alkalinity (mg/L) from different paving systems.

Total dissolved solids

The term "Total dissolved solids" refers to materials that are completely dissolved in water or wastewater [8]. These solids are known as filterable residue [8]. These dissolved minerals or organic constituents may produce bad color, taste and odor in the water samples. Also, some dissolved solids may deplete the dissolved oxygen (DO) in receiving waters. Hence, the analysis of this parameter is very important. The results from the Stormwater samples of this has been shown in Table 3.

Table 3. Total Dissolved Solids for different paving systems.

Parameter (N=3)	PC	PA	IC	NPA	IPC	PPC
TDS (mg/L)	182.4	156.3	338.2	298.3	295.7	180.2

As shown in Figure 3, it can be seen that pervious sections appear to be better in contaminant removal than impervious surfaces. Total dissolved solids concentration in porous asphalt averaged 156.3 mg/L and did not show any fluctuations between the tests. Runoff that percolated through both porous concrete and porous asphalt had significantly lower Total Dissolved Solids (TDS) than impervious pavement.

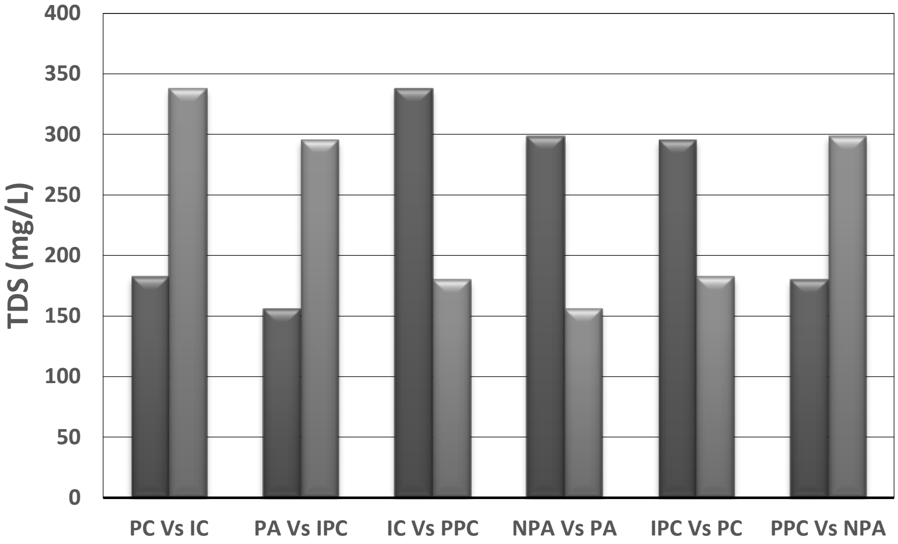

Figure 3. Graphical representation of average levels of TDS (mg/L) from different paving systems

Total Suspended Solids (TSS)

The term "Total Suspended Solids" refers to the materials that are non-filterable in nature. In definition, residue upon evaporation of non-filterable sample on filter paper [8]. These suspended solids are extremely valuable in the analysis of polluted waters. In addition, they exclude light, reducing the growth of plants which produce oxygen [2]. The total suspended solids in porous concrete and porous asphalt averaged 52.4 and 46.3 mg/L which was lower than Porous photocatalytic concrete pavement as shown in Figure 4 and the values can be seen in Table 4. Porous concrete and Porous asphalt reduce the TSS. Also, porous asphalt and porous concrete reduce TSS in runoff to a similar degree. In addition, suspended solids accumulates in matrix and clogging may be a consequence.

Table 4. Total Suspended Solids for different paving systems.

Parameter (N=3)	PC	PA	IC	NPA	IPC	PPC
TSS (mg/L)	52.4	46.3	132	128.3	78.4	104.4

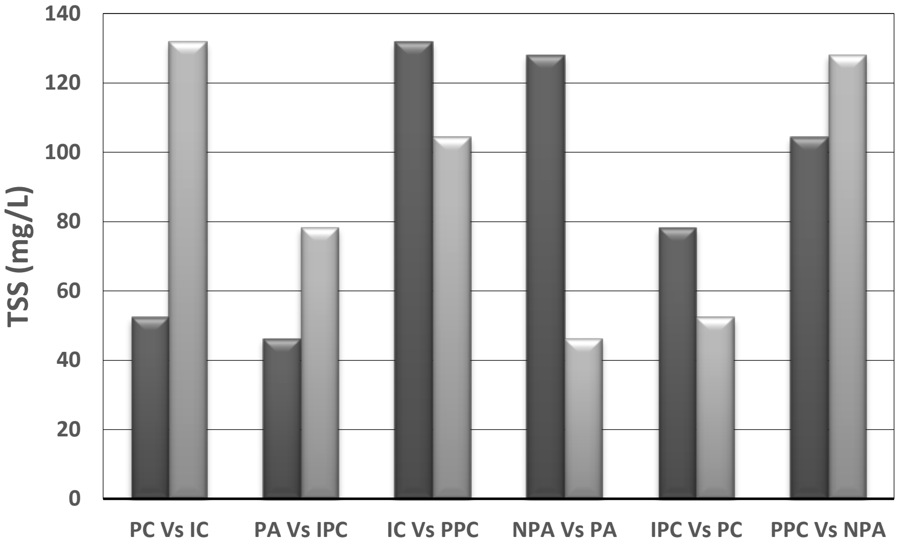

Figure 4. Graphical representation of average levels of TSS (mg/L) from different paving systems.

Chloride, Nitrate, Nitrite, Phosphate, Sulphate, and Bromide

These parameters were tested using a Dionex ion chromatograph available at the Civil Engineering Department, Auburn University. The Ion chromatograph works by injecting small amounts of filtered water sample into an anion exchange column where various anions present are separated out. Then, they enter the conductivity detector which measures the anions. The conductivities are plotted and a software is used to integrate the area for the individual anion.

Further, these areas are compared to standard sample areas and concentrations of the various parameters are determined. Figure 5 shows an example of a chromatogram for a standard sample.

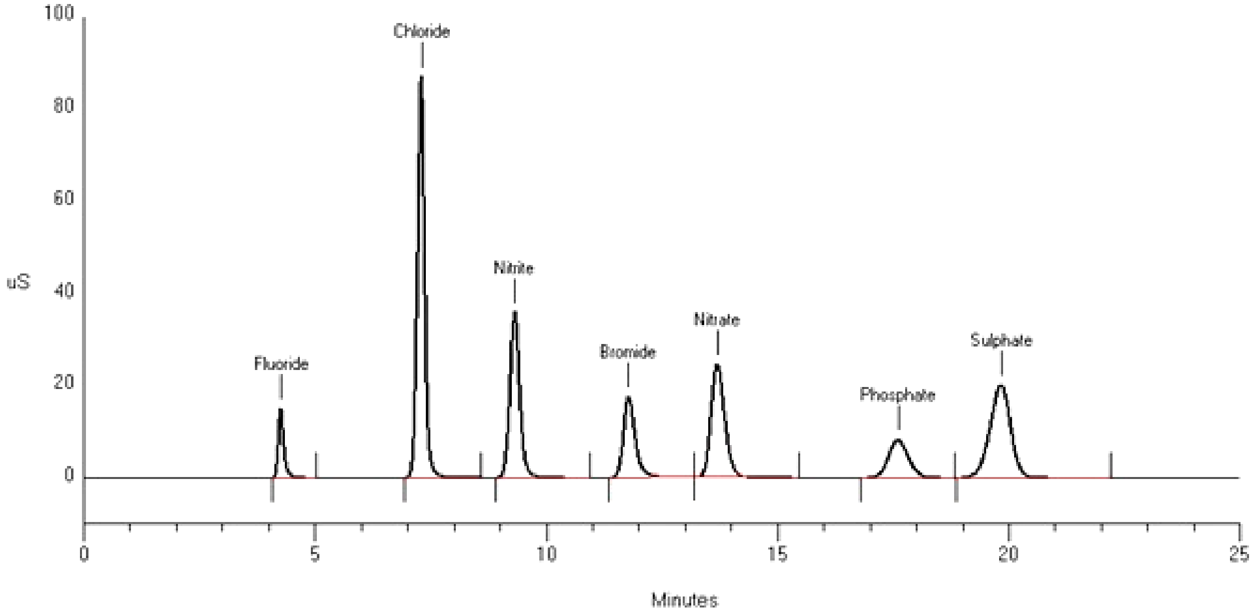

Figure 5. Simple chromatogram for a standard sample

The results for this parameters are shown in Table 5. All the pervious pavements showed good contaminant removal for nutrients, phosphate, sulphate and chloride. However, the bromide was not detected from any of the pavement surfaces. Impervious concrete reduced the anions relative to impervious asphalt. Porous concrete and porous asphalt reduce the anions and porous concrete had significantly lower anions in runoff as shown in Figure 6 and Figure 9. This can be due Ca^{2+} which may play a role in reducing anions. Most importantly nutrients (NO_3^-& PO_4^-) that are problematic in runoff and groundwater were significantly reduced by porous sections (Fig. 7 and Fig.8). However, there was approximately 50% reduction in NO_3^- by concrete. Porous Asphalt did not reduce NO_3^-. This could be important because nitrate is a major contaminant in surface and groundwater. In addition, there was approximately 70% reduction in PO_4^- by concrete. This shows concrete sections were better in reducing nutrients than asphalt sections. Clearly, there seems to be no significant issue concerning interference effects for these parameters.

Table 5. Chloride, Nitrate, Phosphate, Sulphate and Bromide for different paving systems

Parameter (N=3)	PC	PA	IC	NPA	IPC	PPC
Chloride (mg/L)	45.3	76.7	60	120.3	20.8	18
Nitrate (mg/L)	0.3	0.44	0.55	0.40	0.49	0.28
Phosphate (mg/L)	0.05	0.02	0.16	0.1	0.12	0.02
Sulphate (mg/L)	32.2	25	48.4	38.3	26.7	14.2
Bromide (mg/L)	ND	ND	ND	ND	ND	ND

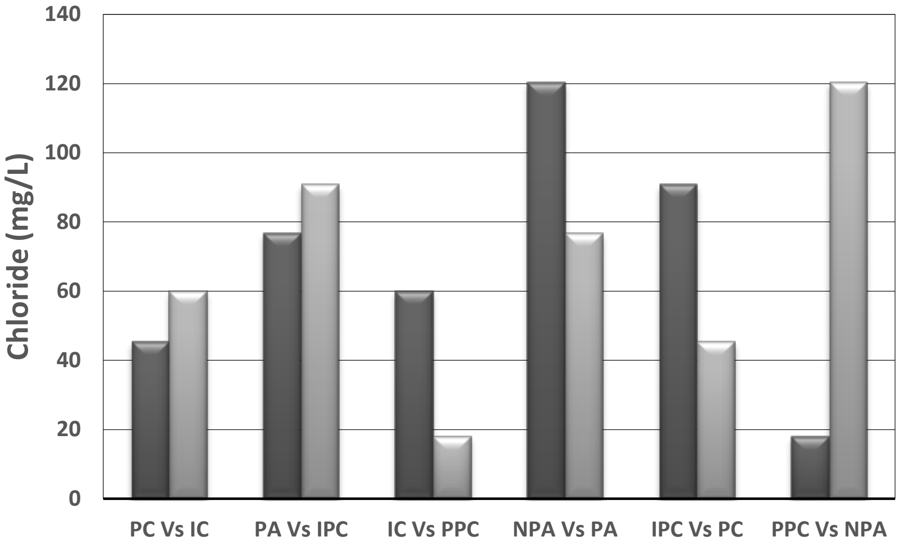

Figure 6. Graphical representation of average levels of Chloride (mg/L) from different paving systems

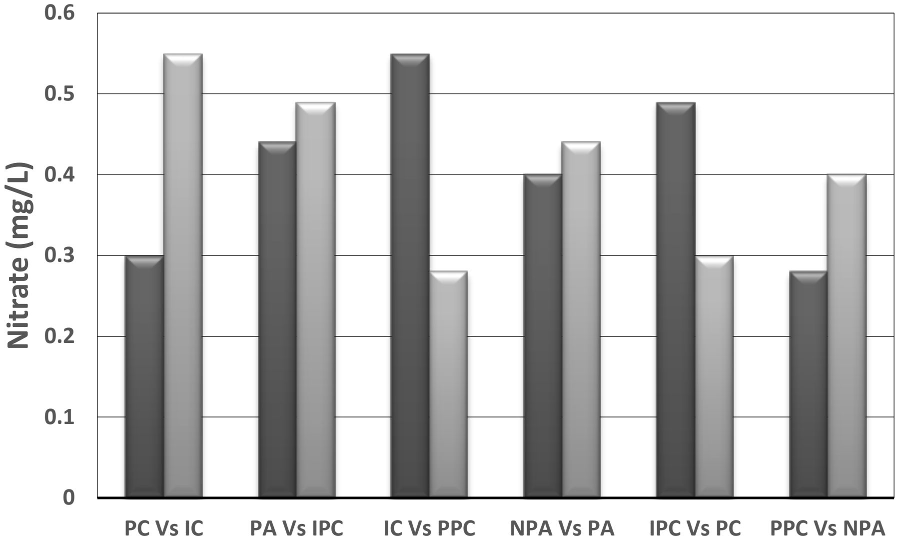

Figure 7. Graphical representation of average levels of Nitrate (mg/L) from different paving systems.

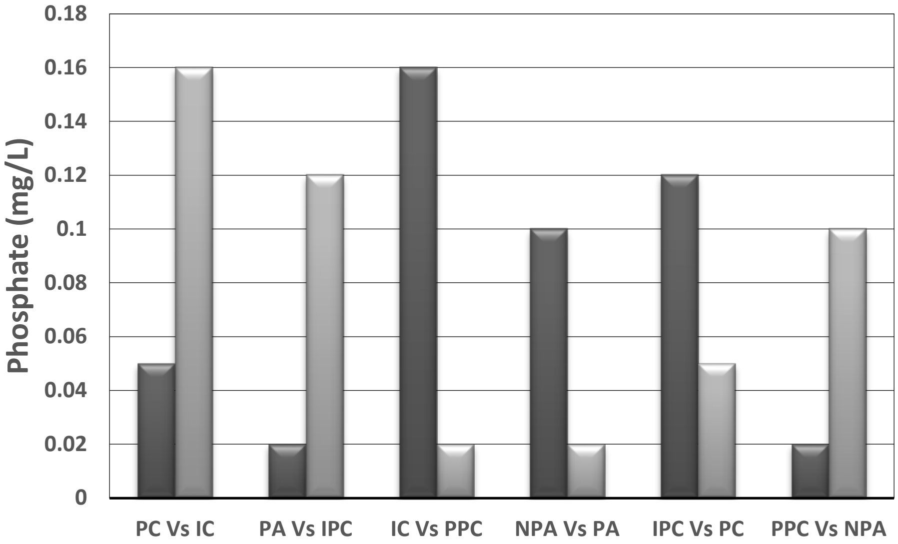

Figure 8. Graphical representation of average levels of Phosphate (mg/L) from different paving systems.

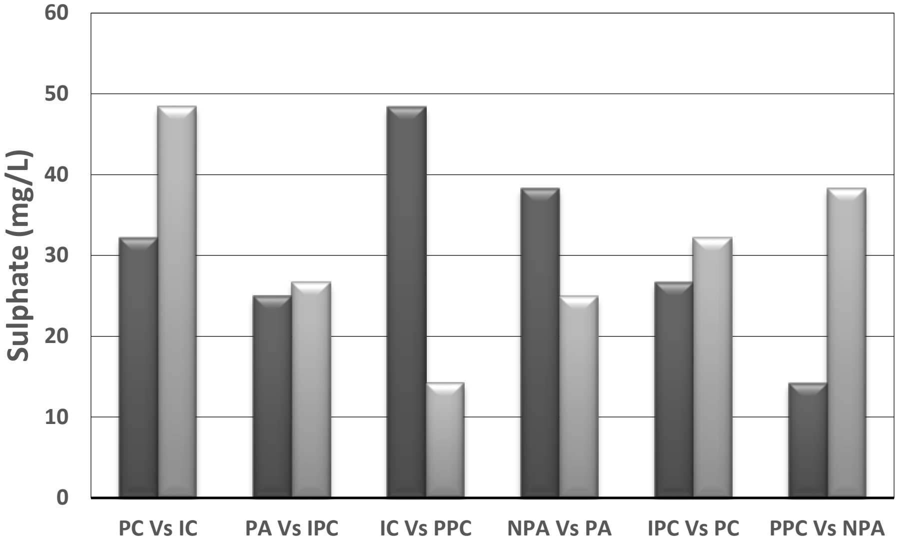

Figure 9. Graphical representation of average levels of Sulphate (mg/L) from different paving systems.

Hydrocarbons

The dispersed concentration of oil and grease (OG) is very important parameter for water quality [8]. OG when discharged in surface or ground waters can cause health risks [2]. In this study methylene chloride was used as the solvent to extract any hydrocarbons that are found in the samples. The results from storm water samples has been shown in Table 6. It is very evident from the Figure 10 that there was a considerable decrease in the contaminant through porous concrete and asphalt pavements compared to non-porous pavement sections. Porous concrete reduced OG by approximately 50% and Porous asphalt reduced OG by 33%. However, Photocatalytic concrete did not show any reduction in OG. There was no exact reason for this and more research should be conducted before drawing any conclusions

Table 6. Oil and grease (OG) for different pavement systems

Parameter (N=3)	PC	PA	IC	NPA	IPC	PPC
Oil & Grease (mg/L)	0.03	0.8	0.06	1.2	0.45	0.78

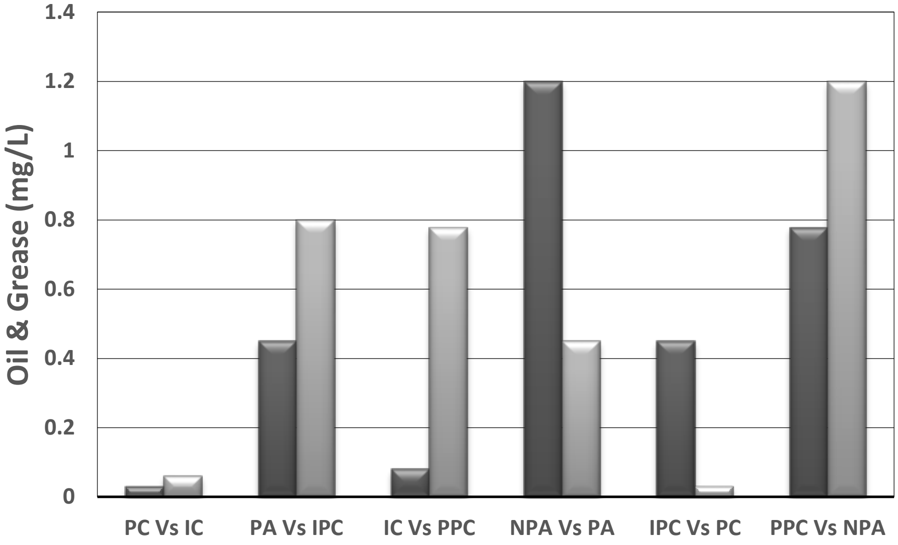

Figure 10. Graphical representation of average levels of oil and grease from different paving systems.

PAHs

The US EPA identifies 16 different PAH molecules among which 7 are potential human carcinogens [1, 2]. From studies it has been proved that the molecules which have more rings are less soluble in water, and are more toxic. Table 7 shows US EPA 16 priority-pollutant PAHs [2]. In the Table 7, US EPA has classified PAHs in italics as probable human carcinogens.

Gas chromatography Mass spectroscopy set up was used in this study. Each sample was analyzed using an Agilent 5975C gas chromatograph mass spectrometer (GCMS) installed with a column [8]. After the analysis no PAH compounds were found in any of the samples. PAH were below levels of concern in all systems. In the porous asphalt sample, 6 out of 16 PAH compounds were detected but those were below detection limit.

Table 7. Selected properties of US EPA 16 priority PAHs [8].

PAH	Structure (# of rings)	Molecular Weight (g/mole)	Solubility (mg/L)
Naphthalene	2	128.17	31
Acenaphthene	3	154.21	3.8
Acenaphthylene	3	152.20	16.1
Anthracene	3	178.23	0.045
Phenanthrene	3	178.23	1.1
Fluorene	3	166.22	1.9
Fluoranthene	4	202.26	0.26
Benzo(a)anthracene	4	228.29	0.011
Chrysene	4	228.29	0.0015
Pyrene	4	202.26	0.132
Benzo(a)pyrene	5	252.32	0.0038
Benzo(b)fluoranthene	5	252.32	0.0015
Benzo(k)fluoranthene	5	252.32	0.0008
Dibenz(a,h)anthracene	6	278.35	0.0005
Benzo(g,h,i)perylene	6	276.34	0.00026
Indeno[1,2,3-cd]pyrene	6	276.34	0.062

Heavy Metals (Pb, Cu, Zn, Cd, Cr, Fe)

With the development of industrialization, smelting and mining activities, heavy metals are increasingly being found in water. This can pose serious human health risks and also affects crops productivity [2, 8].

In this study, a Varian Inductively Coupled Plasma Instrument (ICP) was used to determine metals in the water sample. Table 9 shows operating conditions for Inductively Coupled Plasma Instrument (ICP). After the analysis, it was found very low concentrations of all the heavy metals through different pavement systems. The heavy metals concentration for all the porous systems were found to have big reductions when compared to impervious sections. Porous concrete reduced lead (Pb) by 75% and Porous asphalt reduced lead (Pb) by approximately 85%. This shows there is not much difference between concrete and asphalt with respect to lead. Further, Photocatalytic concrete had removal efficiency of 60%, which is slightly lower than concrete and asphalt. When copper was considered, it was found approximately similar reductions in concrete, asphalt and photocatalytic concrete. While considering Zn, it was found that pervious concrete reduced it by 96% whereas asphalt and photocatalytic concrete had approximately similar reductions of 67% and 65%. When asphalt samples was compared to concrete samples with respect to Cr and Fe, the reduction observed by asphalt was 75% and 97% respectively. This shows asphalt was better in reducing Cr and Fe. This could be possibly due to the components of the Portland cement used in the mix. Table 10 shows the results obtained. Concentrations of all the metals Pb, Cu, Zn. Cd, Cr and Fe are shown in the Figure 11, Figure 12, Figure 13, Figure 14, Figure 15 and Figure 16 respectively. In addition, it can be seen that overall performance of pervious paving surfaces was effective in reducing the impacts of heavy metals.

Table 8. Operating conditions for Inductively Coupled Instrument (ICP)

Incident rf power	1100 watts
Reflected rf power	<5 watts
Viewing height above work coil	15 mm
Argon supply	liquid argon
Argon pressure	40 psi
Auxiliary (plasma) argon flow rate	300 mL / min.
Sample uptake rate controlled to	1.2 mL/ min.

Table 9. Heavy metals concentration for different pavement systems

Parameter (N=3)	PC	PA	IC	NPA	IPC	PPC
Pb (µg/L)	2.6	3.4	10.5	22.3	21.3	8.5
Cu (µg/L)	3	5.6	7.1	11.6	15.3	5.4
Zn (µg/L)	0.7	6.4	18.2	19.4	66.7	23.5
Cd (µg/L)	ND	ND	ND	ND	ND	ND
Cr (µg/L)	2.75	1.1	5.6	4.5	4.6	1.3

Fe (µg/L)	0.6	0.1	2.1	3.2	2.4	0.8

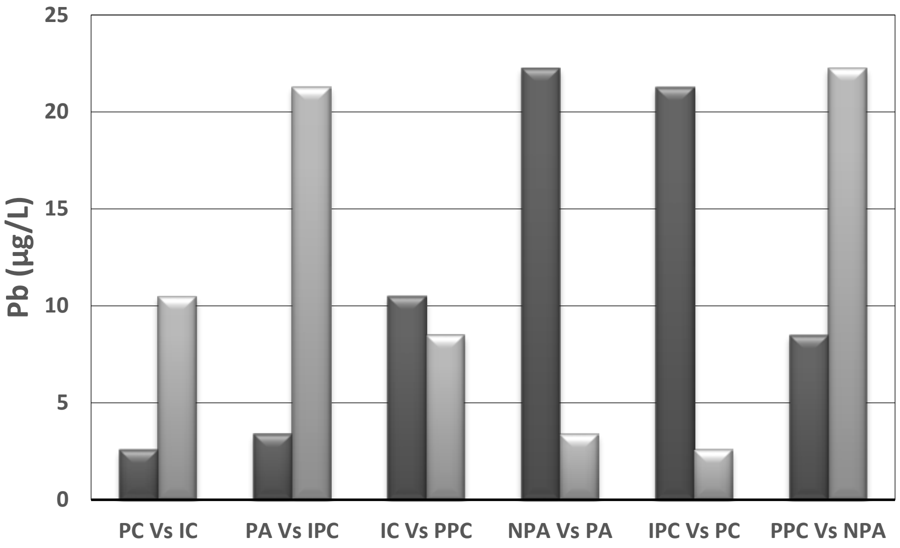

Figure 11. Graphical representation of average levels of Pb (mg/L) from different paving systems.

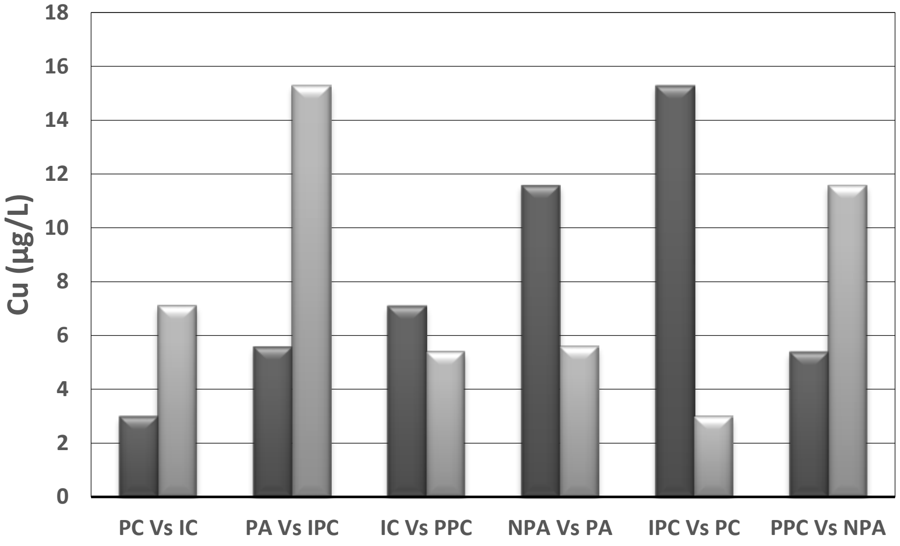

Figure 12. Graphical representation of average levels of Cu (mg/L) from different paving systems.

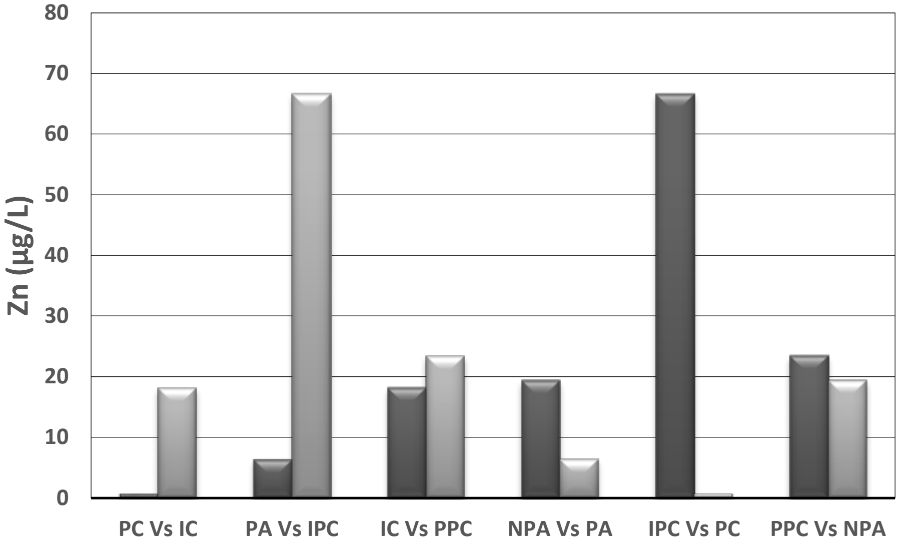

Figure 13. Graphical representation of average levels of Zn (mg/L) from different paving systems.

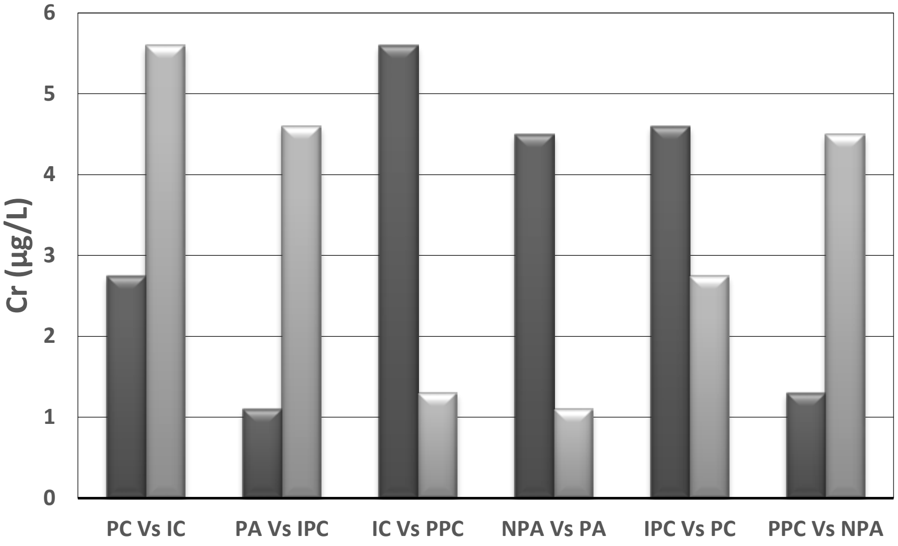

Figure 14. Graphical representation of average levels of Cr (mg/L) from different paving systems.

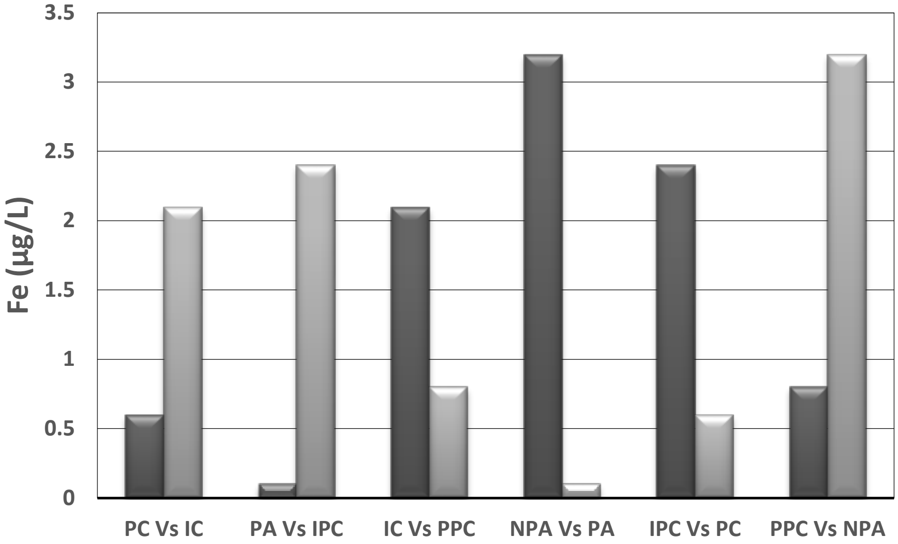

Figure 15. Graphical representation of average levels of Fe (mg/L) from different paving systems.

Chapter 5

Summary and Recommendations

This research demonstrated the assessment of pavement alternatives with respect to storm water runoff. A series of side-by-side quantified water quality comparisons of six different pavement systems was investigated.

Summary

The biggest environmental concern today is dispersal of industrial and urban wastes into the soil and water. The active stormwater runoff further contributes to nonpoint source pollutants causing water impairment downstream and effecting the aquatic life. In this study, after the analyses, it can be concluded that pervious paving systems over a sub-base of porous gravel are extremely effective in reducing the impacts of stormwater runoff contaminants like Sediments, Nutrients, Heavy metals, Chloride, TDS.

When the stormwater quality performance of porous sections and non-porous sections were compared, pH and alkalinity did not show much removal from porous paving sections. This could be due to the chemical composition of fresh concrete and the aggregate layer underlying the pavement.

As expected there was similar levels of performance in terms of TDS removal efficiency between porous concrete and porous asphalt sections. They had significantly lower TDS than the impervious pavement.

Total suspended solids (TSS) showed similar degree of reduction from both porous concrete and porous asphalt sections. However, photocatalytic porous sections did not show good removal efficiency when compared to impervious photocatalytic section. This can be due to lack of photocatalytic oxidation. More in-depth research should be conducted to investigate overall effect of photocatalytic reaction.

When anions were compared, Impervious concrete reduced the anions relative to impervious asphalt. This can be due to calcium ion present in the porous concrete. Porous concrete had significantly lower anions in the runoff. However, overall both porous asphalt and porous concrete provide good performance in terms of anions in the runoff.

Most importantly nutrients pollution which is not a new problem in runoff and groundwater but it among the most persistent. Porous concrete sections better at removing nutrients when compared to porous asphalt sections. Porous concrete sections maintained a 50% Nitrate reduction and 70% phosphate reduction.

Overall, both porous asphalt and porous concrete provide similar levels of performance for the parameter, oil and grease (OG). Porous concrete showing approximately 50% OG reduction and 33% OG reduction by porous asphalt.

PAH was not a problem in this system. PAH compounds were not discovered in concentrations above the detection limit.

Finally, runoff that percolated through both porous concrete and porous asphalt had significantly lower heavy metal concentrations than impervious pavement sections. Porous concrete showed 96% Zinc reduction whereas Porous asphalt showed 97% Iron reduction. When Lead was considered, porous asphalt (85% reduction) was slightly better than porous concrete pavement (78% reduction). Both porous asphalt and porous concrete reduced copper to a similar degree. Further, Porous asphalt was better at removing chromium (75% reduction) when compared to Porous concrete (50% reduction). Among all the pervious paving systems, porous asphalt paving systems contaminant removal efficiency was better than porous concrete and photocatalytic concrete paving system.

Recommendations

Although, much has been investigated in this study regarding pervious pavements and their effectiveness in reducing stormwater runoff contaminants, there are few areas which need to be investigated to make designing full scale porous pavement parking lots practical. Future avenues for research should include the following:

- Maintenance of porous asphalt, porous concrete and photocatalytic concrete paving systems
- More details about phytoremediation effect in photocatalytic concrete pavement system.
- Clogging effect in porous pavements and strategies to mitigate clogging concerns.
- Cost analyses of these different paving systems and strategies to reduce porous pavement cost.

Appendix A

Table 10. Heavy metals concentration of Tap water (City of Auburn, 2014) and Rain water from different pavement systems.

Heavy Metals	Tap Water (µg/L)	PC (µg/L)	PA (µg/L)	IC (µg/L)	NPA (µg/L)	IPC (µg/L)	PPC (µg/L)
Lead (pb)	ND	2.6	3.4	10.5	22.3	21.3	8.5
Copper (Cu)	0.096	3	5.6	7.1	11.6	15.3	5.4
Zinc (Zn)	N/A	0.7	6.4	18.2	19.4	66.7	23.5
Cadmium (Cd)	ND	ND	ND	ND	ND	ND	ND
Chromium (Cr)	ND	2.75	1.1	5.6	4.5	4.6	1.3
Iron (Fe)	N/A	0.6	0.1	2.1	3.2	2.4	0.8

Table 11. PAHs for Tap Water (City of Auburn, 2014) and Rain water from different pavement systems.

Parameter	Tap Water	PC	PA	IC	NPA	IPC	PPC
PAHs	ND	ND	ND	ND	ND	ND	ND

Table 12. Nitrate and Nitrite for Tap water (City of Auburn, 2014) and Rain water from different pavement systems.

Parameter	Tap Water (mg/L)	PC (mg/L)	PA (mg/L)	IC (mg/L)	NPA (mg/L)	IPC (mg/L)	PPC (mg/L)
Nitrate	0.63	0.3	0.44	0.55	0.4	0.49	0.28
Nitrite	ND	ND	ND	ND	ND	ND	ND

Appendix B

Table 13. Heavy metals concentration of Tap water (City of Auburn, 2013) and Rain water from different pavement systems.

Heavy Metals	Tap Water (µg/L)	PC (µg/L)	PA (µg/L)	IC (µg/L)	NPA (µg/L)	IPC (µg/L)	PPC (µg/L)
Lead (pb)	0.04	2.6	3.4	10.5	22.3	21.3	8.5
Copper (Cu)	0.279	3	5.6	7.1	11.6	15.3	5.4
Zinc (Zn)	0.241	0.7	6.4	18.2	19.4	66.7	23.5
Cadmium (Cd)	ND	ND	ND	ND	ND	ND	ND
Chromium (Cr)	ND	2.75	1.1	5.6	4.5	4.6	1.3
Iron (Fe)	0.15	0.6	0.1	2.1	3.2	2.4	0.8

Table 14. PAHs for Tap Water (City of Auburn, 2013) and Rain water from different pavement systems.

Parameter	Tap Water	PC	PA	IC	NPA	IPC	PPC
PAHs	ND	ND	ND	ND	ND	ND	ND

Table 15. Nitrate and Nitrite for Tap water (City of Auburn, 2013) and Rain water from different pavement systems.

Parameter	Tap Water (mg/L)	PC (mg/L)	PA (mg/L)	IC (mg/L)	NPA (mg/L)	IPC (mg/L)	PPC (mg/L)
Nitrate	0.141	0.3	0.44	0.55	0.4	0.49	0.28
Nitrite	ND	ND	ND	ND	ND	ND	ND

Table 16. pH, Alkalinity, TDS for Tap water (City of Auburn, 2013) and Rain water from different pavement systems.

Parameter	Tap Water (mg/L)	PC (mg/L)	PA (mg/L)	IC (mg/L)	NPA (mg/L)	IPC (mg/L)	PPC (mg/L)
pH	7.37	7.38	7.56	7.42	7.63	7.49	7.24
Alkalinity	68	225.3	185.6	145	124.2	225.4	185
TDS	ND	182.4	156.3	338.2	298.3	295.7	180.2

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