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Investigating the Physical Properties and Runoff Treatment Capability of Pervious Concrete Containing Granular Activated Carbon

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INVESTIGATING THE PHYSICAL PROPERTIES AND RUNOFF TREATMENT CAPABILITY OF PERVIOUS CONCRETE CONTAINING GRANULAR ACTIVATED CARBON

By

Mark Elias Elkouz

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May 2014

ABSTRACT

Investigating the Physical Properties and Runoff Treatment Capability of Pervious Concrete Containing Granular Activated Carbon

by

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A current environmental concern is that of urban stormwater runoff, which can carry a multitude of contaminants and could threaten or impair surface waters. Pervious concrete (PC) is a type of concrete with significant void spaces that can facilitate infiltration and lead to less runoff. The EPA cites previous research to show that pervious pavement structures reduce such contaminants as metals and total suspended solids. Since Granular Activated Carbon (GAC) is a well-known contaminant adsorbent, the purpose of this research was to determine if PC with added GAC would result in improved runoff treatment, while still maintaining its material properties.

Tests for compressive and tensile strengths, porosity and permeability were done on plain and GAC-containing PC mixtures. To test runoff treatment effects, samples of each mixture were subjected to synthetic runoff water containing several typical runoff contaminants. All mixtures were found to attain typical values for material properties. Changes in strength characteristics for the different mixtures were noted, although some experimental variations suggest that caution should be practiced when comparing within and between mixtures. Both plain PC and GAC-containing PC were found to significantly reduce overall concentrations of metals. None of the concrete mixtures were found to have any significant impacts on overall treatment for acetate.

In spite of the significant reduction of many contaminants, no significant differences were found in overall treated runoff quality between mixtures or between plain and GAC containing PC. It was considered that GAC became covered within the concrete matrix to the extent that it was no longer beneficial for runoff treatment. It is proposed that future work focus on modifying the method of GAC usage so that it is readily available for contaminant sorption.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Nationwide Stormwater Runoff Concerns

The United States and the world currently face a multitude of environmental challenges. Many of these are concerned with water quality, specifically surface water quality, which affects the lives of human beings as well as the lives of animals, plants and the ecosystems that house them. The United States Environmental Protection Agency's (EPA) *Federal Water Pollution Control Act* (2002), also known as the *Clean Water Act*, integral to the protection of these waters, states that:

> In carrying out the provisions of this section, the Administrator shall conduct, on a priority basis, an accelerated effort to develop, refine, and achieve practical application of: (1) waste management methods applicable to point and nonpoint sources of pollutants to eliminate the discharge of pollutants, including, but not limited to, elimination of runoff of pollutants and the effects of pollutants from in place or accumulated sources (EPA, 2002).

EPA (2000) also elaborates on the contaminants that can be found in stormwater runoff. These include inorganic contaminants, "such as salts and metals, which can be naturally-occurring or result from urban stormwater runoff," pesticides and herbicides, "which may come from a variety of sources such as agriculture, urban stormwater runoff," and organic chemical contaminants, "including synthetic and volatile organic chemicals, which are by-products of industrial processes and petroleum production, and can also come from gas stations, urban stormwater runoff, and septic systems."

The problems associated with runoff are also thought to be far reaching. In EPA (2014), the agency lists Urban-Related Runoff/Stormwater as a probable source that is threatening or impairing 56,068 miles of rivers and streams, 522,320 acres of lakes, reservoirs and ponds and 2,249 square miles of bays and estuaries.

The Las Vegas Valley suffers from many of these same contaminants. Nutrients, pathogens, hydrocarbons, organic compounds, pesticides & herbicides, sediment, metals, selenium, litter/floatables, hydromodification and other, are categories of pollutants of concern (CCRFCD, 2009).

It is evident, therefore, that a major contributing factor to the contamination and deterioration in the quality of surface waters is stormwater runoff. This is not merely an academic debate about stormwater, contaminants, and measures of impaired waters; stormwater may bring about real, adverse results. According to the EPA, “Uncontrolled storm water discharges from areas of urban development and construction activity negatively impact receiving waters by changing the physical, biological, and chemical composition of the water, resulting in an unhealthy environment for aquatic organisms, wildlife, and humans” (EPA, 1999).

1.2 Pervious Concrete as a Stormwater Management Method

As areas become more urbanized, the quantity of stormwater runoff increases, as pervious surfaces are replaced by impervious ones (Roesner et al., 2001; Kang et al., 1998). One possible method employed to decrease the amount of stormwater runoff is the use of pervious concrete as a paving surface (NRMCA, 2004; Brown, 2003; Kevern et al., 2006). Pervious concrete has little to none of the fine aggregates typically found in concrete mixes, which leads to more porosity and allows water to seep through at a far higher rate than that of traditional concrete (Tennis et al., 2007). As a result, pervious concrete can be used to increase infiltration, thus reducing the amount of urban runoff generated (ACPA, 2006). Even though pervious concrete has lower strength than conventional concrete mixtures because of its high porosity and low mortar content, it has been successfully used, according to Tennis et al. (2007), in applications such as: low-volume pavements, parking lots, tennis courts, walls (including load-bearing), etc.

The use of pervious concrete while designing sustainable buildings is also a consideration. The U.S. Green Building Council (USGBC) developed the Leadership in Energy and Environmental Design (LEED) rating system that is used to evaluate buildings from an "environmental performance" viewpoint (Ashley, 2008). According to this source, many LEED categories can be helped by pervious concrete. These categories include water efficiency and materials and resources. Pervious concrete is already one of the EPA's Best Management Practices (BMP), for preventing stormwater pollution (Tennis et al. 2007). BMPs are practices used to manage and improve stormwater quantity and quality, respectively (EPA, 2013a). In fact, the EPA states that pervious concrete can decrease stormwater runoff and also cites research showing permeable concrete to reduce Total Suspended Solids (TSS) and Metals (EPA, 2009a).

1.3 Activated Carbon - Containing Pervious Concrete for Water Treatment

Activated carbon (AC) can be produced from such starting materials as peat, wood, coal and coconut shells. The two steps used to produce AC are pyrolytic carbonization and activation. Activation may take place concurrently with the carbonization step or it may follow it. From starting materials, carbonization leads to the formation of graphite. Chemical or physical activation is used to activate the carbon.

Essentially, this means that chemicals and heat (in chemical activation) or heat and steam, usually (in thermal activation), are utilized to remove carbon “from an opening of closed porosity” and increase mean micropore sizes. Activated carbon is well known for its capacity as an adsorbent (MWH, 2005).

Pervious concrete has previously been studied for its ability to filter contaminants from runoff water (Luck et al., 2008; Luck et al., 2009), but to the knowledge of the researchers in this study, AC has never been added to pervious concrete to determine if it provides additional sorption/filtration capabilities. Pervious concrete, as mentioned earlier, has been shown to be effective at reducing solids and metals in runoff water. This research will analyze plain and AC-containing pervious concrete to try and determine if the sorptive qualities of AC improve the efficiency of the removal of solids and metals. The concrete mixes will also be studied for their ability to remove or decrease contaminants such as acetate, oil and grease, and nitrate. In order to establish the feasibility and utility of pervious concrete with the addition of AC, it is important to analyze the effects of the AC on the structural and physical properties of the pervious concrete. Again, to the knowledge of the author of this research, such testing has never been reported.

1.4 Research Requirements and Objectives

This research was intended to improve the runoff treatment capabilities of pervious concrete through the incorporation of Granular Activated Carbon (GAC), while monitoring physical and mechanical properties.

A preliminary step of this research project was the production of pervious concrete test samples. These were batched in the UNLV Civil Engineering Materials and

Structures Laboratory. Samples of pervious concrete were made with no GAC. Other test samples of pervious concrete were mixed with two differing amounts of GAC.

The first objective of the current study was to investigate the physical and mechanical properties of the samples produced. All three categories of samples were tested for compressive strength, tensile strength, permeability and porosity. The second and final objective was to test the feasibility of AC-containing pervious concrete to remove contaminants from urban runoff.

Samples from the three categories were subjected to simulated runoff, containing various contaminants typically found in stormwater runoff. The runoff was permitted to seep through the samples. The water was then tested to determine changes in concentrations of most of the contaminants.

1.5 Thesis Structure

This thesis is divided into 5 chapters. Chapter 1 provides some general background on the topics of urban stormwater concerns and pervious concrete as a management method. It also addresses the concept of increasing the capacity of pervious concrete to treat runoff. In Chapter 2, a literature review is presented which discusses several major topics pertaining to this research. Chapter 3 presents Paper 1, which addresses the pervious concrete material testing component of the study and its results. Chapter 4, or Paper 2, covers the runoff water treatment testing of the pervious concrete samples and an analysis of the obtained data. The overall conclusions of the research are discussed in Chapter 5, tying in the results from the two previous chapters.

CHAPTER 2

LITERATURE REVIEW

The following literature review addresses several topics pertaining to the current study. Each of the following four sections, Constituents in Urban Runoff, Current Runoff Regulations, Pervious Concrete and AC Sorption, should provide important insight on these topics, and lay a basis for the experimental discussion that follows. A short synopsis can be found at the end of this chapter.

2.1 Constituents in Urban Runoff

McLeod et al. (2006) studied the urban runoff water quality from four catchment areas with different land uses in the Canadian city of Saskatoon. The research also provided insight into the contaminant loads associated with the runoff as compared to two local point sources. Regression and site mean concentration (SMC) approaches were utilized in this study and the contaminants reported on were: total suspended solids (TSS), total Kjeldahl nitrogen (TKN), total phosphorous (TP), chemical oxygen demand (COD), and chloride (Cl^-). The SMCs were not found to be affected by land use, although the opposite was true for the regression equations that were developed. The authors suggested that the absence of effect in the SMC by land use may be due to the fact that the total runoff volume is used to derive the values. Commercial areas, they proposed, with expected high levels of contaminant and large amounts of runoff, may have similar results to an area with less contaminants and lower flows. The authors also reported that different results were found by Smullen et al. (1999). Unit loads of pollutants were found to vary based on land type, with commercial land use having unit loads that were considerably higher than the residential areas. The authors pointed out that when planning methods of pollution abatement that are affected by area (e.g. street sweeping), unit load differences are significant.

The research also was concerned with the comparison of pollutant loads on the South Saskatchewan River, from runoff and from two local point sources, a wastewater treatment plant and an industrial facility. The authors mentioned that the facility's effluent stream contained average constituent concentrations that were higher than that of the City of Saskatoon WWTP, although it is smaller. It was determined that the runoff load of TSS was higher than the load from the WWTP, while the opposite was found for TP; COD loads from the two sources were similar. Loads from urban runoff were higher than those from the industrial facility (for the three components reported on by that facility: TSS, TKN and COD). The authors pointed out that "in view of the relatively large TSS load to the South Saskatchewan River from urban runoff, along with the fact that TSS is a common carrier of toxic substances, increased attention should be given to the water quality of Saskatoon's urban runoff."

This article was of interest in particular for the manner in which it shows the significance of urban runoff as a contaminant source in water sources. The authors pointed out that the study was driven by the improvement in the treated sanitary sewage effluent quality into the river and the impending urban runoff legislation changes. As effluent standards and treatment methods improve for point sources, runoff water treatment methods and standards are most likely to also do likewise. This study did not compare runoff contaminant loads to the total loads from point sources but rather gave some idea of the impact of urban runoff contamination. Obviously, the current research is focused on a more micro scale. The focus is to consider specific contaminant concentrations in runoff water and the possibility of removing such contaminants. Whereas, the research by McLeod et al. (2006) depicts a more macro scale and emphasizes the importance of such contaminant removal methods.

Focusing more on the scale of contaminant levels in runoff, Smullen et al. (1999) were partially concerned with assembling runoff water quality data from various sources. The United States Environmental Protection Agency's Nationwide Urban Runoff Program (NURP) data were utilized, in addition to the United States Geological Survey National Urban-Storm-Runoff Data Base, and stormwater National Pollutant Discharge Elimination System (NPDES) permit data. The data were used to compute the Event Mean Concentration (EMC) mean and median values for the populations (for the ten original indicator chemical constituents of the NURP), and to compare this pooled data with the original NURP data. The following table, taken from their research, shows the results:

Table 2.1 Select data of interest, adapted from Smullen, et al. 1999

Constituent	Pooled Event Mean Concentration (EMC) mean
Total Suspended Solids (mg/L)	78.4
Chemical Oxygen Demand (mg/L)	52.8
Total Phosphorus (mg/L)	0.315
Nitrite and Nitrate (mg/L)	0.658
Copper (µg/L)	13.5
Lead (µg/L)	67.5
Zinc (µg/L)	162

The authors mentioned that the values shown in their original table for the NURP data were slightly different from the original NURP data, due to the larger sample size. They also elaborated on the concentration variations among the different data sets. When addressing the lower concentrations for metals found for the NPDES data, they explained that potential causes may involve sampling problems. However, the authors stated that cleaner techniques for sampling, etc., more common in the 1990s, may explain these results. The authors also expressed that among future work expected to be done on the data was to attempt to analyze it, by land use, etc. The previous NURP work by the EPA did not establish any statistically significant concentration differences based on such variables as the type of land use or geographic region.

Indeed, Smullen et al. (1999) proves very interesting and useful for the current research on pervious concrete and the treatment of urban runoff water. First, it gives a list of some of the primary contaminants found in runoff water and the concentrations at which they might be expected. Additionally, it presents results based on a very large compilation of data, courtesy of the NURP, USGS and NPDES. This information was used to direct our current research on the types and concentrations of contaminants that we considered when preparing runoff water samples for tests.

James et al. (2010), considered the presence of organic contaminants in urban stormwater runoff. In their research, water samples were collected from impervious and pervious locations to compare contaminant levels. According to the authors, asphalt and concrete lots were among the impervious sites and drainage ditches or grassy areas were pervious sites. A chemical oxygen demand (COD) analysis was performed on samples. A second sample from locations with more than 35 mg O_2/L was tested for oil and grease and total petroleum hydrocarbons (TPH). There was found to be no relation between the amounts of oil and grease in samples and the portion of those that were TPHs. In some cases, the oil and grease values were found to be higher than the COD values, which the authors stated were difficult to explain and were thought to be due mostly to carry over of salt from the drying step. However the authors explained that this would have no effect on the TPH data.

The impervious samples' oil and grease concentrations were found to average 250 mg/L and their TPH levels averaged 62.6 mg/L. These were both higher than the pervious samples, with their average oil and grease values of 36.3 mg/L and TPH concentrations of 12.0 mg/L. According to the researchers, the impervious surfaces' first flush appeared to be more concentrated in O & G and TPH. The authors mentioned that dilution in drainage ditches and soil and clay particle interactions decrease the concentrations of organic matter in the water from the pervious sources.

Certain Polycyclic aromatic hydrocarbons (PAHs), fluoranthene and pyrene (probably carcinogenic to humans, present in gasoline, asphalt and motor oils and always resulting from incomplete combustion) were found in all impervious water samples and sediment samples from waters receiving the impervious runoff. The pervious runoff had very low concentrations in some samples. It was proposed that the lack of contaminants in pervious runoff and receiving waters was possibly due to sediment adsorption. Other PAHs were also found, but not in all of the sediment samples and at much lower concentrations. The authors concluded that pervious surfaces reduced loadings of pollutants through adsorption and filtration of organics. Fluoranthene and pyrene, however, due to their large distribution coefficients, collected in sediments at potentially toxic levels.

This article is of interest, first for the analysis of organic contaminants. These are of widespread interest in urban areas. As the authors mentioned, known carcinogens and/ or mutagens include several four-to-six-fused-ring PAHs. Additionally, this research focuses on adsorption as a treatment method for these contaminants. Adsorption is one of the primary mechanisms that was presumably emphasized in our research on pervious concrete for contaminant removal. If materials such as clay and soil are suitable for the adsorptive removal of these organic contaminants, it was projected that pervious concrete (with the incorporation of additional adsorptive GAC) would do likewise.

2.2 National Stormwater Runoff Regulations

As previously discussed, stormwater runoff can result in widespread environmental contamination, and potentially severe problems. The Environmental Protection Agency has set forth several regulations to address this threat. The following are some of the major landmarks of these regulations.

In 1948, water pollution in the United States was significantly legislated for the first time through the Federal Water Pollution Control Act of 1948. The Clean Water Act became the widespread name of the amended 1972 version of that previous act (EPA 2013b). The Clean Water Act of 1972 required National Pollution Discharge Elimination System (NPDES) permits for point sources of pollution, but usually only limited storm water effluent from some categories of industry. The EPA was then made “to establish phased NPDES requirements for storm water discharges” by a 1987 Congressional amendment to the CWA (EPA 1996). In 1990, Phase I of the program required NPDES permits for stormwater discharges from: “(1) ‘medium’ and ‘large’ municipal separate storm sewer systems (MS4s) generally serving populations of 100,000 or greater, (2) construction activity disturbing 5 acres of land or greater, and (3) ten categories of industrial activity" (EPA 2005b). The Stormwater Phase II Final Rule (1999), or 40 CFR Parts 9, 122, 123, and 124, which replaced the Interim Phase II Rule of 1995 (EPA 1999), broadened Phase I, to also cover small urbanized area MS4 operators (those not included in Phase I) and small construction activity operators. It is also required for these operators to use Best Management Practices (EPA 2005b).

In 2005, the EPA published a document titled: Extension of National Pollutant Discharge Elimination System (NPDES) Permit Deadline for Storm Water Discharges for Oil and Gas Activity That Disturbs One to Five Acres, postponing the matter (for the second time) until June of the following year (EPA 2005a). That same year, the Energy Policy Act of 2005 amended

> the Clean Water Act by changing the definition of oil and gas exploration and production to encompass field activities or operations associated with all facets of the industry '… **including activities necessary to prepare a site for drilling and for the movement and placement of drilling equipment, whether or not such field activities or operations may be considered to be construction activities**' (EPA 2006b).

This expanded the definition of facilities to be exempted (in most cases) from NPDES permit requirements. Notably, acreage was not considered. Mining operations were also exempted in the CWA (EPA 2002). In 2006, the CWA changes—from the Energy Policy Act of 2005—were codified in the EPA document titled Amendments to the National Pollutant Discharge Elimination System (NPDES) Regulations for Storm Water Discharges Associated With Oil and Gas Exploration, Production, Processing, or

Treatment Operations or Transmission Facilities (EPA 2006a). According to EPA (2006b),

> This rule exempts the oil and gas industry, including associated construction activities, from Federal NPDES storm water permits, except in very limited instances. Facilities that have a discharge of a reportable quantity release or that contribute pollutants (other than non-contaminated sediment) to a violation of a water quality standard are required to obtain and maintain NPDES permit coverage for storm water for the entire operating life of the facility.

According to EPA (2006a), the use of BMPs for activities and operations in oil and gas fields is encouraged by the action, in order to protect water quality and minimize pollution of storm water runoff.

In 2008, the EPA was challenged in court in *Natural Resources Defense Council vs. United States Environmental Protection Agency* for the previously mentioned exemption for discharges of sediment. The court decided against EPA and vacated the rule (United States Court of Appeals 2008). The court's opinion in that case should provide useful information for those interested in the topic. An EPA attempt to re-hear the case was denied. Accordingly, "[n]ow that the 2006 rule has been vacated, the effective requirements are the regulations in place prior to the 2006 rule plus the additional Energy Policy Act clarification of the activities included in the CWA 402(*l*)(2) exemption" (EPA 2009b).

New EPA stormwater rules are now anticipated which are intended to strengthen the EPA's stormwater program and to have sites that are newly developed and redeveloped decrease their discharges of stormwater (EPA 2013c). After at least one delay in preparing a draft of the rule, the final rule is due in December 2014 (Mannion, 2013).

As can be seen in the preceding paragraphs, the nation’s stormwater regulations are continually changing. These regulations may become highly politicized at times. It is apparent, however, that the overall trend is towards a broadening of regulations. These may be with the objective of improving water standards, of combating increasing sources of contamination or for various other reasons. The important concept here is that as laws change or develop, new solutions will likely be sought to address them. This research was focused on one such solution: taking a known stormwater Best Management Practice and attempting to improve it from a water treatment perspective.

2.3 Pervious Concrete

This part of the literature review focuses on various topics that relate to pervious concrete. The first section is a quick overview of pervious concrete as a material. The next considers pervious concrete as a filtering medium and potential pathway to groundwater contamination. Finally, the third section provides a quick look at the possibility of modifying pervious concrete for contaminant removal.

2.3.1 Pervious Concrete Introduction

According to Tennis et al. (2007), pervious concrete is a type of concrete that is made with coarse aggregates and no sand, or little sand. The aggregates are bound together by the cementitious paste; however, the absence of fine aggregates causes the mix to contain considerable voids. Water is able to permeate through these voids and infiltrate into the ground. As a result, pervious concrete significantly reduces surface runoff. It is considered by the US Environmental Protection Agency to be a Best

Management Practice (BMP) to manage stormwater runoff. Although lower in strength than traditional concrete, pervious concrete has been used in a multitude of applications, including: low-volume pavements, sidewalks, parking lots, slope stabilization, pavement edge drains, etc… Pavements, however, are the main area of use for pervious concrete.

2.3.2 Pervious Concrete Filtration/Potential for Groundwater Contamination

Luck et al. (2008) conducted research on pervious concrete, specifically, on its ability to retain solids and reduce nutrients from composted beef cattle manure, as water was applied to the surface. Various pervious concrete specimens were prepared, with different sizes and types of aggregates. Mixtures were also varied, with respect to amounts of cement and incorporation of fly ash and fiber. Wood shavings and composted beef cattle manure (compost) were placed in cylinders which were put on top of the concrete samples. One liter of water was poured in each cylinder and this was repeated 24 hours later. It was found that more than 92% of the compost was retained on the surface of the different samples. A significantly higher amount (<97%) was retained on the surface of the specimens with the finest aggregates. The authors proposed that smaller aggregate size likely led to smaller pore size in the concrete and, therefore, to more retention of solids. The various additives were not found to have significant impacts on the concrete's ability to retain compost.

Luck et al. (2008) also reported on the analysis of the effluent water from the pervious concrete samples for the presence of certain constituents. The constituents considered were: pH, electrical conductivity, 5-day biochemical oxygen demand (BOD), dissolved organic carbon, ammonium, nitrate, nitrite, total nitrogen, soluble phosphorus and total phosphorus. The results (with the exception of BOD) were compared to those of a similar setup (run for three days), with wire screen used in place of pervious concrete. The results varied in concentration by constituent and day, but no relationship was established between aggregate type, fly ash, fiber and the resultant pervious concrete effluent nutrient levels.

The BOD analysis for the pervious concrete specimens was considered to show that for this type of compost, additional treatment would likely be required to meet water discharge regulations. In general, pervious concrete was less efficient than the wire screen in eliminating ammonium, nitrate and nitrite from the effluent water although it was more efficient in removing total nitrogen. Luck et al. (2008) cited USDA-NRCS (1997) and Sung-Bum and Mang (2004) to explain that the likely cause of this decrease was entrapment of particles within the concrete where they were reduced by attached microorganisms. Sung-Bum and Mang (2004) were again cited to explain the reduced total phosphorus using pervious concrete. This was also attributed to microbial activity. Soluble phosphorus was also found to be lower. Luck et al. (2008) cited information from Collins (2007) and Lindsay (1979) to propose that calcium or magnesium phosphate precipitates may be another way of accounting for the decrease of soluble phosphates. The inclusion of calcium containing fly ash in the pervious concrete mixes, however, showed no significantly improved treatment capacity. This mechanism, the authors proposed, could decrease with concrete age.

The authors described several reasons for pervious concrete's superior nutrient removal when compared to that of wire screen. They cited Meyer et al. (2007) to suggest that this could indicate that pervious concrete separates solid particles better than wire screen. Another explanation was that concrete has higher specific retention or absorption and therefore some effluent is trapped within the concrete itself. Finally, the authors cited Haselbach and Freeman (2006), who discuss porosity variations between the surface and bottom of pervious concrete slabs (due to compaction). The authors mention that this may result in more absorption at the top.

Luck et al. (2008) address many of the concepts that are applicable to the current research on GAC-containing pervious concrete. Although it discussed agricultural contaminants, it is a study that very much focuses on pervious concrete as a water treatment method. Some of the contaminants considered are common to urban runoff, a major component of this research. The proposed mechanisms for contaminant removal will also be of assistance in any research of this kind. Finally, it is interesting that the authors considered the effects on treatment of the various aggregates, fly ash, fiber, and cement proportions. Although they were not added with the sole intention of filtering water, their proportions in concrete mixes made them interesting factors to consider for their effects on effluent treatment capacity.

Luck et al. (2009) considered pervious concrete in agricultural settings during simulated rainfall. In the study, pervious concrete cores were produced using various mix designs. The variations included the use of differing types of coarse aggregates, the presence or absence of fly ash and/or fiber, and different amounts of cement. Manure was applied on concrete samples and these were exposed to weekly simulated rainfall for a period of three weeks. The effluent water was tested for various contaminants, including: dissolved organic carbon (DOC), ammonium, nitrate, nitrite, total nitrogen (TN), soluble phosphorus (SP), and total phosphorus (TP) (Luck et al., 2009). No correlation was found between the concrete mixture design and the concentration of contaminants in the effluent. It was also found that the highest concentration of contaminants in the effluent water was not necessarily found after the first rainfall simulation; some contaminants increased, some decreased and some remained statistically similar during the three-week study.

Luck et al. (2009) also reported on tests evaluating carbon dioxide and ammonia emissions from the test samples. Ammonia production was found to be similar for the variety of concrete mixes, as was that of carbon dioxide. The carbon dioxide emissions were explained to be most likely produced by the respiration of microbes and the decay of organic matter. The authors also addressed the potential for these microbes to treat nutrients found in manure. Finally, tests were conducted on faecal coliform concentrations in the effluent water. Again, the various mixes (aggregates, fly ash, fibers) showed no significant influence on effluent coliform concentrations. During the first rainfall event, 35.8% of the total coliform in the manure passed through the pervious concrete. In the following two weeks, the effluent coliform concentration plummeted to less than the detection limits (0.2 %). One possible explanation referenced from their earlier article (Luck et al., 2006) was that the coliform became trapped in the material. Another proposed explanation, based on information from (Coyne & Howell, 1994; Luck et al., 2008) was that the high pH of concrete could adversely affect the survival of faecal coliform. This effect, the authors proposed, could be diminished as a consequence of concrete aging.

Once again, Luck et al. (2009) present detailed findings concerning pervious concrete and its capacity to treat contaminated water. It is useful for the purpose of this research to note that contaminant levels are not necessarily highest after a primary rainfall event and that the levels could potentially increase with further events. The authors also showed interesting findings about this material's potential to eliminate faecal coliform.

In Kwiatkowski et al. (2007), the authors conducted research on the use of pervious concrete and infiltration beds as a best management practice for infiltration of stormwater. They utilized an actual infiltration setup located on Villanova University's campus. One of the goals of their research was to evaluate the setup from a hydrological viewpoint; another was to determine if contaminant infiltration into the soil and groundwater was an issue for such stormwater management methods.

In hydrological terms, the tested setup was found to work as designed; however, it behaved differently during different seasons. The authors cited Freeze and Cherry (1979) and Emerson et al. (2006) to partially explain this observation in terms of viscosity effects and to mention that more research on this phenomena was ongoing. The final analysis of the site's stormwater included the evaluation of: pH, conductivity, total suspended solids (TSS), total dissolved solids (TDS), chloride, total nitrogen and copper levels. The pH levels in the samples from beneath the infiltration beds and within the lower infiltration bed were found to be higher than the rainwater's determined pH. This was attributed to the basicity of the limestone aggregate and pervious concrete, which was illustrated by other laboratory tests (using the limestone), conducted and reported by the authors. Research by Dempsey and Swisher (2003) that was cited also showed similar findings.

The contaminants of importance in Kwiatkowski et al. (2007) were chloride and copper. Chloride was an issue due to deicing on campus and, as a result, the chloride levels beneath and within the infiltration beds varied with the seasons. The authors stated that since no reactions that occur in the soil can reduce ionic chloride content, it was not eliminated from the runoff in the infiltration beds or during infiltration. In spite of this and in view of the non-priority pollutant classification for chloride by the USEPA, the authors stated that normal deicing processes will not generate pollution.

The levels of copper (a material present on the roof of the building in the study) were generally found to decrease from the roof downspout to within the infiltration bed. This was attributed to dilution by non-roof runoff, specifically during certain storms. The soil samples from below the bed were found to be even lower in copper concentration. The authors cited Mikkelsen et al. (1996), Blaszczyk and Nowakowska-Blaszczyk (1997), Mason et al. (1999) and Welker et al. (2006), and their own research data, to suggest that the soil must adsorb most of the copper in the initial 0.3 m below the infiltration bed.

Conductivity in the soil water samples beneath the infiltration bed was found to vary on a seasonal basis, with calcium chloride (used for deicing) as the proposed cause. Total dissolved solids from within the infiltration bed showed similar seasonal variations. Total suspended solids and dissolved solids were generally slightly higher within the infiltration bed than from the roof downspout. The increase in total suspended solids, the authors explained, was likely due in part to the runoff from other surfaces than the roof, which probably had higher concentrations of fines. Even though the authors stated that the pervious concrete would serve as a filter, the increase in solids was additionally explained by the notion of fines (resulting from construction of the beds), that were located within the infiltration bed. The concentration of total suspended solids decreased with the number of storms, which the authors proposed showed that particles within the infiltration beds were washed away.

Kwiatkowski et al. (2007) is of real interest for the current study because that research was based on a real world application of a pervious concrete containing infiltration system. The researchers looked not only on the hydrological properties of the system, but also on the possible introduction of contaminants into the groundwater and soil, through stormwater infiltration. Their study, however, was mainly focused on the end results: would the groundwater and soil be affected by contaminants? This research focuses on the specific ability of pervious concrete to remove contaminants. In the current study, it was important to know the initial concentrations of each contaminant in order to calculate the amount that the pervious concrete is or is not removing. Additionally, it was important to limit the filtration to that of only pervious concrete and avoid other variables such as the possible treatment by the infiltration bed and soil. It was also of interest in this research to determine if pervious concrete, with the addition of GAC (with its sorptive capacity), could remove contaminants which regular pervious concrete did not remove.

Horst et al. (2010), considered pervious concrete-covered infiltration beds for their hydrologic and water quality effects. This infiltration Best Management Practice (BMP) was located on the Villanova University campus and was studied over a two-year period. The first objective of that research was to determine the infiltration capacity of the BMP by comparing inflow with overflow from the infiltration beds. Overall, the site was found to allow for the infiltration of more than 91% of the excess runoff. Generally, the rate of infiltration was found to vary with the season. The authors cited Emerson and

Traver (2008) to explain that this was mostly due to the changes in viscosity of water, which is temperature dependant, and to mention that the infiltration rate did not change over time with statistical significance.

Next, Horst et al. (2010) compared the change of several water quality parameters, before the water entered the basin and after it exited the basin (water in excess of the capacity of the lower basin that was not infiltrated). The components considered were: pH, conductivity, copper, total nitrogen, total phosphorous, chloride, suspended solids, and dissolved solids. On a mass basis, copper, total nitrogen, total phosphorous, and suspended solids were found to decrease by well over 90%. This was explained first by the fact that the mostly infiltrated water carried with it the pollutants into the soil beneath. The slightly higher amounts of contaminant reduction, as compared to infiltrated water, were most likely attributed to the 'first flush.' This was captured immediately and percolated through the basin. The first flush is usually thought to have the largest pollutant concentrations for such components as nutrients and metals. According to the authors, this 'first flush' concept was supported by Batroney et al. (2010), for small impervious surfaces. The second explanation concerned the possible overestimation of initial pollutants due to sampling methods. Two constituents that increased in mass across the infiltration basin were chloride and dissolved solids; these increases were potentially attributed to salt applications relating to snowfall.

Next, water samples were analyzed from 0.3 m beneath the infiltration basin and were compared to samples from beneath an adjoining area at 0.3 m beneath the soil surface. The samples were analyzed for: pH, conductivity, copper, total nitrogen, total phosphorous, and chloride. Conductivity, copper and total nitrogen were found to be significantly higher underneath the adjoining soil. This result surprised the authors, since it was their expectation that infiltration basins would concentrate pollutants. The mean concentrations of total phosphorus and chloride were not found to differ significantly.

Finally, water samples were taken from within the lower infiltration bed, at 0.3 m, 0.6 m, and 1.2 m below the lower infiltration bed and tested for five of the six previously mentioned constituents. The average concentrations of conductivity, total phosphorous, and chloride were not found to change significantly with the location. Generally, pH decreased with depth. Horst et al. (2010) mentioned that this was likely due to the generally low pH of the tested stormwater causing, with time, a more acidic soil. Copper was found to decrease to below detection levels. The authors cited Welker et al. (2006) and Mason (1999) to explain that this result met expectations since metals tend to bind to soil within the first 2 cm beneath the ground. Total nitrogen levels were below the detection levels in most cases and therefore were not statistically analyzed.

The research of Horst et al. (2010) is of interest because it considers again the application of pervious concrete and infiltration basins, and takes into account their effects on the amount of contaminants in surface waters and infiltrated water. Once again, this research involves more variables than are acceptable for the determination of pervious concrete’s filtration capacity. Not only can the water interact with pervious concrete, it also can interact with the aggregate infiltration bed as well as with the soil. Furthermore, at the given site, it was possible for stormwater to enter the infiltration beds without even passing through the pervious concrete. Again, for the purposes of this current research, it was necessary to limit the variables in order to quantify the effects of various pervious concrete mixtures alone.

In *Porous Pavement and Groundwater Quality Technical Bulletin* (The University of Rhode Island, n.d.), the authors presented some results from previous research. The main focus of their review was on the issue of porous pavements and the potential for groundwater contamination, through the infiltration of contaminants. Their review included results from Ranchet et al. (1993) and Pratt et al. (1999) on porous concrete pavement and porous concrete pavement systems, respectively, and reported that the materials decreased the load of suspended solids, lead and COD (Ranchet et al., 1993) and could degrade hydrocarbons (Pratt et al., 1999), where, according to the review, breakdown efficiency was affected by nutrient supply, its apparent limiting factor.

In spite of these reductions, the authors also addressed some of the recommendations for the use of porous pavements. They recommended light-duty use of such pavements for groundwater protection to be ensured. They mentioned that the EPA's *Storm Water Technology Fact Sheet: Porous Pavement* (1999), recommends that between the porous pavement system and the bedrock or water table underneath, there be at least 4 feet of separation. The authors cited further EPA recommendations, among them, that, in areas with significant windblown sediment quantities from wind erosion, porous pavements should not be used. They also mentioned that porous pavements are not suitable for stormwater hotspots, such as: commercial nurseries, fueling stations, industrial rooftops, etc…

Naturally, when contaminant-laden stormwater is to be infiltrated, the risk of groundwater contamination is present. Pervious concrete helps to attenuate the risk, somewhat, through its propensity for contaminant reduction. Nonetheless, as discussed above, additional measures should be taken to protect groundwater. If the contaminant treatment capacity of pervious concrete can be improved in this study, through the addition of GAC, it should only help to assuage the risks of groundwater contamination and possibly increase the potential applications for the material.

2.3.3 Modified Pervious Concrete

In related research, Shen et al. (2012), considered the incorporation of titanium dioxide in pervious concrete, for the photocatalytic removal of atmospheric environmental pollution. They considered various methods to incorporate the $TiO_{2.}$ Among them, they studied cement slurry mixture coatings, or combining the TiO_2 with finer aggregates and cement in thin pervious concrete layers. The authors observed that for the first case, more cement in the slurry may have been the cause of poorer pollutant removal performance. In terms of infiltration rates, however, the mixed thin pervious layers were the only methods of application of TiO_2 that did not show noticeably reduced infiltration rates, although other reductions for other methods were not significant.

Shen et al. (2012) is of interest for this current research primarily due to its similar concept. In their research as with the current research, pervious concrete is modified with a certain additive material with the objective of decreasing certain environmental pollutants. Although Shen et al. (2012) is focused on atmospheric pollutants while the current research is on pollutants found in stormwater runoff, there are significant similarities between the two. Additionally, Shen et al. (2012) offers useful insight into additive application methods and their impact on infiltration rates and on contaminant reductions. This insight is very relevant to the current research.

2.4 AC Sorption

It is now important to view the various contaminants of concern—for the present case these include several of the 10 NURP contaminants listed above—and consider if each of those is a candidate for AC sorption.

Ahmad et al. (2005) reported on jar tests that were conducted with the objective of removing residual oil from palm oil mill effluent. The authors considered three adsorbents. For the removal of residual oil, activated carbon (one of the three) was found, to be a bad selection of adsorbent, although it did result in decreases of residual oil. Additionally, they studied the removal of suspended solids, since the solids contained, in suspension, some of the oil. Activated carbon was also found capable of reducing suspended solids.

Ayoub et al. (2011) studied the additional treatment of wastewater from a tannery. This treatment consisted of coagulation/flocculation, followed by adsorption using activated carbon in the procedures of interest here. The analysis included several contaminants many of which are of primary concern for this research. It was shown that adsorption with activated carbon could decrease pH, TSS, TDS, conductivity, apparent color, turbidity, COD, BOD, TN, chromium, arsenic and limitedly decreasing TP.

Issabayeva et al. (2011) showed that palm shell activated carbon can remove copper and zinc ions from solution. The metal concentrations used in their research, however, were considerably higher than the runoff values presented by Smullen et al. (1999) that were used in the current research. The pH range the authors tested may also have differed from the experimental conditions here.

According to Calgon Carbon's product bulletin (Calgon Carbon, 2012), Filtrasorb® 400 Granular Activated Carbon was developed for dissolved organic compound removal from water and wastewater, etc… Included in those contaminants are "taste and odor compounds, organic color, total organic carbon (TOC), and industrial organic compounds such as TCE and PCE."

Wang et al. (2010) considered the adsorption of phosphorus using activated carbon, zeolite, and ceramisite. At an initial concentration of 200 µg/L the adsorptive capacity of activated carbon for phosphorus was found to be 15.90 µg/g. They found that the activated carbon's surface isoelectric point pH was above 7, therefore, they noted that anion phosphate was adsorbed more easily by the AC than by the other media they studied. Also, abundant micropore and their sizes were considered to be a major factor for the AC's higher removal rate of phosphorus.

Dias et al. (2007) provide a review which relates to activated carbons and their ability to remove various contaminants. They provide a wealth of references, some of which are discussed below. Goyal et al. (2001) studied the removal of copper using granulated activated carbon. The copper concentrations ranged from 40 – 1000 mg/L, orders of magnitude higher than in the current work. The maximum removal was found at pH 4. The studies stopped at pH higher than 6 because of $Cu(OH)_2$ precipitation. Periasamy et al. (1996) looked at pH effects on copper adsorption on GAC. They considered 10, 15 and 20 and 25 mg/L Cu(II) concentrations. The authors found that that GAC removal of Cu(II) increased with increasing pH, and was highest between pH 6.0 – 10.0. They found that hydroxide precipitation seemed to be dominated by adsorption for the lower two copper concentrations at pH values above 5.4.

AC has also been studied for removal of lead. Goel et al. (2005) found AC to have a 21.88 mg/g adsorption capacity for Pb(II).

Dabek (2003), reported on Zn(II) adsorption tests on activated carbon. Different initial concentrations were considered, ranging from 2 – 20 mmol/dm^3 and the pH range was 4-6. KCl was added to the mixtures. The zinc ions were found to adsorb to the activated carbon. Galiatsatou et al. (2002) found that aqueous zinc species could be treated with activated carbons from solvent extracted olive pulp. They had higher adsorption capacity than other carbons studied. The authors found that in the approximate 5.5-7 pH range, zinc adsorption was favored by those carbons. They mention that factors such as “a significant number of basic groups,” and “an efficient macroporous volume” and others, which resulted in adsorption levels that were higher in spite of the positive charge of the carbons.

2.5 Synopsis

The review just presented has considered many topics that are directly related to the research at hand. The first two sections were titled constituents in urban runoff and national stormwater runoff regulations. These two topics clearly present a motivation for the current research. The first provides what may be considered social and ethical reasons for considering urban runoff treatment and the second, more political and legal ones. The third section considers pervious concrete as a material used for filtration, as a possible route for groundwater contamination, and as a potentially viable means for pollution reduction. Finally, AC sorption is briefly discussed in terms of its utility as a contaminant sorbent. This literature review, albeit not exhaustive, should provide the reader with ample background for the research that is hitherto presented.

CHAPTER 3

INVESTIGATING THE MECHANICAL AND MATERIAL PROPERTIES OF PERVIOUS CONCRETE INCORPORATING GRANULAR ACTIVATED CARBON

3.1 Introduction

Pervious concrete contains little if any, fine aggregates, which leads to the considerable amount of void spaces typically found in pervious concrete. Due to its high porosity and low mortar content, the strength of pervious concrete is usually lower than that of traditional concrete. Pervious concrete (PC) that is properly placed can attain strength and flexural strength values of more than 3000 and 500 psi, respectively (Tennis et al., 2007). It has been successfully used in such applications as walls and residential roads and driveways. Moreover, a major advantage of pervious concrete’s void content is that it is possible for water to infiltrate through these void spaces and into the ground beneath. The use of such infiltration capable materials can reduce the amount of urban stormwater runoff, which EPA (2014) notes as a probable source that threatens or impairs 56,068 miles of rivers and streams, 522,320 acres of lakes, reservoirs and ponds and 2,249 square miles of bays and estuaries. Pervious concrete is already included on the EPA’s *National Menu of Stormwater Best Management Practices for Stormwater Phase II*. The EPA’s National Pollutant Discharge Elimination System (NPDES) page mentions that pervious concrete can decrease stormwater runoff and also cites research showing it to reduce Total Suspended Solids (TSS) and Metals (EPA, 2009a).

Incorporating a sorptive material, such as activated carbon, in PC could potentially provide for improved runoff water treatment. Activated Carbon (AC) is a well-known contaminant sorbent. It has been found to be capable of decreasing the presence of many contaminants (Ahmad et al., 2005; Ayoub et al., 2011; Issabayeva & Aroua, 2011) that are typically found in urban runoff. Incorporating AC in PC could potentially improve its water treatment capability; however, in the absence of data on the strength and material properties of the modified material, such applications may prove impracticable.

The purpose of this component of the research was to test PC, with and without added AC, for compressive and tensile strengths, as well as porosity and permeability. With the resulting data, it was possible to look at each material's properties and determine if such a mixture would attain expected levels for each property.

3.2 Materials and Methods

3.2.1 Pervious Concrete Mixture Designs

Three types of concrete were produced. Plain PC, which contained no GAC, and PC samples with 5% and 10% carbon to cementitious were batched. Cementitious refers to the total weight of cement and fly ash, combined. The GAC used was Filtrasorb 400 activated carbon, from the Calgon Carbon Corporation. Properties of that GAC are shown in Table A-1 in Appendix A. The components in the concrete mixtures are given as percentages of the total weight of the mixture and key material ratios are also presented. These can be found in Tables 3.1 and 3.2, respectively.

Table 3.1 Percent weights of various components for plain, 5% and 10% PC

Component	Plain	5%	10%
	% by weight		
Cement	13.13	12.97	12.81
Fly Ash	3.28	3.24	3.20
Water	5.42	5.79	6.16
# 89 Aggregate	78.17	77.19	76.23
GAC	0	0.81	1.60

Table 3.2 Key values and ratios for plain, 5% and 10% PC

Item	Plain	5%	10%
	Value		
Water/Cementitious	0.3300	0.3575	0.3850
Cementitious:			
% Fly Ash	20.00	20.00	20.00
% Cement	80.00	80.00	80.00
Cementitious/Aggregate	0.2100	0.2100	0.2100
Carbon/Cementitious	0.0000	0.0500	0.1000

As shown in Table 3.2, the ratios were largely kept experimentally constant, with the exception of the carbon content and the water/cementitious ratio. That ratio increased with the increasing carbon content since the water was increased to compensate for water that could be retained by the GAC. A test was previously performed to determine the approximate amount of water that GAC might retain in roughly saturated surface dry (SSD) conditions. This test is described in more detail in the “GAC Water Sorption Testing” section in Appendix A-1. Table 3.3 shows the raw data on the various mixes.

Table 3.3 Raw data for concrete mixtures

Component	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
	Weight (lbs)					
Cement	17.266	17.266	17.266	16	16	16
Fly Ash	4.316	4.316	4.316	4	4	4
Water	7.121	8.308	7.7145	6.6	7.7	7.150
# 89 Aggregate	102.768	102.768	102.768	95.238	95.238	95.238
GAC	0	2.158	1.079	0	2	1

More details on the mixing procedures can be found in Appendix A-2.

3.2.2 Preparation of Pervious Concrete Samples

In this research, two types of concrete samples were prepared: cylinders and slabs

Cylinder molds. The cylinders were prepared in 4” x 8” plastic molds. Figure 3.1 shows 4” x 8” concrete cylinder molds. The diameter of the molds is approximately 4” and the length approximately 8”.

Figure 3.1. Concrete 4” x 8” cylinder molds

Cylinder compaction. The samples were poured in two layers. Efforts were made to remove lumps. Each layer was rodded approximately 25 times and tapped around the perimeter roughly 15 times with the small steel rod[1]. The top was then rolled to level with the steel rod. It is important to note that these numbers are not exact and may have varied due to errors in counting.

Slab molds. The molds used to prepare the slab samples were plastic packing boxes cut off at approximately six inches, as shown in Figure 3.2.

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[1] In order to achieve relatively full and level samples, the second layer would be poured and rodded, tapped, or rolled, until reasonably level, adding concrete as necessary.

Figure 3.2. Cut-off box (at roughly 6 in depth) and regular box

The approximate cross sectional dimensions of the resultant slabs, parallel to the surface, were 9.0625 inches in width, by 13.375 inches in length for an approximate cross sectional area of 121.211 square inches.

Slab compaction. The slabs were also poured in two layers, rodding each layer approximately 60 times with the large steel rod[1]. Again, errors in counting may have resulted in slight variations. The surface was leveled with the rod. Then the slabs were placed on a Syntron PowerPulse™ vibrating table (please see Figure 3.3) for roughly 15 seconds.

Figure 3.3. Machine used to assist in concrete compaction

3.2.3 Concrete Curing

After the cylinders were cast in their molds, they were covered. The following day, they were removed from their molds and immersed in tap water in the curing tank until tested. The curing tank is shown in Figure 3.4.

Figure 3.4. Concrete curing tank

The tank was housed in the UNLV Materials and Structures Laboratory. It is important to note that even though the tank was outfitted with a heater to maintain the water temperature at optimal conditions, the heater at one point was found to have stopped working during the research. This may have had some impact on the material properties of the concrete samples. As a result, it is not necessarily possible to directly compare the results across mixtures. It is possible, however, to conclude that the observed resultant properties from the testing are indeed attainable for the different mixtures.

The concrete slabs were also cast and left until the next day. They were then placed inside plastic boxes and covered with water to cure. These boxes housed in a different lab had no heater to maintain water temperature, but the ambient temperature is generally about 22 ± 2 ºC. The concrete samples were each cured for over 5 months. At the end of curing, the slabs were scrubbed and rinsed, in an attempt to decrease what appeared to be a brownish/yellowish residue, shown in Figure 3.5, which had accumulated on the samples, probably as a result of the long-term storage in the boxes.

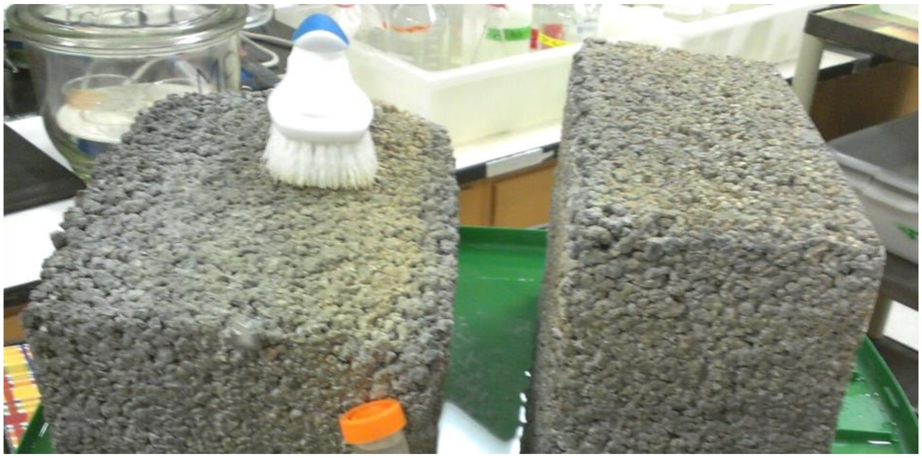


Figure 3.5. Residue on PC slabs after curing

3.2.4 Compression Tests

Compression tests were conducted on the 4” x 8” cylinders of each of the three PC mixtures. The tests were performed to determine the 3, 7 and 28- day compressive strengths of the samples. The samples were loaded until failure using a CM-5000 hydraulic compression machine as shown in Figure 3.6.

Figure 3.6. Loading machine used for compression and tensile tests

Prior to testing, the diameter of the cylinders was measured twice. These diameters were used to calculate the cross sectional area of the samples. The test failure load was divided by the calculated area of the cylinders to calculate the compressive strength. For each of the 9 tests (days 3, 7 and 28 and mixtures 1, 2, and 3) more than one sample was tested, except for 5% day 7. The average compression values for each day and mixture are presented in the results section (section 3.3.1). The raw data are presented in Appendix B. It is important to note that initially cylinders were broken with either the top, or bottom face (as was cast in the mold) upward in the compression machine. As testing progressed, tests were done with only the top face upwards. This is considered to be more reasonable, since the top faces of the concrete samples are often less flat and the top of the compression machine is able to adjust somewhat to the lack of perpendicularity. Again, this may affect direct comparisons between and within mixtures, but allows for conclusions on the attainable compressive strength of each mixture.

3.2.5 Tensile Tests

Tensile tests were also conducted on 4” x 8” cylinders from each of the three mixtures. The tests were conducted on the same samples that were previously used for porosity and permeability tests, where they may have incurred some minimal damage during placement and removal in the plastic molds (see section 3.2.6 porosity testing below). The samples were all re-measured prior to the tensile tests to account for the loss of any small aggregates. This test was done only to determine the 28-day tensile strength. The same hydraulic compression machine was used and the samples were loaded until failure along their lengths (as shown in Figure 3.7).

Figure 3.7. Layout for concrete samples in tensile tests (front and side angles)

The length and diameter of each test cylinder was measured three times and averaged. The tensile strength was calculated using the following formula from ASTM C496/C496M – 04 (ASTM, 2010) presented in Quiroz (2011) and slightly modified here:

(Equation 3.1)

$$T_s = \frac{2P_{ult}}{\pi \bar{l} \bar{d}}$$

T_s = Tensile strength

P_{ult} = Peak load

$\bar{l}$ = Average length of specimens

$\bar{d}$ = Average diameter of specimens

The average tensile strength values for each day and mixture are presented in the results section (section 3.3.2). The raw data are presented in Appendix B. For the splitting tensile test results, more than one sample was tested and the results averaged, except in the case of the 10% carbon to cementitious ratio specimens. Unsatisfactory testing procedures resulted in only one value remaining.

3.2.6 Porosity Tests

The porosity testing was done in a manner mostly similar to that presented in Quiroz (2011), who referenced the Florida Concrete and Products Association (1991) *Portland cement pervious pavement manual*. Prior to porosity testing, the concrete samples were brought to a moisture level considered to be close to SSD conditions. The procedure used is outlined in Appendix A-3. In this test, 4” by 8” cylinders were used. Three samples were used from each mixture. They were put in plastic molds, similar to the forms used to shape the cylinders themselves. It was often necessary to lightly hammer the samples into the molds since they fit very tightly. The samples in the molds were then placed on an HP-30K precision industrial balance and filled to the top with water. Figure 3.8 depicts the process.

Figure 3.8. Images of porosity testing process

The weight of water was then converted into a volume, which was taken to represent the volume of voids (V_v), using the approximate specific weight of water of 62.3 lb/ft^3 (The Engineering Toolbox, n.d.; USGS, 2014). The volume of the concrete cylinders (V_c) was determined from the averages of three diameter and length measurements. The percent of voids, or porosity, was calculated as:

(Equation 3.2)
$$Porosity = \frac{V_v}{V_c} x\ 100$$

3.2.7 Permeability Tests

Permeability tests were conducted on samples that were considered to be at saturated surface dry (SSD) conditions as presented in Appendix A-3. Concrete cylinders were used for this test which again had 4 inch diameters and lengths of 8 inches. The samples were rolled in plastic approximately 30 inches wide by 13 inches in height. As a timer was started, 800 mL of water were poured on the top face of the concrete. The height of the rolled plastic contained the water as it flowed through the surface of the concrete. Figure 3.9 gives an idea of the setup used in these tests.

Figure 3.9. Various stages of the permeability testing process

As the water disappeared into the surface of the concrete cylinders, the timer was stopped and the time was recorded. The data from two specimens were used for each mixture. To calculate the surface area of each of the specimens, the average of three diameters was used. Considering the water volume, time of infiltration and concrete surface area, it was possible to calculate the flowrate per surface area of the concrete samples.

3.3 Results and Discussion

3.3.1 Compression Tests

The results for the compression tests are shown in Figures 3.10 to 3.12. The raw data are included in Table B1 in Appendix B. Table D-1 in Appendix D shows standard deviation values for multiple results. For various reasons, including problems with the samples, loading rate or data collection, some test values were not included in the graphs of average values, but they are included (highlighted) in the raw data Table B1. The first graph, Figure 3.10, shows the average compressive strength results for the plain pervious concrete (no added GAC).

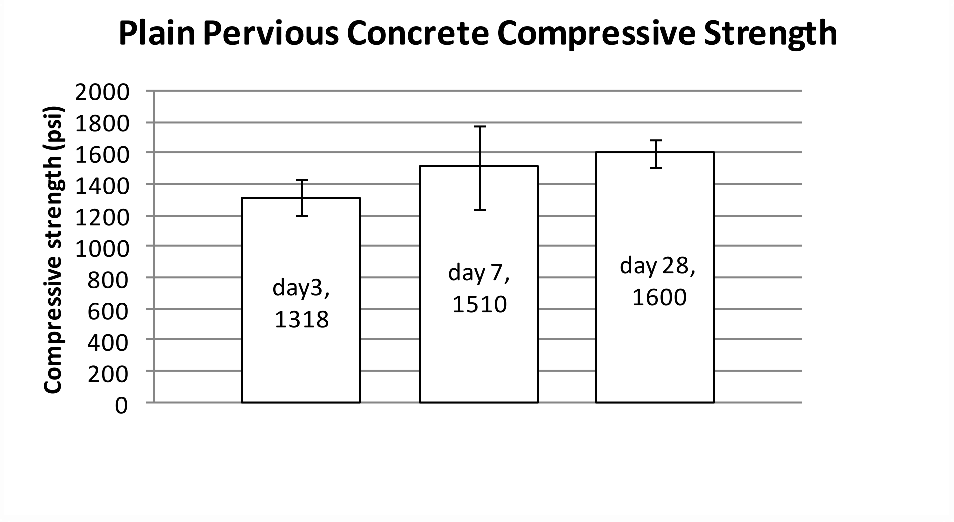


Figure 3.10. Graph of compressive strength vs. time for plain PC. Error bars show ± one standard deviation, where applicable.

As seen in Figure 3.10, the 28-day compressive strength of the plain PC was 1600 psi. The graph shows a typical increase in strength over time. The initial increase is steep and then tapers off over time.

Figure 3.11 shows the results for pervious concrete with 5% carbon to cementitous content.

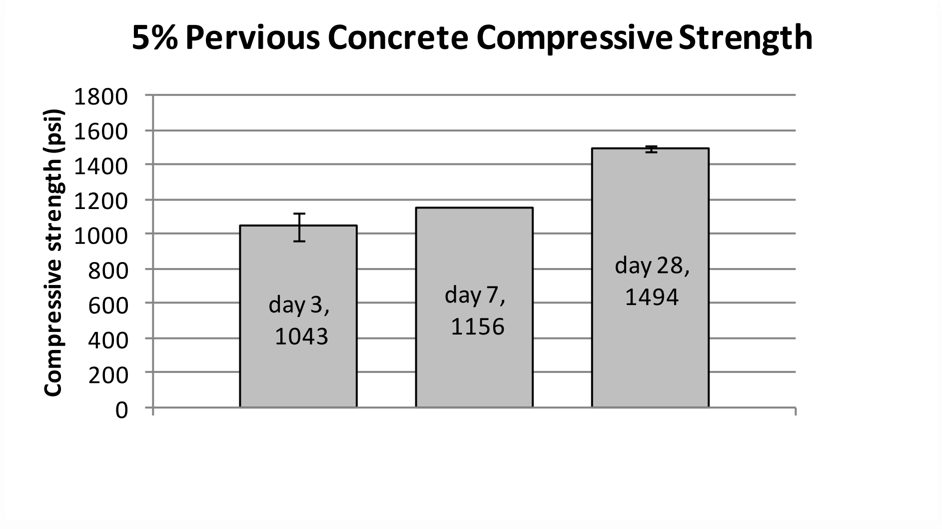


Figure 3.11. Graph of compressive strength vs. time for 5% PC. Error bars show ± one standard deviation, where applicable.

As seen in Figure 3.11, the compressive strength attained at 28 days is almost 1500 psi.

The graph of compressive strength vs. time for the 10 % carbon to cementitious concrete is presented in Figure 3.12.

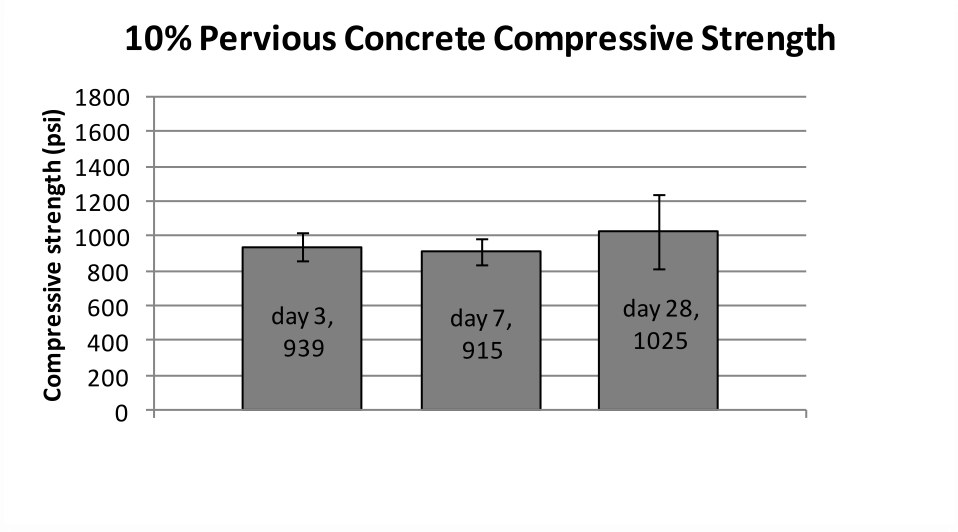


Figure 3.12. Graph of compressive strength vs. time for 10% PC. Error bars show ± one standard deviation, where applicable.

As seen in Figure 3.12, the 28-day strength is considerably lower than for both the other concrete mixtures.

Figure 3.13 presents images of one of the 28-day compressive failures for each concrete mixture. No particular analysis was done on the failure methods of the various samples and it is not proposed that these images represent the typical failure modes expected for a given mixture.

Figure 3.13. Select compression failures (left to right) for plain, 5% and 10% PC

3.3.2 Tensile Tests

The results for the 28-day concrete tensile strengths are presented in Figure 3.14. Again, for reasons such as sample and loading issues, some test values were not included in the average tensile strength results; they too, however have been included in the raw data Table B-2 in Appendix B. Table D-2 in Appendix D shows standard deviation results for multiple samples. Figure 3.14 presents the average tensile strength of the samples used, for each of the three mixtures.

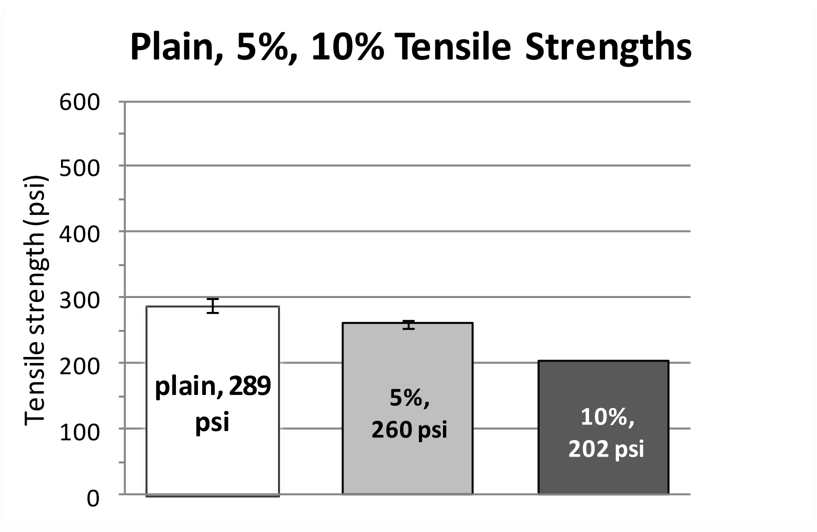


Figure 3.14. Graph of average 28-day tensile strength for plain, 5 and 10% PC. Error bars show ± one standard deviation, where applicable.

The tensile strengths followed the same pattern as those for compression, showing decreasing strength with increasing carbon content.

Figure 3.15 shows images of select tensile failures for the three mixtures. Again, no particular analysis was done on the failure modes of the various samples and it is not proposed that these images represent the typical failure modes expected for a given mixture.

Figure 3.15. Select tensile test failures for (from left to right) plain, 5% and 10% PC

3.3.3 Porosity Tests

The results for porosity tests are presented in Figure 3.16.

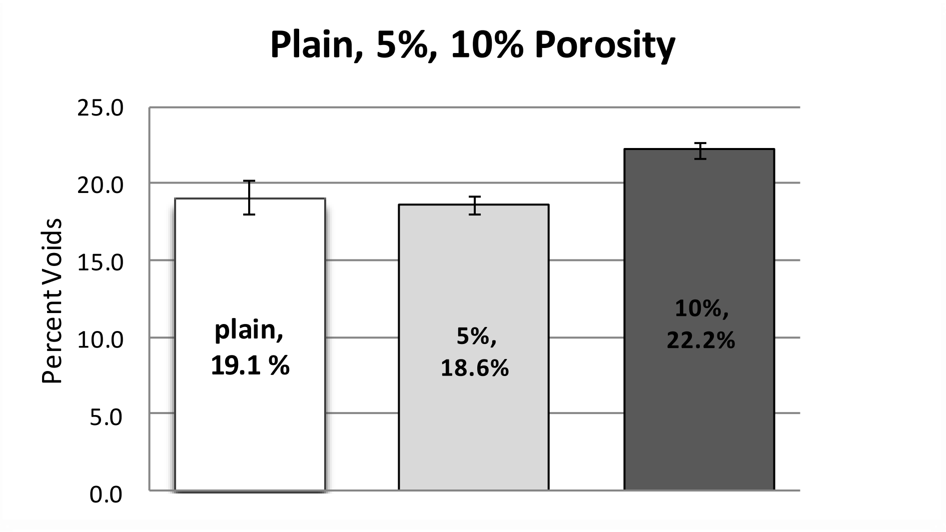


Figure 3.16. Graph of porosity, or percent voids for plain, 5% and 10% PC. Error bars show ± one standard deviation, where applicable.

As seen in the bar graph (Figure 3.16), the three mixtures showed similar porosity results. In this case the highest porosity value was found for the 10% GAC containing samples, followed by the plain PC and the 5% GAC samples. The experimental raw data is presented in Table B3, in Appendix B. Table D-3 in Appendix D shows standard deviation values for multiple test results.

3.3.4 Permeability Tests

The following graph, Figure 3.17, shows the permeability results for the plain and 5% samples. Some data points (for the plain and 5% samples) are not included in the graph due to testing issues, but are included (highlighted) in Appendix B. Table D-4 in Appendix D shows standard deviation values for multiple test results. There was some uncertainty in the water volume used in testing the 10% samples; those results in their entirety were not included in the graph, but are also included (highlighted) in appendix B.

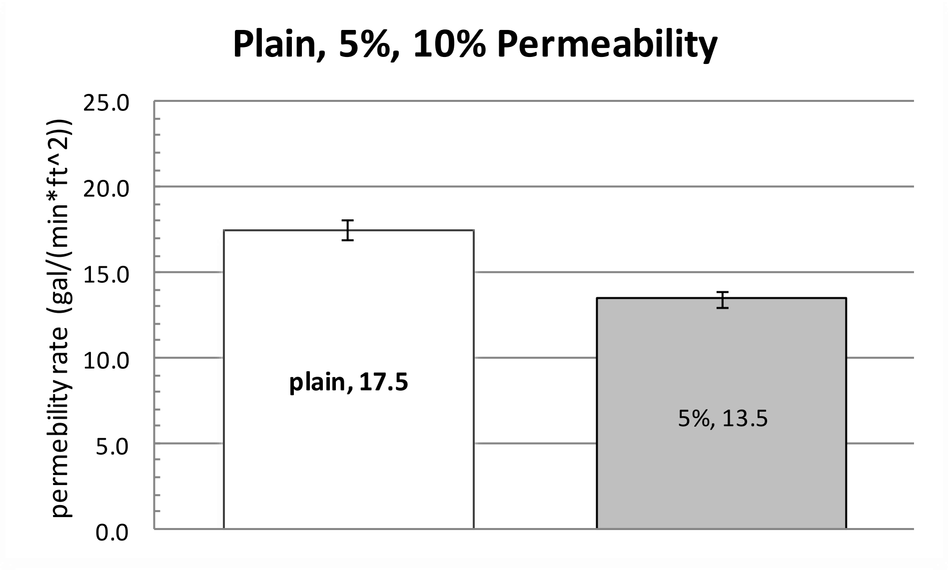


Figure 3.17. Graph of permeability for plain and 5% PC. Error bars show ± one standard deviation, where applicable.

The plain concrete had an average permeability rate of 17.5 gallons per minute per square foot and the 5% concrete resulted in an average value of 13.5 gallons per minute per square foot.

3.4 Conclusions

Direct comparisons of the preceding results between and within mixtures are discouraged, due to potential variations in curing temperatures, and in the case of compression tests, the direction of samples. However, potentially valuable insight may be gained on the achievable material properties obtainable for the different mixtures. It is useful to compare these attainable values to typical values that might be expected for PC. Table 3.4 (A) compares the test results with values presented in Tennis et al. (2007) and Obla (2010). Table 3.4 (B) shows minimum 28-day strengths for concrete in different applications presented in various sources.

Table 3.4 (A) Comparison of experimental pervious concrete results and ranges presented in Tennis et al. (2007) and Obla (2010)

Item	This study			Range presented by (Tennis, et al. 2007)	Range presented by (Obla, et al. 2010)
	plain	5%	10%		
Compressive strength (psi)	1600[a]	1494[a]	1025[a]	500 - 4000	400 - 4000
Tensile (flexural) strength (psi)	289[a]	260[a]	202[a]	150-550	
Percent Voids (%)	19.1	18.6	22.2	15-25	18 - 35
Permeabiliy (gal/(ft^2*min))	17.5	13.5	—	3 - 8, up to 17 and more in lab measurements (Crouch 2004)	2 - 18

[a] 28-day

Table 3.4 (B) Concrete 28-day compressive strength requirements from various sources and applications

Min. 28-Day Compressive Strength (psi)	Use	Source
3000	general use and reinforced structures	a
2500	sidewalks, driveways, curbs and gutters	b
3000	sidewalks, driveways and curb and gutter	c
4000	parking, drive and loading area pavement sections	d

[a] Regional Transportation Commission of Southern Nevada (RTCSN)

[b] City of Andrews, TX (2011)

[c] City of Sanford NC (n.d.)

[d] Madrid, G. A., (n.d.)

As shown in Table 3.4 (A), all three concrete mixtures fell well within the ranges presented in Tennis et al. (2007) and Obla (2010), for almost all parameters. This shows, therefore, that for this research, each of the three concrete mixtures, plain, 5% and 10% PC, has been able to reach the ranges of values that might be expected. Naturally, more specific values may be required for particular applications that the concrete may be used for, but the results show that even with added GAC, PC still can attain reasonable values for all of the tests that are presented.

CHAPTER 4

INVESTIGATING THE URBAN RUNOFF TREATMENT CAPABILITIES OF REGULAR AND GRANULAR ACTIVATED CARBON-CONTAINING PERVIOUS CONCRETE

4.1 Introduction

Pervious concrete (PC) is known to be effective at removing certain contaminants that are found in urban stormwater runoff. It has been proposed that adding a sorptive material such as granular activated carbon (GAC) to the concrete mixture, may improve or expand its runoff treatment capabilities. The previously discussed portion of this research (Chapter 3) presented three mixes of concrete. One contained no GAC and the other two contained different amounts of GAC. Various mechanical and material properties of these mixtures were analyzed and discussed, presenting data that hopefully proved helpful in determining attainable values for several of those properties.

The purpose of the research described here was to analyze, under simulated rainfall conditions, the runoff treatment capability of concrete slabs made from three different mixes. They were subjected to synthetic runoff containing COD (oil or acetate), copper, lead, nitrate phosphorus, TSS and zinc. Such components were chosen because they are major pollutants present in urban runoff. The “treated” runoff (i.e. effluent) that left the concrete was analyzed to determine if PC removed any of the contaminants.

4.2 Materials and Methods

4.2.1 Experimental Set-up

To test the PC slabs, an experimental set-up was constructed as shown in Figure 4.1. It consisted of containers to house the previously prepared slabs, a partially reinforced PVC frame supporting the containers, plastic effluent collection containers, a plastic synthetic runoff reservoir and a runoff spraying system (for simulated rainfall). The runoff spraying system consisted of perforated Masterflex® 96400-16 tubing attached to a Cole Parmer 7553-80 peristaltic pump and to the synthetic runoff reservoir.

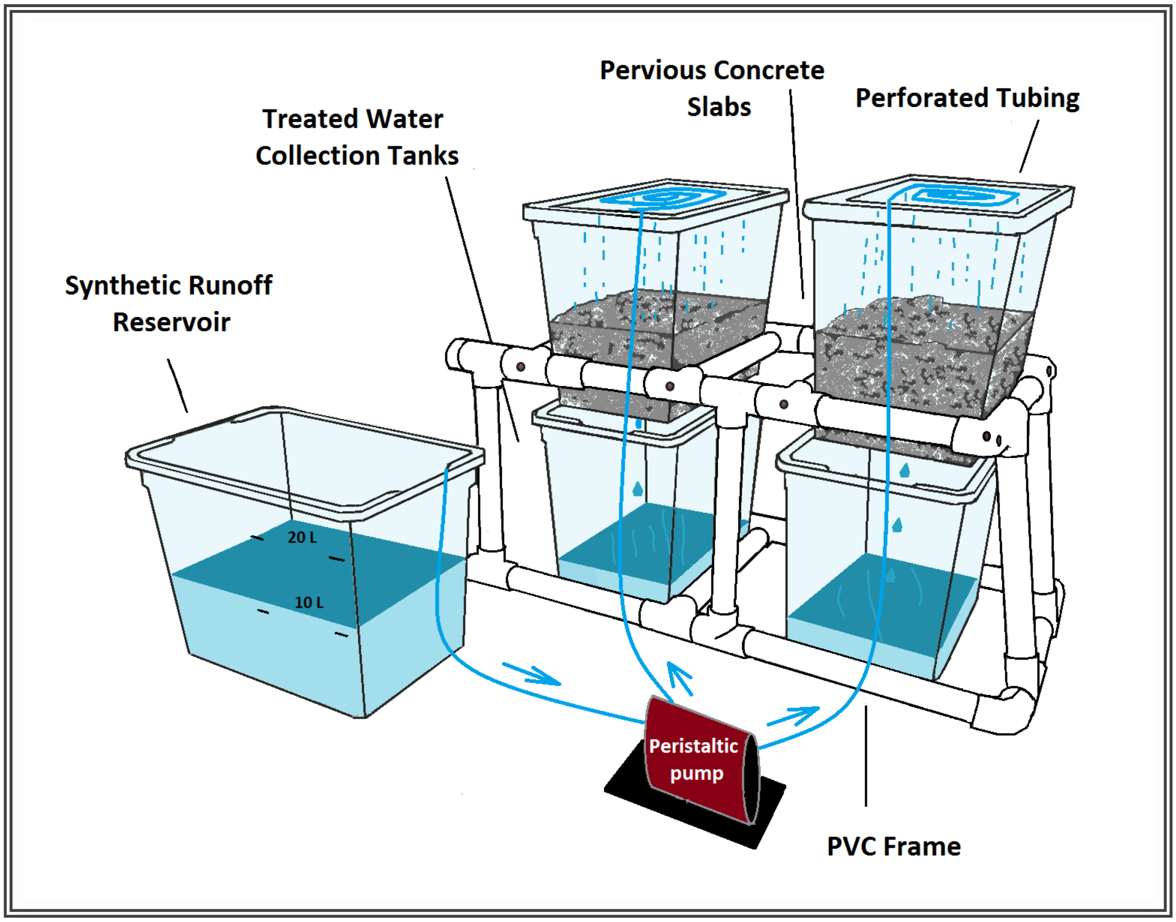


Figure 4.1 Sketch of Pervious Concrete, Runoff Water Test Set-Up

As shown in Figure 4.1, water was pumped from the simulated runoff reservoir to perforated tubing at the top of the test setup. Once the water made its way through the concrete (some water sprayed around the perimeter of the concrete between the plastic containers and the samples), it emptied into the collection tanks.

4.2.2 Preparation of Synthetic (Influent) Runoff Water

The target constituent concentrations for the runoff were obtained from Smullen et al. (1999) and represent common pollutants found in urban runoff water. The runoff experiments were divided into parts A and B. For the samples in part A, the COD reported by Smullen et al. (1999) was replaced with an equal weight of waste oil from a local mechanic shop. In part B, soluble acetate was used to meet the target COD concentration. Table 4.1 shows the constituents in the synthetic runoff, the target concentration for each, as well as the compound used.

Table 4.1 Constituents, target concentrations and compounds used in synthetic runoff for concrete samples A and B

Constituent/units	Target concentration	Compound used
Total Suspended Solids (mg/L)	78.4	soil from local detention basin
COD (oil or acetate) (mg/L)	52.8	waste oil from a local mechanic shop or Sodium Acetate Trihydrate ($C_2H_3O_2Na*3H_2O$)
Total Phosphorus as P (mg/L)	0.315	Sodium Phosphate Monobasic ($NaH_2PO_4*H_2O$)
Nitrate as NO_3 (mg/L)	0.658	Sodium Nitrate ($NaNO_3$)
Copper (µg/L)	13.5	Cupric Sulfate 5-Hydrate ($CuSO_4*5H_2O$)
Lead (µg/L)	67.5	Lead (II) Chloride ($PbCl_2$)
Zinc (µg/L)	162	Zinc Chloride ($ZnCl_2$)

Notes:
- Constituents and target concentrations primarily from Smullen et al. (1999)
- References such as Hsieh et al. (2005); Davis et al. (2001); Hsieh et al. (2003); Hong et al. (2006); Davis et al (2003) were used as a guide to determine the compounds to use.

Synthetic runoff water was prepared by pipetting concentrated stock solutions of one or more of the above chemicals into the synthetic runoff reservoir. The reservoir was then filled with reverse osmosis (RO) or distilled water, to the previously measured 10 or 20 L marks, depending on whether one or two slabs were being tested. For the first round of tests (samples A), all of the constituents in Table 4.1 were included in the synthetic runoff, except for the TSS and oil which were applied to the surface of the concrete prior to each test. For the samples in part B, since soluble sodium acetate was used for COD, only the TSS was applied to the surface of the slabs prior to experiment and all the other constituents were included in the synthetic runoff solution.

4.2.3 Computation of Volume and Flowrate of Synthetic Runoff Events

It was important to determine the amount and flowrate of simulated rainfall that was to be pumped through the runoff spraying system above the PC slabs. Each slab was subjected to three consecutive days of rainfall "events". Each event was to approximate the volume of rain expected to fall in Las Vegas, Nevada, in one year for a given surface area. This volume did not include considerations of water flowing from other areas but rather just the rain that would fall over an area the size of one of the slabs. Using data presented by NOAA (2014), the average annual rainfall for Las Vegas was determined to be roughly 4.17 inches/year. Using the approximately 121.21in^2 cross sectional area of the concrete slabs, the total daily volume was calculated to be 505.44 in^3, or 8.28 L.

The peristaltic pump was used to transfer water from the synthetic runoff reservoir to the surface of the concrete samples (Figure 4.1). Each day the pump was run at approximately 32.4 mL/min for about 256 min (roughly 8.3 L of influent per slab). This translates to about 0.489 inches of "rain" every 30 minutes, given the approximate cross sectional concrete slab area. This is relatively close to the 0.44 in of rain expected over 30 minutes for the recurrence interval of 2 years "for [the] McCarran airport rainfall area" (CCRFCD, 1999). The important difference here is that the rate of rainfall (0.489 inches per 30 min) was maintained not for thirty minutes, but for approximately 4 hours and 16 minutes for the various samples, in order to total 4.17 inches, roughly the total annual rainfall in Las Vegas. In other words, a rate near that of a 2-year return interval

30 min rainfall was maintained until one year's worth of synthetic runoff had been transferred each day.

The flowrate, volume, and number of rainfall events used, took some real world criteria into consideration while maintaining ease and practicality of testing. A two year event represents a not very unusual magnitude flowrate. Even though in reality this rate would only be expected for 30 minutes, by maintaining that rate for over 4 hours, it was possible to simulate an entire year's worth of rain in a single day. Finally, it was expected that 3 years worth of rain (3 events) might provide enough information while also being simple to implement.

4.2.4 Concrete Runoff Water Treatment Tests

From each of the three types of PC mixtures (plain, 5% and 10% carbon to cementitious), duplicate slabs were made and tested for their runoff water treatment capacity. The first samples of each mix tested were labeled samples A and the second round of tests samples B. With the exception of one contaminant (oil vs. acetate) the B samples were mainly a duplication of the A samples. Table 4.2 shows the experimental matrix in which the samples are labeled by type of concrete, sample ID and test day. For example, P-A-1 is for plain PC, sample A, day one; 10-B-3 is for 10 % carbon to cementitious PC, sample B, day 3.

Table 4.2 Experimental matrix for PC runoff treatment tests

PC Mixture Type	Samples (A)			Samples (B)		
	day 1	day 2	day 3	day 1	day 2	day 3
Plain	P-A-1	P-A-2	P-A-3	P-B-1	P-B-2	P-B-3
5%	5-A-1	5-A-2	5-A-3	5-B-1	5-B-2	5-B-3
10%	10-A-1	10-A-2	10-A-3	10-B-1	10-B-2	10-B-3

In order to determine what contaminants might be contributed to the effluent by the PCs themselves, another PC slab was subjected to three rainfall events with reverse osmosis water instead of runoff. The trials are shown in Table 4.3.

Table 4.3 Experimental matrix for plain PC reverse osmosis tests

PC Type	Reverse Osmosis		
	day 1	day 2	day 3
Plain	RO-1	RO-2	RO-3

At the end of each rainfall event, the effluent water collected in the treated water collection tanks was sampled for analysis of compounds of interest.

4.2.5 Analysis of Synthetic Runoff (Influent)

Many of the prepared runoff samples were tested by spectrophotometric analysis with Hach methods (Table 4.4). Additional information is provided on the Hach methods in Table A-2 and section A-4 in Appendix A. Round samples cells were used in place of the square cells that were called for by various Hach methods. These tests, however, were primarily on prepared synthetic runoff solutions and were generally quite close to expectations. The resultant values were used in the results and analysis unless otherwise noted.

Table 4.4 Analysis methods for influent runoff testing

Contaminant	Analysis method
COD	Hach (Method 8000)
copper	Hach (Method 8143)
lead	not tested
nitrate	results not considered reliable
oil	weighed
pH	pH paper and Thermo Electron Corporation Orion 720A+ and/or Accumet® Research AR10 pH meter
TP	Hach (Method 8048)
TSS	soil weighed and sprinkled
zinc	Hach (Method 8009)

This testing helped build confidence that the prepared runoff water conformed to the target concentrations. The constituents that were tested in this method were COD (in part B), copper, total phosphorus (TP), using the reactive phosphate test, and zinc. TSS and oil (for part A) were weighed and applied to the surface of the concrete samples. TSS was also applied in this manner for part B. The two Hach tests used for nitrate did not appear reliable for the given concentration range. Runoff influent was not analyzed for lead. As a result, the influent concentrations for both nitrate and lead in samples A and B were assumed to be at the target concentrations, as presented in Tables 4.1 and 4.2.

4.2.6 Analysis of Treated Runoff Water (Effluent)

Initially, the part A samples were collected and refrigerated. It was observed that white solids or precipitate; were present in the samples as seen in Figure 4.2.

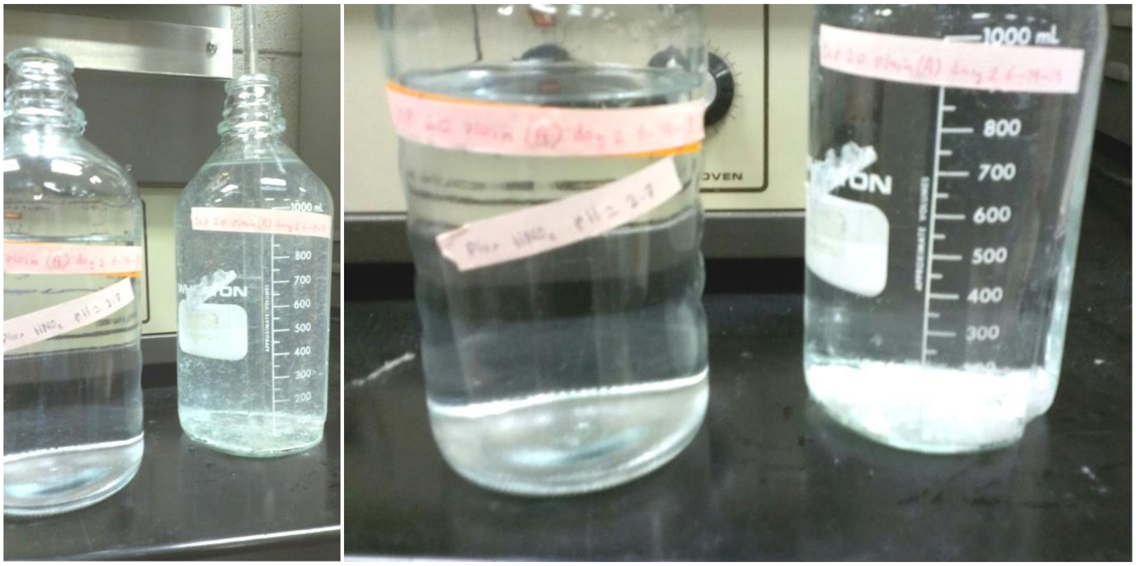


Figure 4.2. Plain A Day 2 samples: acidified (bottles on left of pictures), non-acidified (bottles on right). Picture on left shows samples after stirring, picture on right shows samples without stirring.

It was also observed that the pH of the effluent was high, greater than 10.5 on average in all cases. Since these solids could possibly be some form of metal hydroxides due to the high pH, the samples were acidified using nitric acid prior to testing for various components, to release any constituents that may have precipitated.

Some of each of the part B samples was collected, and acidified prior to storage. Table 4.5 shows the contaminants along with some relevant procedures and testing methods.

Table 4.5 Procedures and analysis methods for effluent runoff testing

Contaminant(s)	Preservation/Samples Used	Laboratory/testing method
COD	Acidified (B) samples	UNLV Environmental Laboratory/Hach (Method 8000)
Copper, Phosphorous, Lead, Zinc	In general, A samples were refrigerated but not acidified till later to dissolve solids, and B samples were acidified but not refrigerated until later	Utah State University Analytical Labs/Thermo Electron iCAP ICP (inductively-coupled plasma Spectrophotometer)
Nitrate	No reported test results	No reported test results
Oil	Acidified (A) samples, were tested qualitatively.	UNLV Environmental Laboratory/Hach (Method 8000)
TSS:	No reported test results for A samples. B samples, both acidifed and non-acidifed, were qualitatively tested.	UNLV Environmental Laboratory/Hach (Method 8006)

Effluent testing was attempted for nitrate using Hach test Methods 8192 and 8171. These tests did not appear to give reliable results for the low concentrations presents. Further attempts to test effluent nitrate concentrations using Ion Chromatography did not prove successful, likely due to the high conductivity of the solution. No results for effluent nitrate are presented.

The results for oil concentrations (for part A samples) should be considered qualitative. On at least one occasion there appeared to be oil residue on the effluent water collection tank. Apparently, the collection technique was not suitable to obtain accurate results for oil since some oil was evidently left behind and not included in the samples that were tested. Additionally, a COD test was done to assess the amount of remaining oil in the effluent; however, there is no definite expectation that the entire mass of oil would be translated into COD.

Attempts were made to determine the remaining TSS in the effluent samples. Filtration and weighing did not appear successful, possibly because the mass filtered was too small. The samples from part B were studied for TSS both acidified and un-acidified using Hach Method 8006, again with round sample cells in place of the recommended square. It must be noted that the test was purely qualitative. It was not calibrated to measure the specific particles that may be found in the PC effluent.

4.2.7 Experimental Considerations and Methods Used for Analysis of Results

In this research four general issues were considered. The following sections present them and the methods used to address them.

4.2.7.1 PC mixtures studied for their contaminant treatment of synthetic runoff. This portion of the research was meant to study how contaminant concentrations were affected by the PC mixtures. The change in concentrations between influent and effluent, for each of the PC types, and for each of the test days, is presented. Welch two sample t-tests were performed, using the statistical software R, to determine if the changes in concentrations in the overall resulting effluent were statistically significant.

4.2.7.2 Comparison between PC mixtures and their effect on effluent water quality. In order to determine if the different concrete mixtures resulted in different effluent water quality, a single factor Analysis of Variance (ANOVA) was performed with $\alpha = 0.05$ using Microsoft Excel. The overall effluent results for each contaminant for each concrete type (plain, 5% and 10%) were analyzed in this manner. This analysis showed if there were any significant differences in effluent quality between any of the three mixes. Afterwards, the combined results of the 5% and 10% PC were compared to the plain PC using a Welch two sample t-test with the statistical software R. The intention here was to determine if samples with GAC differed overall in their runoff treatment from PC with no GAC.

4.2.7.3 PC and its contaminant contribution to effluent water. PC contains various components that are subject to leaching while water infiltrates through the concrete's void spaces. It was important to understand which compounds may leach from PC and at what concentrations. A single slab of plain PC was subjected to the same three days of infiltration experiments. The water used was obtained from a reverse osmosis system, but the contaminants of the synthetic runoff were not added. Some effluent contaminant concentrations with large values, which differed substantially from those of the runoff, were compared using a Welch two sample t-test.

4.2.7.4 Analysis of PC effluent precipitates. In order to determine the composition of the white precipitates found in the concrete effluent samples, two samples were tested acidified (as for the other tests) and un-acidified. The un-acidified samples were filtered prior to testing to remove the precipitates. The acidified samples were not filtered and were considered to have all contaminants in a soluble form, available for analysis. It is proposed that the composition of the precipitates may be determined from any major differences in the two analyses results.

4.3 Results and Discussion

The data for the influent and effluent contaminant concentrations of all PC mixtures are presented in Tables C-1 to C-3 in Appendix C. The graphs are included for each contaminant and concrete mixture in this chapter. In addition to their incorporation in the graphs, the standard deviations for duplicated samples are presented in Table D-5 in Appendix D.

A couple of comments now on preservation/sampling issues:

- The B samples that were sent to Utah State University Analytical Labs for elemental analysis were acidified but not refrigerated on collection; some algal growth later became apparent. This would likely have had the most significant effect on phosphorus concentration results.
- The first portion of effluent (roughly one quarter) was not collected for samples 10-B-3. Analysis results are for the remaining volume that was collected.

4.3.1 PC mixtures studied for their contaminant treatment of synthetic runoff.

4.3.1.1 Influent and effluent pH and precipitate formations. A major result that likely had a strong effect on the removal of many contaminants was the high pH of the concrete effluents. The results of runoff influent and effluent pH values are shown in Figure 4.3 (A to C). pH was measured using straight measurements. No corrections were made for the interference of high pH values on the measurements.

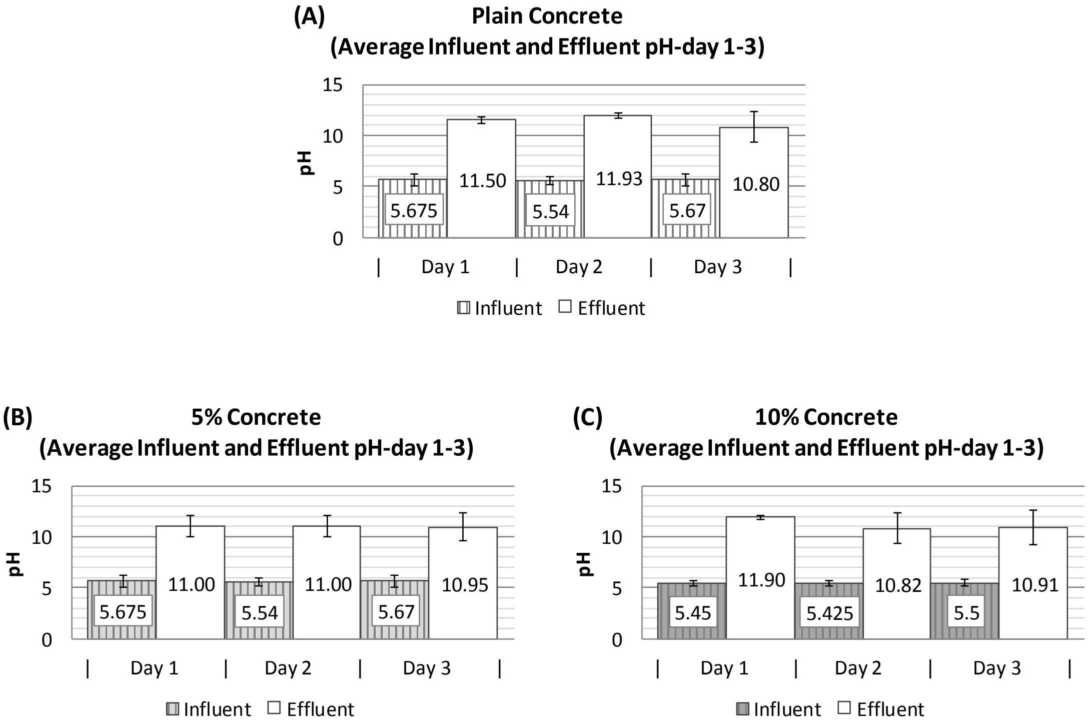


Figure 4.3 (A, B, C) Graphs of average influent and effluent pH (day 1 – day 3) for plain, 5% and 10% pervious concrete, respectively. Error bars show ± one standard deviation, where applicable.

It is clear that in all cases the effluent pH was significantly higher than that of the influent. Such an increase in pH is not surprising. Luck et al. (2008) compared effluent from pervious concrete with that from wire mesh screen. They found the pervious concrete to result in significantly higher pH (9.3 vs. 7.7). They mentioned that their concrete samples had not been saturated for extended periods and explained that the increased pH resulted from the concrete's "higher alkaline environment." The results from this research show high effluent pH values (while considering that the concrete samples were cured for over 5 months each and then rinsed). Kwiatkowski et al. (2007) considered a pervious concrete infiltration basin with storage beds made of limestone aggregates. They mentioned the basicity of both the limestone aggregate and pervious concrete. They found increased pH values as rainwater was collected from either within or below the infiltration basin. They also discussed an experiment were the pH of rainwater, in contact with the same limestone aggregate, was increased. The increase of effluent pH in this current work most likely played an important role in the treatment of many other contaminants that are discussed in some of the following paragraphs. For that reason, pH results were presented first.

4.3.1.2 Copper influent and effluent concentrations. As shown in Figure 4.4 (A to C), the copper content of the runoff was significantly decreased by all three pervious concrete mixes.

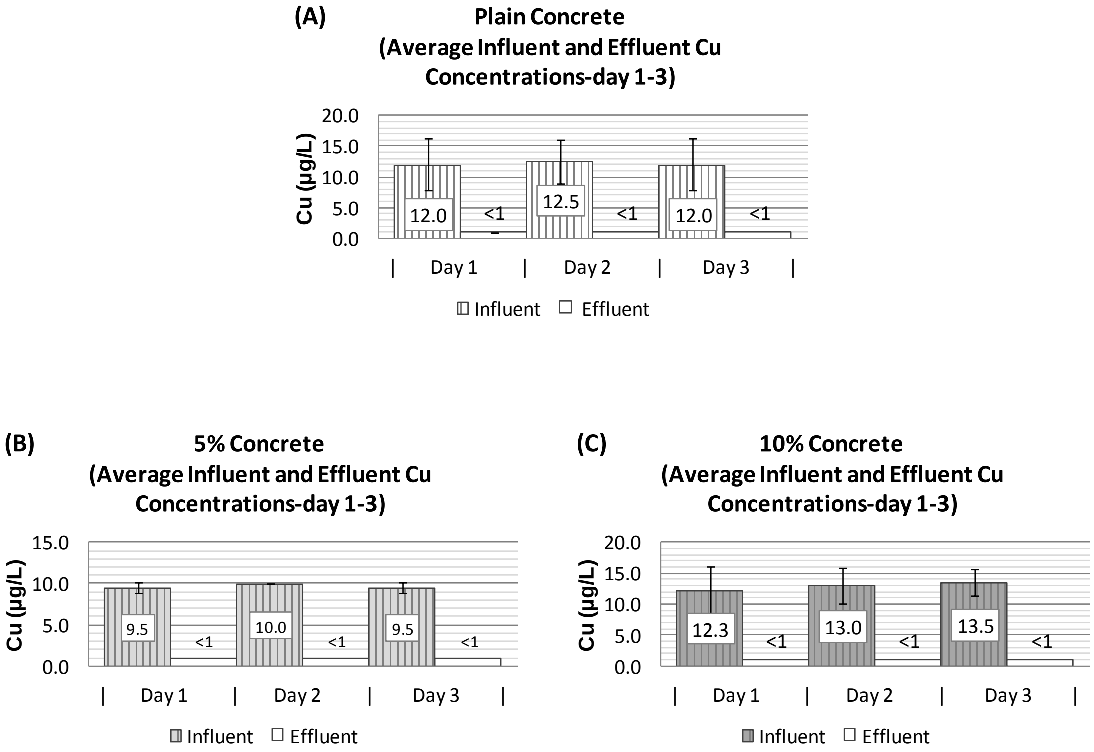
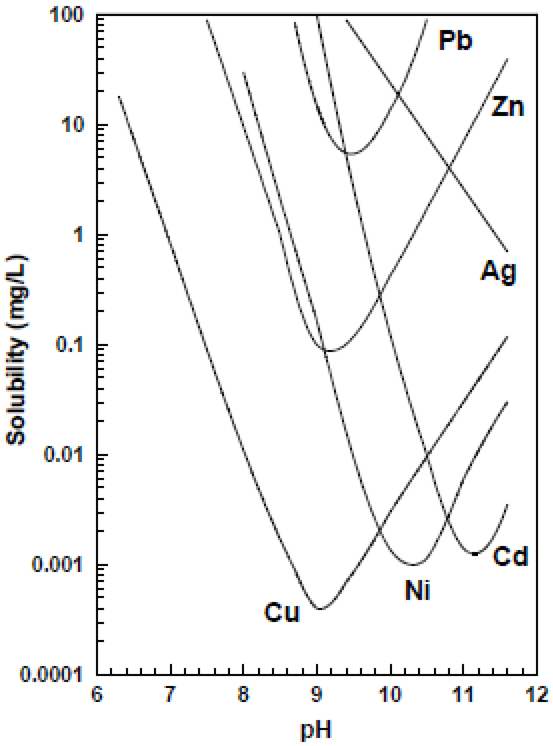


Figure 4.4 (A,B,C) Graphs of average influent and effluent Cu concentrations (day 1 – day 3) for plain, 5% and 10% pervious concrete, respectively. Error bars show ± one standard deviation

One possible mechanism for the removal was adsorption of the copper to the concrete and/or GAC, following the pattern of copper adsorption to soil which seems well documented (Kwiatkowski et al. 2007). Horst et al. (2010) in explaining the reduction of copper concentration with depth under a pervious concrete and aggregate infiltration bed cited Welker et al. (2006) and Mason (1999) and discussed metals binding to soil within 2 cm below the ground. It is possible that this mechanism also played a role in the decrease in copper content in the concrete effluent in this current research as sorption onto the concrete mixtures may have occurred.

Precipitation as hydroxide is another mechanism that can be used to remove copper. According to Armenante (1997), copper can be precipitated from wastewater as hydroxide between a pH of 9 and 10.3. The pH values of the influent water for this current research were in the 5.0 to 6.1 range and those of the effluent in the 9.5 to 12.1 range. It is logical to assume that the optimal copper precipitation range (9 - 10.3) was reached at some point within the concrete. The copper could very well have precipitated from solution and become entrapped within the PC. This is supported by the results for the solids analysis presented in Table 4.13. In those results, the samples that had been acidified to dissolve solids and those that had not been acidified all contained copper below the detection limit. Therefore it would appear that no significant portion of copper was contained in the precipitates found in the effluent. Furthermore, as shown in the diagram for hydroxides (Figure 4.5) copper has by far the lowest possible solubility of the three metals included in the simulated runoff (Cu, Pb, and Zn).



After EPA, 1983

Figure 4.5 P. Armenante (1997): Solubility of metal hydroxides as a function of pH

As indicated, at the optimal pH range, the solubility of copper hydroxide is well below 0.001 mg/L. Accordingly, if most of the copper was present as insoluble hydroxide precipitate and was removed by the concrete, the soluble portion remaining in the effluent would be expected to be very low, below 0.001 mg/L.

4.3.1.3 Lead influent and effluent concentrations. Figure 4.6 (A to C) show the results of influent and effluent lead concentrations for the various concrete mixtures.

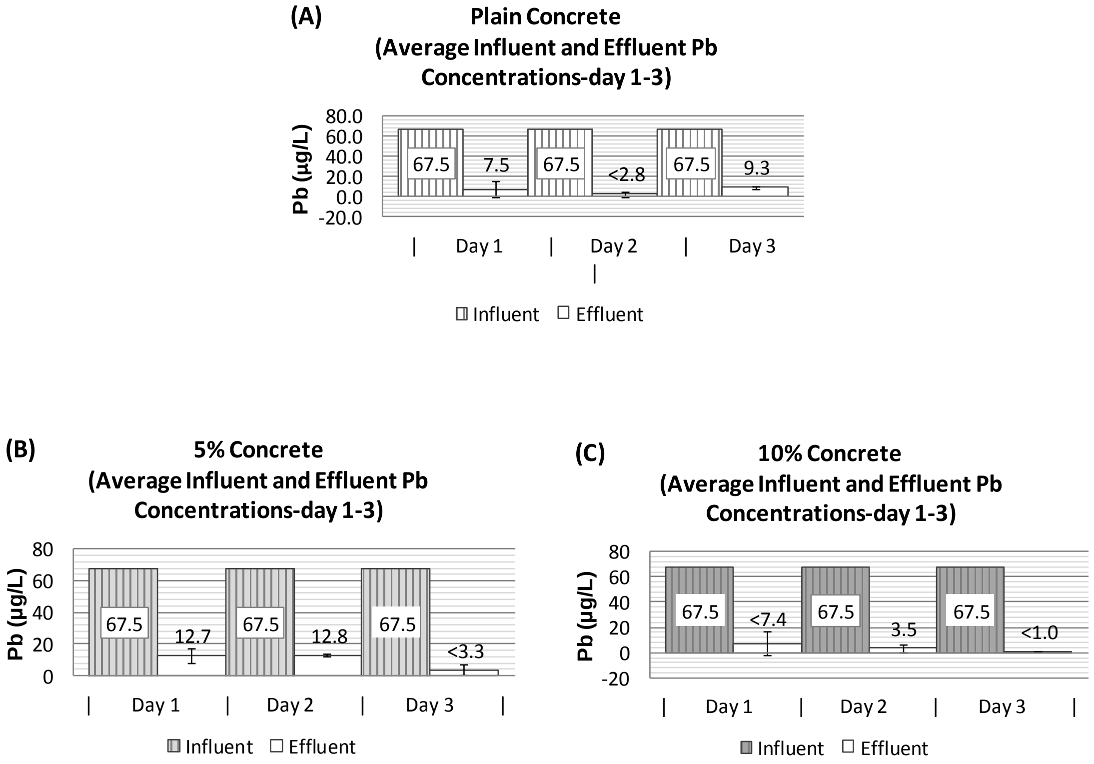


Figure 4.6 (A,B,C) Graphs of average influent and effluent Pb concentrations (day 1 – day 3) for plain, 5% and 10% pervious concrete, respectively. Error bars show ± one standard deviation, where applicable. The influent 67.5 µg/L come from calculations, not testing.

As previously mentioned, influent lead concentrations were taken to be the intended runoff concentration, therefore no variation is found for those values in Figure 4.6 (A to C). The figure also shows lead reductions for all PC mixtures. Unlike the copper results, however, some lead (above the detection limit) remained for most samples. In attempting to explain the apparently less thorough removal of lead by the concrete mixtures, Armenante (1997) is again of interest. According to that source, precipitation removal of lead hydroxide from industrial wastewaters may be accomplished at a pH of 11.5, with a lower limit effluent concentration range of 0.02 to 0.2 ppm (0.02 to 0.2 mg/L or 20 to 200 µg/L). Figure 4.5 shows a somewhat lower pH for minimum solubility. In any case the average effluent concentrations found in this work are below 20 µg/, so it is likely that precipitation played a role in the reduction of lead, in addition to possible other mechanisms such as adsorption.

4.3.1.4 Zinc influent and effluent concentrations. The results of influent and effluent zinc concentrations are shown in Figures 4.7 (A to C).

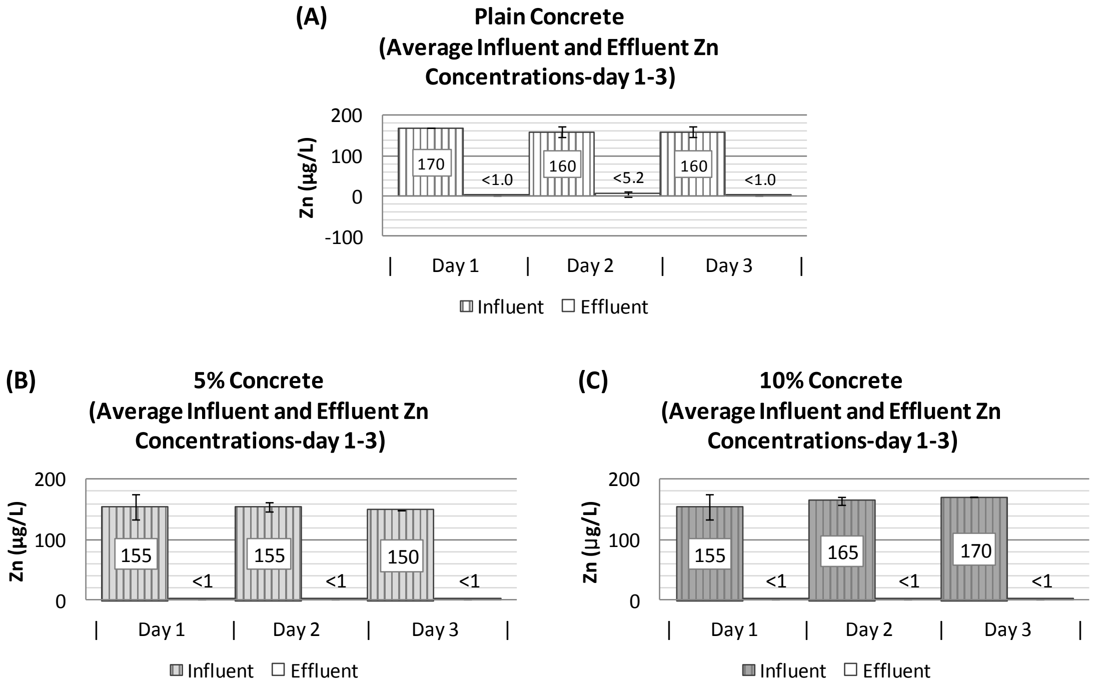


Figure 4.7 (A,B,C) Graphs of average influent and effluent Zn concentrations (day 1 – day 3) for plain, 5% and 10% pervious concrete, respectively. Error bars show ± one standard deviation, where applicable.

Once again, as in the case of copper, a very significant reduction of Zinc was shown. Only one sample was found to contain Zinc above the detection limit of 0.001 mg/L. Once again considering Figure 4.5, it would not be expected for zinc to reach levels much lower than 0.1 mg/L based on precipitation alone. Perhaps adsorption was also responsible for some of this removal.

4.3.1.5 TP influent and effluent concentrations. Figure 4.8 (A to C) shows values for influent and effluent phosphorus concentrations.

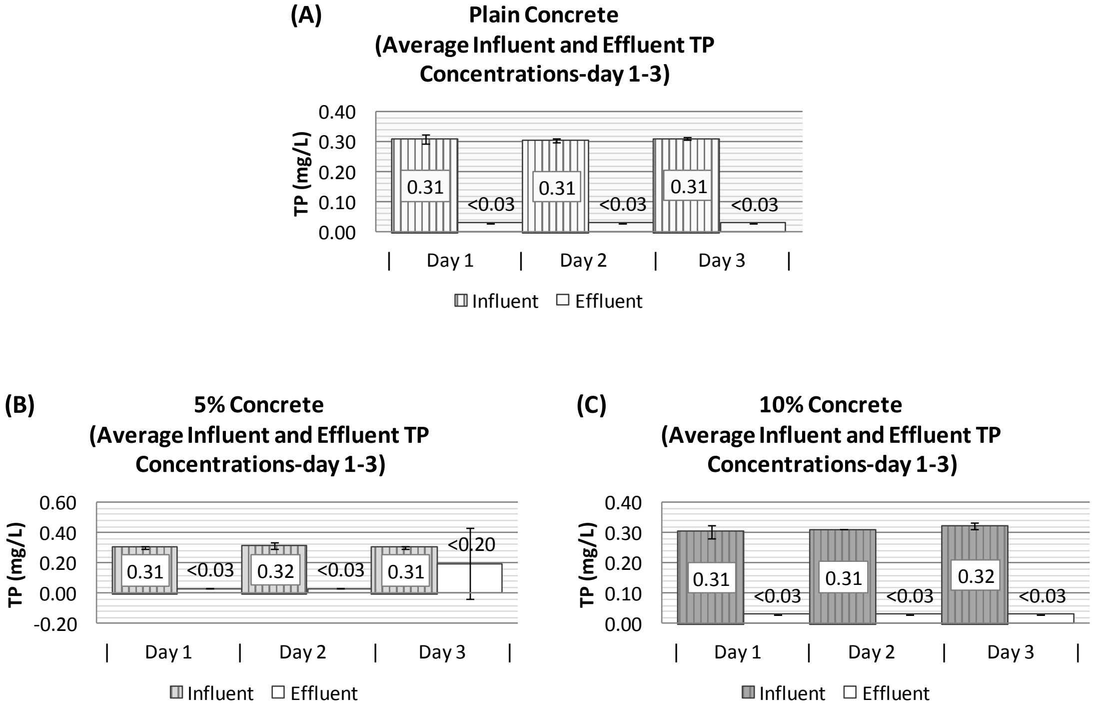


Figure 4.8 (A, B, C) Graphs of average influent and effluent TP concentrations (day 1 – day 3) for plain, 5% and 10% pervious concrete, respectively. Error bars show ± one standard deviation, where applicable.

Clearly, in all but one case the effluents are seen to be below detection levels. In one case the very high result for 5-A-3 skewed average results for day 3. However, 5-B-3 was again below detection levels. The standard deviation bars indicate the large variance in those results. A likely explanation is that 5-A-3 was somehow contaminated. Although almost all samples showed dramatic reductions in phosphorus, it is still possible that the previously mentioned observed algal growth in the B samples played a role in such reductions. Luck et al. (2008) indicate that the reductions are not anomalous. They found that PC reduced total phosphorus and soluble phosphorus significantly more than filtering through wire screen. The authors cite Sung-Bum and Mang (2004) to say that microbial activity was attributed for the potential of pervious concrete to remove TP from water. While this was a possible mechanism for the finding in the current research, it does not seem to be to be the only one present. Not all samples were observed to have algal growth, yet all except one showed dramatic phosphorus reductions. Additionally, because the experiment was run for a short period of time it likely did not allow for significant microbial growth within the concrete.

Precipitation is again a likely mechanism. Luck at al. (2008) also cite Collins (2007) in mentioning that pH increases may partially result from magnesium carbonate or calcium oxides available in finished concrete. The authors state that the concentrations of these components are reasonably assumed to be higher in the non-highly leached specimens. They proceed to cite Lindsay (1979) who reportedly found that phosphorus can precipitate as magnesium or calcium phosphates when magnesium and calcium are added in soil environments with higher pH. The authors mention that this could be an additional explanation for the soluble phosphorus decrease. They mention that concrete aging could decrease this effect. This could be a very likely mechanism for the observed phosphorus reductions since the pH values were found to be high as presented earlier. It would seem that the precipitated phosphorus may have become entrapped in the concrete matrix. Luck et al. (2008) also cite Moore et al. (1994), in mentioning that the levels of SP in effluent from manure decrease upon inclusion of class C fly ash (rich in Calcium) and/or calcium. Luck et al. (2008) also mention that the lower SP levels found in their research may have been contributed to by the calcium and the fly ash (with a lower percentage of calcium than class C) in the PC when compared to the wire screen. But they found that there was no consistently significant effect when PC samples containing fly ash were compared to those with no fly ash. The authors also cite Meyer et al. (2004, 2007) in mentioning that particle removal is another means to reduce nutrients loads. They also suggest absorption and specific retention within PC as a potential mechanism for reducing analytes. In the current work, absorption and specific retention seem to be unlikely mechanisms for contaminant removal.

***4.3.1.6* Oil *influent and COD effluent concentrations*.** Figure 4.9 (A to C) show results for the amount of oil applied on the influent surface and the COD readings for the effluent water.

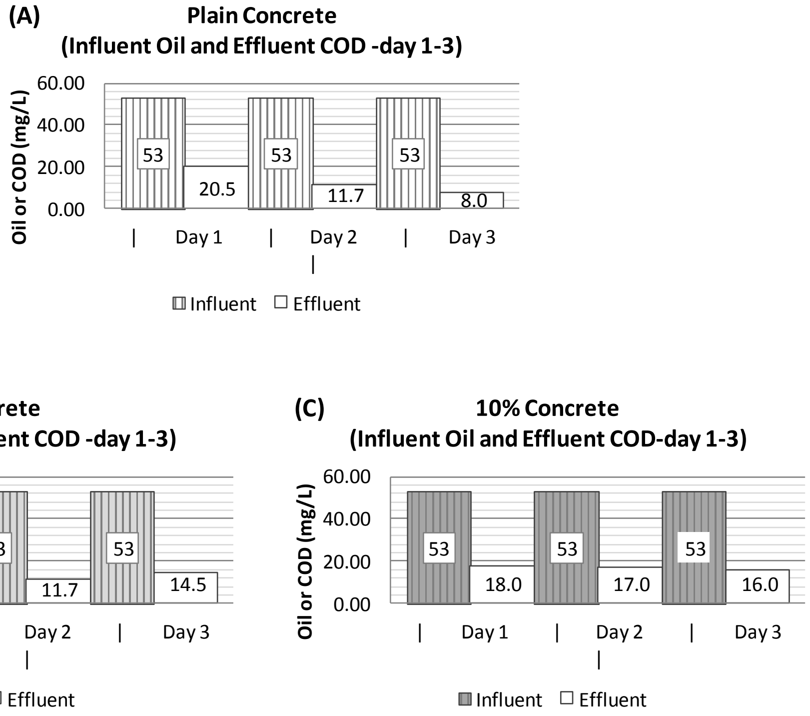


Figure 4.9 (A,B,C) Graphs of average influent oil and effluent COD concentrations (day 1 – day 3) for plain, 5% and 10% pervious concrete, respectively. The influent 53 from weighing, not tests.

As previously mentioned, the sampling methods did not appear satisfactory for a total and reliable recovery of oil for the effluent samples. Additionally, COD tests are not necessarily a direct measure of waste oil with an unknown composition. Therefore, the results presented in Figure 4.9 (A to C) are at the very best, qualitative, and may allow the reader to compare between the various mixes. Interestingly, however, the University of Rhode Island cited Pratt et al. (1999) for saying that hydrocarbons can effectively be biodegraded by “porous concrete pavement systems,” but mention the apparent limitation of nutrient supply for breakdown efficiency. They also cited Newman et al. (2002), who reportedly found that 99 % of applied oil was retained by “the porous pavement system.” The study also mentioned the system’s aptitude, when properly managed and constructed, for trapping and biodegrading accidentally released oil on parking surfaces. The short time frame of water testing in this research would appear to limit the effects of biodegradation of the waste oil; however, partial entrapment of oil within the concrete matrix would appear to have been quite a reasonable expectation.

4.3.1.7* COD *influent and effluent concentrations. Figure 4.10 (A to C) shows the results for influent and effluent COD concentrations.

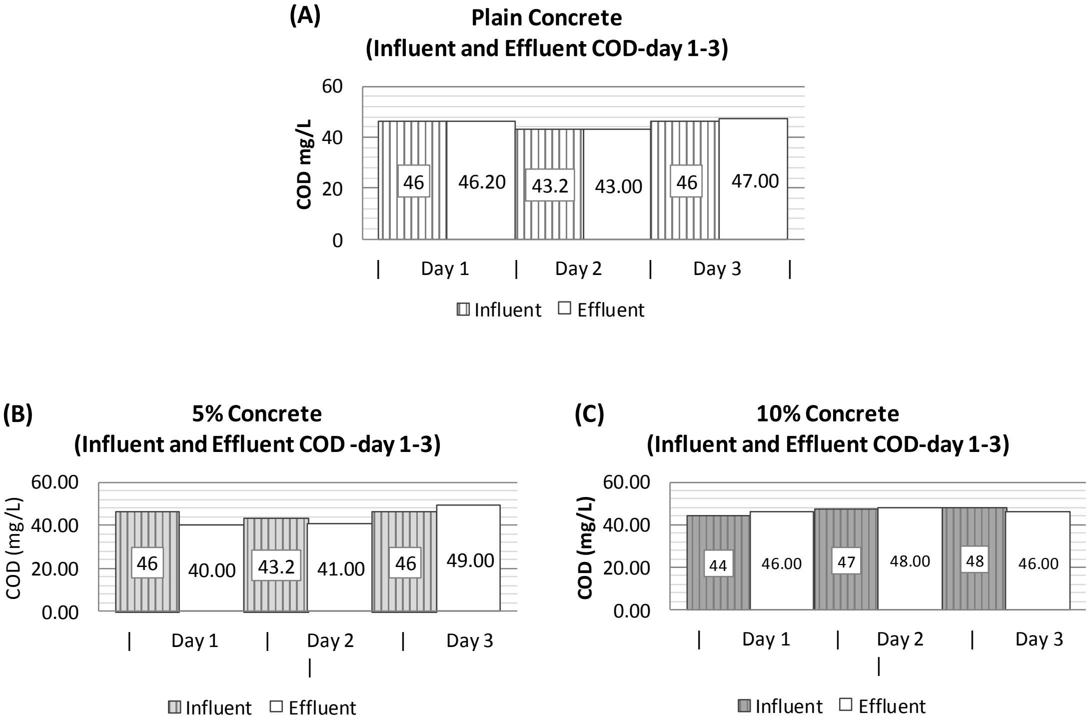


Figure 4.10 (A,B,C) Graphs of average influent and effluent COD concentrations (day 1 – day 3) for plain, 5% and 10% pervious concrete, respectively.

It is clear that the acetate that was used to attain the required COD dose in part

B of this research was not removed by any of the three mixtures. It appears that no mechanism was active for the removal of acetate. This is another reason to exclude biodegradation mechanisms since acetate is highly soluble.

4.3.1.8 Nitrate influent and effluent concentrations. No results were reported for nitrate

4.3.1.9 TSS influent and effluent concentrations. Table 4.6 presents the qualitative results for TSS in the (B) samples.

Table 4.6 Qualitative TSS concentrations for part (B) samples

TSS (mg/L)			
sample	acidifed	non-acidified	influent
P-B-1	<5	35	78
P-B-2	<5	122	78
P-B-3	<5	100	78
5-B-1	<5	49	78
5-B-2	<5	82	78
5-B-3	<5	62	78
10-B-1	<5	52	78
10-B-2	<5	69	78
10-B-3	<5	46	78

The influent 78 from weighing, not tests.

Table 4.6 seems to indicate that a large portion of the effluent TSS was some form of soluble precipitates. In all cases there was a dramatic reduction in TSS after acidification. It is also important to note that the acidification would not dissolve inorganic particles of soil, therefore the reductions were considered to be in other precipitates. Once again, the values presented in Table 4.6 are only qualitative and do not represent actual TSS effluent concentrations.

4.3.1.10 Influent vs. effluent statistical concentration comparison. To summarize the results, Table 4.7 shows the statistical results of concentration comparisons between influent and effluent.

Table 4.7 Overall statistics of influent vs. effluent by contaminant and concrete type (Welch 2-sample t-test)

Contaminant	Concrete Type	p-Value (treatments do not differ)	significant difference?
Copper	plain	3.23E-04	Yes
	5%	1.61E-07	Yes
	10%	6.87E-05	Yes
Lead	plain	7.13E-07	Yes
	5%	1.64E-06	Yes
	10%	7.41E-07	Yes
Zinc	plain	2.41E-08	Yes
	5%	3.06E-07	Yes
	10%	4.93E-07	Yes
COD-COD	plain	0.84	No
	5%	0.61	No
	10%	0.82	No
pH	plain	1.02E-06	Yes
	5%	2.93E-06	Yes
	10%	3.85E-05	Yes
TP	plain	2.96E-09	Yes
	5%	9.76E-03	Yes
	10%	5.00E-08	Yes

H_0: Treatments do not differ P > 0.05 (accept null)

H_1: "[T]rue difference in means is not equal to 0" (HOA 732 Class notes) P < 0.05 (reject null)

As seen in Table 4.7 there were found to be statistically significant reductions in all of the contaminants shown in the table, with the exception of COD (acetate). Oil, nitrate and TSS were not statistically analyzed.

4.3.2 Comparison between pervious concrete mixtures and their effect on effluent water quality.

The results of the single factor Analysis of Variance (ANOVA) are shown in Table 4.8.

Table 4.8 Single factor ANOVA analysis of PC mixtures

Contaminant	p-Value (treatments do not differ)	significant difference?
Copper	n.a.	No
Lead	0.0665	No
Zinc	0.3911	No
COD-Oil	0.6210	No
COD-COD	0.4749	No
ΔpH	0.5611	No
TP	0.3889	No
H_0: Treatments do not differ	$P > 0.05$ (fail to reject)	
H_1: Treatments differ	$P < 0.05$ (reject null)	

As shown, the null hypothesis was that the treatment methods (plain, 5% and 10% PC) did not differ in effluent concentrations. The probability values returned were all above the 0.05 cutoff and the null hypothesis was accepted. To further scrutinize the effects of GAC on runoff treatment, t-tests were used comparing plain PC with the combined results of 5% and 10% GAC-containing PC. Table 4.9 shows these results.

Table 4.9 GAC vs. plain PC samples (Welch 2-sample t-test**)**

Contaminant	p-Value (treatments do not differ)	significant difference?
Copper	n.a.	No
Lead	0.6427	No
Zinc	0.3632	No
COD-Oil	0.5541	No
COD-COD	0.8428	No
ΔpH	0.5405	No
TP	0.3388	No
H_0: Treatments do not differ		$P > 0.05$ (fail to reject null)
H_1: "[T]rue difference in means is not equal to 0" (HOA 732 Class notes)		$P < 0.05$ (reject null)

Again the null hypothesis was accepted for all contaminants, that the type of pervious concrete (with GAC or without) had no significant impact on the effluent water quality.

As discussed previously, all PC mixtures worked very well to remove many of the contaminants studied here. Statistically, however, there were no significant differences in the treatment when GAC was used. A likely explanation for the absence in effect, is that the GAC's ability to adsorb contaminants was no longer present in the concrete mixtures produced. It is fairly obvious that the GAC became covered by cement and aggregates when it was added to the PC mixtures. It would seem that the GAC's large surface area and active sites were covered to an extent that they no longer could affect contaminant removal levels. It is also possible to consider that perhaps some contaminants like metals were in fact sorbed by GAC but that the metals were also removed by plain PC through another mechanism such as precipitation due to raised pH within the concrete. In that case, it would be possible that GAC may continue to treat runoff for such contaminants, even once the alkalinity supply from the concrete is exhausted. This second proposal seems to be weakened by the absence of effect in treatment for COD. It would seem that if GAC active sites were available, they would have decreased the concentration of COD in the runoff effluent. This effect was not seen.

Nonetheless, longer scale studies might add insight into the results of decreasing effluent pH and its effects on contaminant removal. This in turn could illustrate in more detail the treatment effects of pH vs those of GAC. Additionally, research on pervious concrete with GAC incorporated in different ways may prove very valuable.

4.3.3 Pervious concrete, RO water and their contaminant contributions to effluent water.

Table 4.10 shows the resulting concentrations for contaminants of interest in this research when RO water was applied.

Table 4.10 Certain plain concrete effluent water contaminant concentrations from RO test

Contaminant	Condition	Sample ID/ item		
		RO-1	RO-2	RO-3
Cu (µg/L)	E	< 1	< 1	< 1
Pb (µg/L)	E	16.6	18.7	18.9
Zn (µg/L)	E	< 1	< 1	< 1
pH (-log[H^+])	E	11.18	11.36	11.32
TP (mg/L)	E	0.20	0.03	0.03
TSS (mg/L)	E (acidified)	–	–	–
	E (non-acidified)	8.5	15	21.5

E: Effluent

As seen in these results, Copper and Zinc were below detection limits. The results appear to be deceivingly high for lead. Samples were initially tested for lead and the results seemed unexpectedly high. Subsequent tests (two for RO-1, and one for each of RO-2 and RO-3, performed for Cu, Pb, Zn and P) returned much lower values for lead. The data displayed in Table 4.10 for those elements are averages of all of the test results. All values are shown in data Table C-4 in appendix C. It is interesting to note that even the lower concentration values for lead were above detection limits. This would likely suggest that lead was leached, to some extent, from the concrete matrix. There should be no source of phosphorus in plain concrete subjected to RO water. However, one sample returned a high value for phosphorus; it was retested and the result was also high. Another sample from that same day was tested and the resulting phosphorus was below the detection limit. It appears that that first sample must have been contaminated with phosphorus.

Table 4.11 shows an average value comparison for the full analysis results on effluent concentrations from the RO test and from the synthetic runoff on plain PC test.

Table 4.11 Comparison of effluent contaminant concentrations for plain PC receiving RO and synthetic runoff water

Element	Runoff	RO Average	Δ Concentration
Ca	**303.283**	68.324	234.959
Na	**29.827**	20.437	9.390
K	**16.243**	12.483	3.760
Sr	**1.162**	0.290	0.872
Ba	**0.217**	0.031	0.187
Se	**0.035**	0.031	0.004
Zn	**0.002**	0.001	0.001
As	**0.002**	0.001	0.001
Cd	0.001	0.001	0.000
Co	0.001	0.001	0.000
Cu	0.001	0.001	0.000
Mn	0.001	0.001	0.000
Ni	0.001	0.001	0.000
Si	8.765	**35.914**	27.149
S	4.943	**9.722**	4.779
Al	0.947	**1.459**	0.512
Fe	0.012	**0.248**	0.235
P	0.030	**0.101**	0.072
B	0.025	**0.069**	0.044
Mg	0.015	**0.039**	0.023
Pb	0.007	**0.018**	0.011
Cr	0.004	**0.005**	0.001
Mo	0.001	**0.002**	0.001

Notes:

In the original data, all values below detction limits were considered to be at the detection limit for calculations

Red values, presented in bold, indicate the higher value from each comparison

As can be seen in Table 4.11, the effluent from the concrete samples treated with simulated runoff water contain on average, a much more considerable amount of Ca and a relatively large amount of Na, from a mass perspective, as compared to the RO effluent. The RO effluent, on the other hand, contains on average larger amounts of Si and S when compared to the runoff effluent. The numbers are also large in terms of mass. To delve slightly into statistical comparisons, t-tests were done for the two largest concentration differences (by mass) for each condition. From the results, it was concluded that the Ca levels in runoff are significantly higher and the Si levels with RO water are significantly higher. The test results for those four contaminants are shown in Table 4.12

Table 4.12 Effluent Concentrations of RO vs. Runoff (Welch 2-sample t-test**)**

Contaminant	p-Value (treatments do not differ)	significant difference?
Ca	4.01E-05	Yes
Na	0.1157	No
S	0.1326	No
Si	5.64E-06	Yes

H_0: Treatments do not differ — P > 0.05 (fail to reject null)

H_1: "[T]rue difference in means is not equal to 0" (HOA 732 Class notes) — P < 0.05 (reject null)

None of these compounds were added to the runoff. The differences in effluent concentrations are very likely explained by possible differences in influent pH between the RO water and the synthetic runoff water. Lower pH is likely to promote Ca leaching while higher pH releases more silica**.**

4.3.4 Analysis of effluent precipitates

Table 4.13 presents the side-by-side concentration profiles of two effluent samples. In the columns titled acidified, the samples were acidified prior to analysis. In the columns titled filtered, the samples were not acidified but filtered prior to analysis. Acidifying resulted in the dissolution of the precipitates formed. The difference columns show the difference in concentrations for each element in the acidified vs. the filtered samples. The difference columns should theoretically represent the elements that were contained in the precipitates.

Table 4.13 Acidified vs. filtered effluent concentrations for precipitate analysis

Element	Comparison #1			Comparison # 2		
	10-B-1 (acidified)	10-B-1 (filtered)	Δ Concentration (acidified - filtered)	5-B-2 (acidified)	5-B-2 (filtered)	Δ Concentration (acidified - filtered)
Al	0.548	0.206	0.343	0.984	0.451	0.532
As	**0.001**	**0.001**	0.000	**0.001**	0.001	0.000
B	0.031	0.031	-0.001	0.031	0.042	-0.010
Ba	0.105	0.273	-0.168	0.147	0.296	-0.149
Ca	291.400	225.400	66.000	157.800	120.300	37.500
Cd	**0.001**	**0.001**	0.000	**0.001**	**0.001**	0.000
Co	**0.001**	**0.001**	0.000	**0.001**	**0.001**	0.000
Cr	0.003	0.008	-0.005	**0.001**	0.002	-0.001
Cu	**0.001**	**0.001**	0.000	**0.001**	**0.001**	0.000
Fe	**0.001**	**0.001**	0.000	**0.001**	**0.001**	0.000
K	14.450	12.770	1.680	20.640	22.320	-1.680
Mg	**0.001**	**0.001**	0.000	0.049	**0.001**	0.048
Mn	**0.001**	**0.001**	0.000	**0.001**	**0.001**	0.000
Mo	0.005	0.012	-0.007	**0.001**	0.003	-0.002
Na	37.520	35.400	2.120	42.880	45.620	-2.740
Ni	**0.001**	**0.001**	0.000	**0.001**	**0.001**	0.000
P	**0.03**	**0.03**	0.00	**0.03**	**0.03**	0.00
Pb	0.014	**0.001**	0.013	0.014	**0.001**	0.013
S	10.75	10.60	0.15	3.37	3.70	-0.34
Se	**0.025**	**0.025**	0.000	0.036	**0.025**	0.011
Si	17.150	1.780	15.370	19.130	11.330	7.800
Sr	0.601	0.543	0.058	0.795	0.775	0.020
Zn	**0.001**	**0.001**	0.000	**0.001**	**0.001**	0.000

Notes:

All values in mg/L

Bold values indicate the detection limits for results that were below detection limits

In both comparisons, the largest mass differences are for Ca and Si. The acidified samples were found to have concentrations higher than the un-acidified and filtered samples. From these results, it appears logical that the major components of the precipitates found in the effluent samples were Ca and Si precipitates, although other elements also seem to have been present. One could speculate that calcium silicate would be formed under these conditions. If the solids were composed purely of

$Ca_3(SiO_4)_2$, the expected molar ratio of Ca to Si would be 1.5. The molar ratio of calcium to silicon in comparison #1 is about 3 while that of comparison #2 is ≈ 3.4. It is also interesting to observe that Pb seemed to have been partially present in precipitate form in the treated effluent water.

4.4 Conclusions

This research has shown that pervious concrete reduces the concentrations of many of the contaminants found in urban stormwater runoff. There were found to be statistically significant reductions in copper, lead, zinc and total phosphorus (although algal growth may have played a role in the phosphorus results). PC seemed to reduce the concentration of TSS, but no quantitative results were obtained. Collection and testing methods allowed for no conclusions on oil removal. Nitrate testing also proved unsuccessful. A variety of mechanisms probably played a role in the contaminant reductions. The high pH of the effluent from the PC samples is thought to have led to the precipitation and entrapment of such contaminants as copper, lead, zinc and phosphorus. Some other mechanisms, possibly adsorption, might have played a role in the removal since, for example, precipitation may not decrease lead and zinc levels to the values that were obtained. No mechanism was present for COD removal since there were no significant reductions for that contaminant by any of the concrete samples.

The results were analyzed to determine if there were any statistically significant differences in effluent contaminant concentrations when different PC mixtures were used. No such differences were found. The results were also studied to establish if the incorporation of GAC in PC resulted in statistically significant contaminant concentration differences when compared to plain PC. Again no differences were found. The results here show that there were no significant changes in overall effluent quality when GAC was utilized under the given testing regime.

Plain PC was tested with RO water to establish a sort of baseline effluent profile, when no runoff contaminants were added. In addition to slight levels of elements such as chromium and lead, another interesting result was found. There were large concentration differences among contaminants (other than those added) when RO water was used instead of runoff. For example, Ca was significantly higher when runoff water was used and Si was significantly higher when RO water was used; possible pH differences may have been a factor in this result.

Finally, two comparisons between acidified effluent samples and filtered effluent samples seemed to show that a large portion of the precipitates found in the high pH effluent were largely precipitates of calcium and silicon.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

An environmental problem currently of concern is that of urban stormwater runoff. Stormwater runoff is well known to contain and transport a wide variety of contaminants to surface waters. It is a significant cause of the contamination of rivers and lakes. This research considered PC and GAC-containing PC from a material perspective; in addition, their treatment capabilities of urban runoff were studied.

5.1 Conclusions and Recommendations Regarding Physical and Mechanical Properties of PC and GAC-Containing PC

In the first part of this research, PC samples (plain PC, PC with 5% and 10% carbon to cementitious ratio) were produced. They were tested for compressive strength, tensile strength, porosity and permeability. Some variation in curing temperatures and direction of the samples, in compression tests, imply that direct comparison between and within mixtures should be made cautiously; however, valuable insight was reached on attainable properties of the various PC mixtures. For all mixtures, 28-day compressive strength fell within typical literature compressive strength ranges. The highest strength was for plain PC, followed by the 5% and then 10% mixtures. Tensile strength also fell within a reported literature range and the same strength trend was found between mixtures. The porosity, or percent void, values again were well within expected ranges but no trend with mixtures was found. Finally, permeability values were only reported for the plain and 5% PC; again, they were in line with anticipated values.

The following recommendations can be made to improve the measurements of the mechanical and physical property effects of GAC incorporation in PC. Additional testing with more stringent control of variables would be beneficial. It is quite likely that the same trends of strength decrease with increased GAC content would occur, but there would be higher confidence in the results. The same would apply for compressive strength variations over time, within mixes. Additionally, although the results of the various tests appear typical for pervious concrete, different applications have different requirements. In the case where a compressive strength is required that was not reached by the 10% PC, additional research could prove valuable for improving the strength characteristics of GAC-containing PC. For example, mixtures containing GAC could also be studied with small amounts of fine aggregates, fiber or increased/decreased water content to try to improve their strength characteristics.

5.2 Conclusions and Recommendations Regarding Urban Runoff Treatment Capabilities of Regular and GAC-Containing PC

The second part of this research considered the treatment of synthetic runoff water using slabs produced form the three types of PC mixtures. The following conclusions were drawn:

1) All mixtures tested were found overall to significantly reduce contaminants such as copper, zinc, lead and total phosphorus (although some algal growth must be considered).
2) The overall pH of the effluent from all mixtures was determined to be significantly higher than that of the influent.
3) It is proposed that the high pH led to precipitation of the aforementioned elements, and that this mostly took place within the concrete matrix. Other mechanisms, however, such as adsorption, absorption, and specific retention are also possible alternatives.

4) There was no statistically significant change in COD (acetate) concentrations between overall influent and effluent waters, showing that no mechanism was available for the removal of this contaminant. This result seems to indicate that the GAC could very well have been covered by aggregates and/or cementitious materials to the extent that it was unavailable for contaminant sorption.
5) There was not found to be a statistically significant difference in overall treatment results among the three mixtures for any of the runoff parameters that were analyzed.
6) There was not found to be a statistically significant difference in overall treatment results for any of the parameters that were analyzed when plain PC was compared to all GAC-containing PC.
7) All effluent samples of plain PC, when subjected to RO water, contained detectable levels of such elements as Pb and Ba and some were found to contain elements such as Cr and Se.
8) In a limited comparison, overall effluents from plain PC receiving synthetic runoff vs. RO water were found to differ significantly in the concentration of Ca and Si. Those elements were not added to the synthetic runoff. Possible pH differences in the influent may have played a role: lower pH is thought to have leached more Ca from the PC and higher pH to have leached more silica.
9) From an indirect analysis of effluent precipitates, it was concluded that Ca followed by Si were major components of those precipitates. Pb also appeared to have been present.

There were some difficulties encountered during this work. The collection method utilized did not prove suitable for dependable oil measurements since on at least one occasion some of the oil was found to stick to the sample collection container. Additionally, COD analysis which was used for effluent oil concentration measurements was not known to reliably measure waste oil of unknown composition. Effluent TSS concentrations were only determined qualitatively since the attempted filtration and weighing did not prove successful. It is proposed that this was a result of very low concentrations of TSS. Nitrate testing also did not seem to yield reliable results. Nonetheless, a series of conclusions have been drawn on the effects of the various PC mixtures on runoff treatment and on other related issues.

The following is recommended for future studies. In order to obtain more comprehensive results on the runoff treatment by the PC mixtures, it would be important to establish a more effective sampling method for oil and to utilize more suitable testing methods for effluent oil concentrations. TSS could potentially be analyzed well by filtration and weighing; however, a considerable volume of water should be used to either increase the mass of the filtered solids, or to increase the confidence in negligible results. Calibration of the spectrophotometric method for the specific solids could also improve confidence in those results. Nitrate testing that is reliable at concentrations well below 1 mg/L is also important. Since many of the treatment effects are thought to have been caused by increased effluent pH, additional testing concerning the longevity of that effect is recommended. Exposing the PC samples to longer periods of testing with an increased number of analyzed samples could also provide valuable insight into expected contaminant breakthrough times and possible variations, over time, in treatment effect by mixture. Since it is considered to be highly likely that the concrete mixture itself was an impediment to GAC's contaminant treatment properties, it is highly recommended that research be undertaken that considers various other methods of GAC incorporation or utilization with pervious concrete systems.

Although this research did not show any benefits related to GAC incorporation in PC, it should provide some framework for future research. Preliminary studies on the researched combination of GAC/PC materials have been performed on their physical and mechanical properties. Water treatment tests for the combined GAC/PC in the given configuration have been presented. The prospect of decreasing urban runoff and simultaneously trapping contaminants seems to warrant further investigation and it is still possible that utilizing GAC in a different manner may prove much more effective.

5.3 Implications

Although this research did not appear to lead to improved PC runoff treatment characteristics, further work on GAC incorporation or inclusion in PC may prove quite beneficial. A material that can decrease runoff and runoff pollution simultaneously could have a multitude of applications.

If the permeability rates of the researched samples of >13 gpm/ft^2 (>1250 in/hr or 2.78×10^5 m/yr) are close to reliable, pervious concrete would be more than adequate for any imaginable rainfall and would also be able to handle significant amounts of runoff flowing from other areas. Flowrates could very well be limited by the soil permeability beneath the PC. Permeability rates for soils can range from $1 \times 10^4 - 1 \times 10^7$ m/yr for gravels down to $1 \times 10^{-5} - 1 \times 10^{-2}$ m/yr for unweathered marine clay (Hydraulic Conductivity, n.d.). Aggregate subgrades are known to help in this regard but flowrate/volume limits could still be expected. In such cases, PC may only infiltrate some or all of the first flush of stormwater, with subsequent water running off the surface “untreated.”

One of the most obvious uses for modified pervious concrete would be as a paving surface for parking lots. Another possible use would be to place pervious concrete along the sides of roads where gutters are typically located. This would allow infiltration, depending on subgrade and soil permeability. In this case, concerns about introducing water into or near the foundations of roads must be noted (Ten Essentials of a Good Road, 2008).

One method of use for modified pervious concrete which seems to provide many advantages and few disadvantages would be to surround stormwater drop inlets (along the sides of roads) with pervious concrete areas. The concept here is that the runoff flowing in gutters along the roadside would reach the PC and flow through it, before reaching a lowered drop inlet. The PC could be placed over regular concrete, thereby increasing its strength and minimizing infiltration into or near the foundation of the road. In this case, only small amounts of PC would be needed to surround drop inlets. Infiltration beneath the roads should not be of concern and if the PC becomes saturated with contaminants, it should be relatively simple to replace compared to larger areas. Such systems could potentially provide filtration to some or all of the water that enters storm drains.

Clearly, it was found that pervious concrete is expected to be a very useful tool for runoff control and treatment, but further testing, possibly with GAC, could improve it in that regard. Improvements on COD removal and investigations on the removal of such contaminants as pesticides and nitrate could give it increased appeal. Such PC could be better used for applications where runoff control and treatment are desired as well as where only treatment and not infiltration is the objective.

APPENDICES

Appendix A

Additional Properties and Experimental Procedures

Table A-1 Properties of GAC (from Calgon Carbon[a])

Specification	**Filtrasorb 400**
Iodine Number	1000 mg/g (min)
Moisture by Weight	2% (max)
Effevtive Size	0.55 - 0.75 mm
Uniformity Coefficient	1.9 (max)
Abrasion Number	75 (min)
Screen Size by Weight, US Sieve Series	
On 12 mesh	5% (max)
Through 40 mesh	4% (max)

Typical Properties*	**Filtrasorb 400**
Apparent Density	0.54 g/cc
Water Extractables	<1%
Non-Wettable	<1%
*For general information only, not to be used as purchase specifications.	

[a] Calgon Carbon (2012)

A-1 GAC Water Sorption Testing

When GAC is added to a concrete mix, it sorbs water from the mixture and can cause it to become very dry. To alleviate this problem, additional water was added to the mixtures that contained GAC. It was important to have some rough idea of the amount of water that GAC might sorb. In order to determine this value, a test was performed to calculate the amount of water retained in GAC in approximately SSD conditions. The process used to determine these conditions was as follows:

1. Filtrasorb 400 activated carbon, from the Calgon Carbon Corporation (the GAC used) was rinsed many times to remove possible oil and/or other impurities from the manufacturing process. The GAC was then placed in the oven at roughly 105-106° C for approximately 24 hours.
2. An amount of the dried GAC was weighed.
3. The GAC was placed in a beaker, covered with water; then the beaker was covered.
4. The next day, the carbon was shaken and stirred to release bubbles that were trapped, and allowed to sit. The GAC was then "dried" using paper towels and tediously transferring the GAC between paper towels. At the end, the GAC no longer really stuck to the paper towels as it did when soaked with water.
5. The GAC was weighed once more in this "SSD" condition.

GAC water sorption results. As per step 2 from A-1, GAC Water Sorption Testing, the initial amount of dried GAC weighed was 26.3 g. After soaking and drying with paper towels (steps 3 and 4), the GAC was again weighed, Figures A-1 and A-2. The resulting SSD weight was 40.7 g. From this it was concluded that GAC is capable of retaining approximately 54.8% of its weight in water. It is important to mention that this result could be approximate. A certain amount of carbon was left behind before the final weighing and extra water/particles may have been transferred while attempting to collect some of the remaining carbon. However, a value of 55% should be of sufficient accuracy and is the amount of extra water that was added in concrete mixtures containing GAC. As an example, if 100 g of GAC are added to a given mix, 55 g of additional water (above the normal water/cement ratio) would also be added.

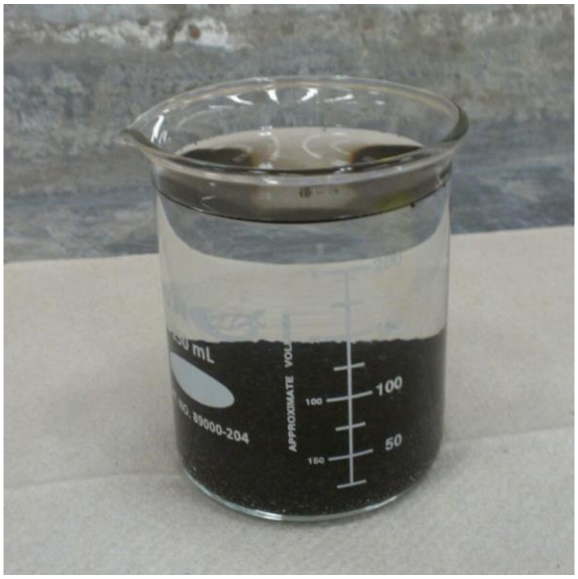


Figure A-1: GAC soaking in beaker

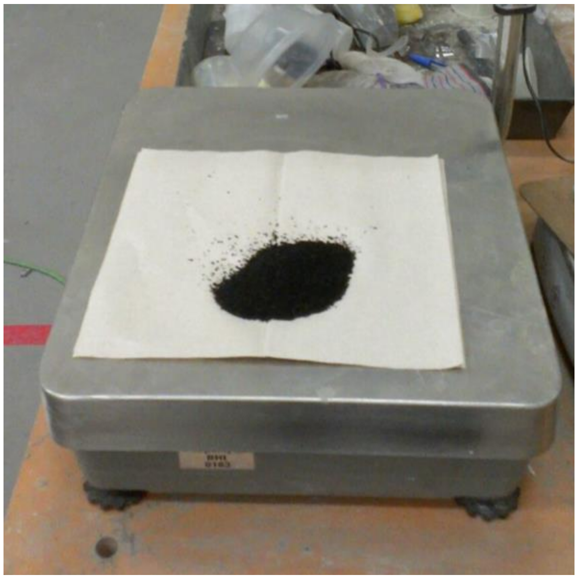


Figure A-2: GAC in "SSD" condition

A-2 Concrete Mixing Procedures

In the following section, the mixing procedures for the various concrete mixtures are described. Each of the 6 mixtures will be presented in this way. The raw data for those mixtures were presented in Table 3.3.

Mixture 1: plain slabs (Sep. 20 2012). The following procedure was used to mix the components:

- Added coarse aggregate + ≈ 1/3 of water and mixed for ≈ 4 min
- Added cement + fly ash + ≈1/3 of water and mixed for ≈ 9 min (the final ≈1/3 of water was added during the first 3 min of the 9 min).

Mixing was stopped several times to crush lumps that were present. When the concrete was placed in the mold, remaining large lumps were avoided. Most were crushed and returned to the batch, some were simply discarded.

Mixture 2: 10% carbon/cementitious slabs, (Sep. 25, 2012). The following procedure was used to mix the components:

- Added coarse aggregate + ≈ 1/3 of water and mixed for ≈ 4 min
- Added cement + fly ash + ≈1/3 of water and mixed for ≈ 7 min (the final ≈1/3 of water was added during the first 3 min of the 7 min)
- Added Granular Activated Carbon (GAC) and mixed for ≈ 3 min

Again, mixing was stopped several times to crush lumps. One and two half lumps were discarded and some were returned to the batch.

Mixture 3: 5% carbon/cementitious slabs (Oct. 4, 2012). The following procedure was used to mix the components:

- Added coarse aggregate + ≈ 1/3 of water and mixed
- Added cement + fly ash + ≈1/3 of water and mixed for ≈ 7 min (the final ≈1/3 of water was added during the first 3 min of the 7 min)
- Added GAC and mixed for ≈ 2 min

Mixing was stopped several times to crush lumps in the mixture. There appeared to be less (perhaps smaller) lumps in this mixture. The remaining lumps were either removed, crushed and returned to the batch, crushed in the mold, or left.

Mixture 4: plain cylinders (Nov. 20, 2012). The following procedure was used to mix the components:

- Added coarse aggregate + ≈ 1/3 of water and mixed for ≈ 4 min
- Added cement + fly ash + ≈1/3 of water and mixed for ≈ 9 min (the final ≈1/3 of water was added during the first 3 min of the 9 min)

Mixing was stopped several times to crush lumps in the mixture. When the concrete was placed in the molds, efforts were made to avoid lumps, many lumps were removed (many of these returned to the batch and some were discarded). A few were crushed in the mix, attempts were made to remove them, but some lumps did end up in the molds.

Mixture 5: 10% cylinders (Dec. 12, 2012). The following procedure was used to mix the components:

- Added coarse aggregate + ≈ 1/3 of water and mixed for ≈ 4 min
- Added cement + fly ash + ≈1/3 of water and mixed for ≈ 7 min (the final ≈1/3 of water was added during the first 3 min of the 7 min. mostly early)
- Added GAC and mixed for ≈ 3 min

In this mix, fewer lumps were observed. Mixing was stopped two or three times to crush lumps before the carbon was added. Once the GAC was added, a lot of the mixture seemed to stick to the back of the mixer. This was poked off a few times with the steel rod. There were not many lumps in the end, but efforts were made to remove or return to the mixture some of them. Some of these lumps may have been larger aggregates.

Mixture 6: 5% carbon/cylinders (Jan. 23, 2013). The following procedure was used to mix the components:

- Added coarse aggregate + ≈ 1/3 of water and mixed for ≈ 4 min
- Added cement + fly ash + ≈1/3 of water and mixed for ≈ 7 min (the final ≈1/3 of water was added during the first 3 min of the 7 min)
- Added GAC and mixed for ≈ 2 min

Mixing was stopped several times to crush lumps in the mixture. Efforts were made to avoid placing lumps in the molds. Many were crushed and returned to the batch, a few small ones were removed and some probably ended up in the molds.

A-3 Saturated Surface Dry (SSD) Conditions

In order to achieve a relatively consistent moisture content close to SSD conditions for the concrete cylinders, a methodology was formulated and used. This methodology consisted of the following steps:

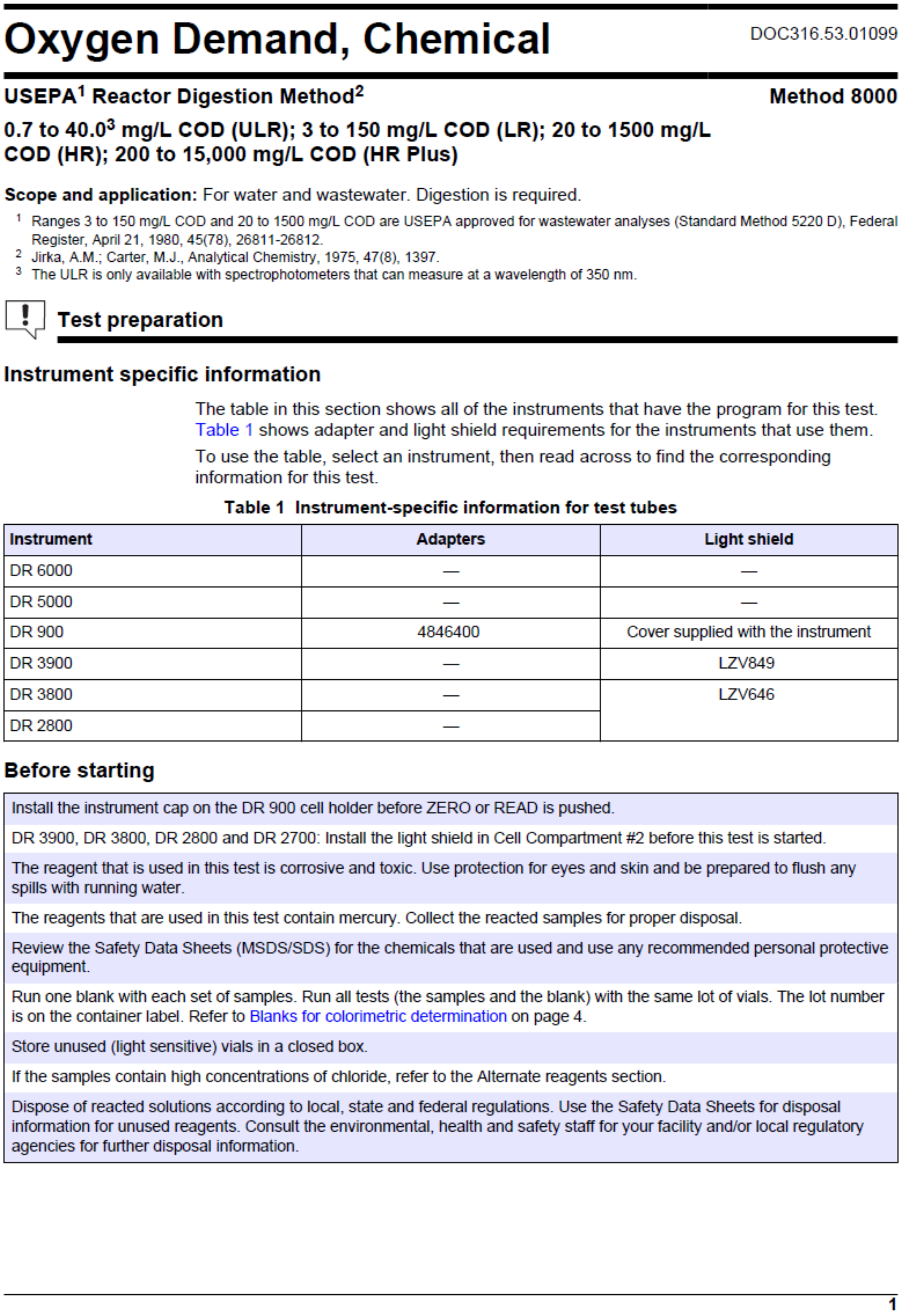
1. The concrete specimens, (4” X 8”) cylinders were removed from immersion in water, and held up in the air for roughly 2 minutes while they dripped.
2. The samples were then placed in a tray on layers of paper towels for 30 minutes.
3. Some samples were then patted dry with paper towels, with the goal of removing residual water on the face of the samples in contact with the paper towels. This step likely had minimal impact and was not always done.

This procedure was used for samples prior to the porosity and permeability tests. It was considered appropriate, because for the porosity test, it was not desired to consider the water absorbed by the cement or aggregates as void volume. For permeability, the absorption may have had some minimal and also undesired effect on the rate of percolation through the concrete samples. On the other hand, excess water would have had the opposite impact on both of those tests.

Table A-2 Hach analytical methods

Constituent	Method	Information	Link	Pages
COD	8000	USEPA Reactor Digestion 0.7 to 40.0 mg/L COD (ULR); 3 to 150 mg/L COD (LR); 20 to 1500 mg/L COD (HR); 200 to 15,000 mg/L COD (HR Plus)	http://www.hach.com/wah	10
Copper	8143	Porphyrin Method 1 to 210 µg/L Cu (LR)	http://www.hach.com/wah	6
Phosphorus, Reactive (Orthophosphate)	8048	USEPA PhosVer 3® (Ascorbic Acid) Method 0.02 to 2.50 mg/L PO_4^{3-}	http://www.hach.com/wah	8
Zinc	8009	USEPA Zincon Method 0.01 to 3.00 mg/L Zn	http://www.hach.com/wah	6
Suspended Solids	8006	Photometric Method 5 to 750 mg/L TSS	http://www.hach.com/wah	4
Nitrate	8192	Cadmium Reduction Method 0.01 to 0.50 mg/L NO_3^- –N (LR)	http://www.hach.com/wah	8
Nitrate, MR	8171	Cadmium Reduction Method 0.1 to 10.0 mg/L NO_3^-–N (MR, spectrophotometers) 0.2 to 5.0 mg/L NO_3^-–N (MR, colorimeters)	http://www.hach.com/wah	8

A-4 Example Hach Method (from http://www.hach.com/wah)



Oxygen Demand, Chemical

DOC316.53.01099

USEPA[1] Reactor Digestion Method[2]

Method 8000

0.7 to 40.0[3] mg/L COD (ULR); 3 to 150 mg/L COD (LR); 20 to 1500 mg/L COD (HR); 200 to 15,000 mg/L COD (HR Plus)

Scope and application: For water and wastewater. Digestion is required.

[1] Ranges 3 to 150 mg/L COD and 20 to 1500 mg/L COD are USEPA approved for wastewater analyses (Standard Method 5220 D), Federal Register, April 21, 1980, 45(78), 26811-26812.
[2] Jirka, A.M.; Carter, M.J., Analytical Chemistry, 1975, 47(8), 1397.
[3] The ULR is only available with spectrophotometers that can measure at a wavelength of 350 nm.

Test preparation

Instrument specific information

The table in this section shows all of the instruments that have the program for this test. Table 1 shows adapter and light shield requirements for the instruments that use them.

To use the table, select an instrument, then read across to find the corresponding information for this test.

Table 1 Instrument-specific information for test tubes

Instrument	Adapters	Light shield
DR 6000	—	—
DR 5000	—	—
DR 900	4846400	Cover supplied with the instrument
DR 3900	—	LZV849
DR 3800	—	LZV646
DR 2800	—	

Before starting

Install the instrument cap on the DR 900 cell holder before ZERO or READ is pushed.
DR 3900, DR 3800, DR 2800 and DR 2700: Install the light shield in Cell Compartment #2 before this test is started.
The reagent that is used in this test is corrosive and toxic. Use protection for eyes and skin and be prepared to flush any spills with running water.
The reagents that are used in this test contain mercury. Collect the reacted samples for proper disposal.
Review the Safety Data Sheets (MSDS/SDS) for the chemicals that are used and use any recommended personal protective equipment.
Run one blank with each set of samples. Run all tests (the samples and the blank) with the same lot of vials. The lot number is on the container label. Refer to Blanks for colorimetric determination on page 4.
Store unused (light sensitive) vials in a closed box.
If the samples contain high concentrations of chloride, refer to the Alternate reagents section.
Dispose of reacted solutions according to local, state and federal regulations. Use the Safety Data Sheets for disposal information for unused reagents. Consult the environmental, health and safety staff for your facility and/or local regulatory agencies for further disposal information.

Items to collect

Description	Quantity
Beaker, 250-mL	1
Blender	1
COD Digestion Reagent vials	varies
DRB200 Reactor	1
Light shield or adapter (For information about sample cells, adapters or light shields, refer to Instrument specific information on page 1.)	1
Magnetic stirrer and stir bar	1
Opaque shipping container for storage of unused, light-sensitive reagent vials	varies
Pipet, TenSette, 0.1- to 1.0-mL, with pipet tips (for use with the 200–15,000 mg/L range)	1
Pipet, volumetric, 2.00-mL	2
Pipet filler safety bulb	1
Test tube rack	2

Refer to Consumables and replacement items on page 7 for reorder information.

Sample collection and storage

- Collect samples in clean glass bottles. Use plastic bottles only if they are known to be free of organic contamination.
- Test biologically active samples as soon as possible.
- Homogenize samples that contain solids to get a representative sample.
- To preserve samples for later analysis, adjust the sample pH to less than 2 with concentrated sulfuric acid (about 2 mL per liter). No acid addition is necessary if the sample is tested immediately.
- Keep the preserved samples at or below 6 °C (43 °F) for up to 28 days.
- Correct the test result for the dilution from the volume additions.

Reactor digestion procedure

1. Put 100 mL of sample in a blender. Blend for 30 seconds or until homogenized.

For samples with large amounts of solids, increase the homogenization time. If the sample does not contain suspended solids, omit steps 1 and 2.

2. For the 200–15,000 mg/L range or to improve accuracy and reproducibility of the other ranges, pour the homogenized sample into a 250-mL beaker and gently stir with a magnetic stir plate.

3. Set the DRB200 Reactor power to on. Preheat to 150 °C.

Refer to the DRB200 User Manual for selecting pre-programmed temperature applications.

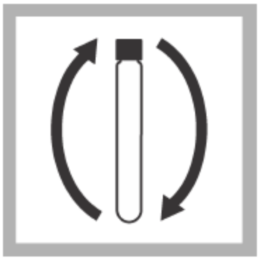
4. Prepare the sample: Remove the cap from a vial for the selected range. Hold the vial at an angle of 45 degrees. Use a clean pipet to add 2.00 mL of sample to the vial.

For 250–15,000 mg/L vials: Use a TenSette Pipet to add 0.20 mL of sample to the vial.

5. Prepare the blank: Remove the cap from a second vial for the selected range. Hold the vial at an angle of 45 degrees. Use a clean pipet to add 2.00 mL of deionized water to the vial.

For 250–15,000 mg/L vials: Use a TenSette Pipet to add 0.20 mL of deionized water to the vial.

6. Close the vials tightly. Rinse the vials with water and wipe with a clean paper towel.

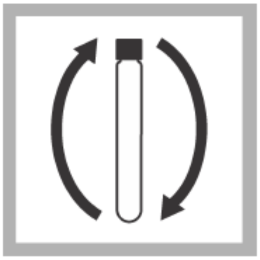


7. Hold the vials by the cap, over a sink. Invert gently several times to mix. **The vials get very hot during mixing.**

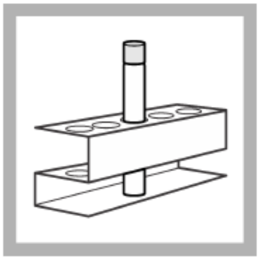
8. Put the vials in the preheated DRB200 reactor. Close the lid.

9. Heat the vials for 2 hours.

10. Set the reactor power to off. Let the vials cool in the reactor for about 20 minutes. The vials should cool to 120 °C or less.

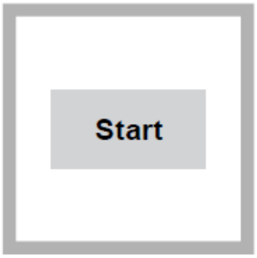


11. Invert each vial several times while it is still warm.



12. Put the vials in a tube rack to cool to room temperature.

Colorimetric procedure

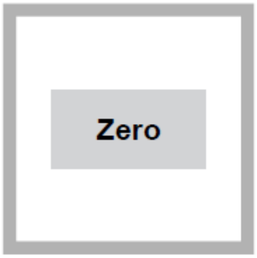


1. Start program **431 COD ULR**, **430 COD LR** or **435 COD HR**. For information about sample cells, adapters or light shields, refer to Instrument specific information on page 1.

Note: *Although the program name may vary between instruments, the program number does not change.*

2. Clean the blank.

3. Insert the blank into the cell holder.



4. Push **ZERO**. The display shows 0 or 0.0 mg/L COD.

5. Clean the prepared sample.

6. Insert the prepared sample into the cell holder.

7. Push **READ**. Results show in mg/L COD.

8. If using High Range Plus COD digestion reagent vials, multiply the result by 10. For the most accurate results with samples near 1500 or 15,000 mg/L COD, repeat the analysis with a diluted sample.

Blanks for colorimetric determination

The blank vial can be used again and again for measurements that use the same lot of reagent vials. Measure the absorbance of the blank vial over time and prepare a new blank vial when the absorbance changes.

1. Put the instrument in the absorbance mode at the applicable wavelength. Refer to Table 3 on page 7.
2. Add 5 mL of deionized water into an empty vial.
3. Put the vial in the instrument and zero the instrument.
4. Put the blank vial that is used in the test procedure into the instrument and record the absorbance value.
5. Keep the blank vial in the dark.
6. Prepare a new blank when the absorbance has changed by approximately 0.01 absorbance units.

Interferences

Chloride is the primary interference in this test procedure. Each COD vial contains mercuric sulfate that removes chloride interference to the level specified in Column 1 of Table 2. Dilute samples that have higher chloride concentrations to the level given in Column 2.

***Note:** For best results, use the low range and ultra-low range vials for samples that have high chloride concentrations (near maximum concentration) and low COD concentrations.*

If sample dilution causes the COD concentration to be too low for accurate measurements, add 0.50 g of mercuric sulfate ($HgSO_4$) to each COD vial before the sample is added. The additional mercuric sulfate will increase the maximum chloride concentration to the level given in Column 3.

***Note:** Bromide interference is not removed with mercuric sulfate.*

Table 2 Chloride concentration limits in the sample

Vial range	Column 1 (maximum mg/L Cl^-)	Column 2 (mg/L Cl^- for diluted samples)	Column 3 (maximum mg/L Cl^- with mercuric sulfate)
ULR[1] (0.7–40.0 mg/L)	2000	1000	N/A
LR (3–150 mg/L)	2000	1000	8000
HR (20–1500 mg/L)	2000	1000	4000
HR Plus (200–15,000 mg/L)	20,000	10,000	40,000

[1] The ULR is only available for spectrophotometers that can measure at a wavelength of 350 nm.

Accuracy check

Standard solution method

Items to collect:

- 1000 mg/L COD standard solution
- 100-mL volumetric flask, Class A
- Volumetric pipets, Class A and pipet filler
- Deionized water
- Potassium acid phthalate (KHP), dried overnight at 120 °C (HR Plus only)

0.7 to 40.0 mg/L ULR

1. Prepare a 30-mg/L COD standard solution as follows:
    a. Use a pipet to add 3.00 mL of the 1000 mg/L standard solution into a 100-mL volumetric flask.
    b. Dilute to the mark with deionized water. Mix well.
2. Use the test procedure to measure the concentration of the standard solution.
3. Compare the expected result to the actual result.
   ***Note:** The factory calibration can be adjusted slightly with the standard adjust option so that the instrument shows the expected value of the standard solution. The adjusted calibration is then used for all test results. This adjustment can increase the test accuracy when there are slight variations in the reagents or instruments.*

3 to 150 mg/L LR

1. Prepare a 100-mg/L COD standard solution as follows:
    - **a.** Use a pipet to add 10 mL of the 1000 mg/L standard solution into a 100-mL volumetric flask.
    - **b.** Dilute to the mark with deionized water. Mix well.
2. Use the test procedure to measure the concentration of the standard solution.
3. Compare the expected result to the actual result.
Note: The factory calibration can be adjusted slightly with the standard adjust option so that the instrument shows the expected value of the standard solution. The adjusted calibration is then used for all test results. This adjustment can increase the test accuracy when there are slight variations in the reagents or instruments.

20 to 1500 mg/L HR

1. Use the test procedure with a 300-mg/L, 800 mg/L or 1000 mg/L COD standard solution to measure the concentration of the standard solution.
2. Compare the expected result to the actual result.
Note: The factory calibration can be adjusted slightly with the standard adjust option so that the instrument shows the expected value of the standard solution. The adjusted calibration is then used for all test results. This adjustment can increase the test accuracy when there are slight variations in the reagents or instruments.

200 to 15,000 mg/L HR Plus

1. Prepare a 10,000 mg/L COD standard solution as follows:
    - **a.** Dissolve 8.500 g of dried KHP in 1000-mL of organic-free deionized water.
2. Use the test procedure to measure the concentration of the standard solution.
3. Compare the expected result to the actual result.
Note: The factory calibration can be adjusted slightly with the standard adjust option so that the instrument shows the expected value of the standard solution. The adjusted calibration is then used for all test results. This adjustment can increase the test accuracy when there are slight variations in the reagents or instruments.

Alternate reagents

Mercury-free COD2 Reagents are available as a mercury-free alternative. These reagents are fully compatible with test procedures and stored programs in the instruments. Chloride and ammonia determinations are recommended for accurate results.

NOTICE

COD2 reagents are not approved for USEPA reporting purposes. Because COD2 reagents do not contain mercury as a masking agent, they exhibit a positive interference from chloride. More information is available for use with specific applications.

Method performance

The method performance data that follows was derived from laboratory tests that were measured on a spectrophotometer during ideal test conditions. Users may get different results under different test conditions.

Program	Standard	Precision (95% Confidence Interval)	Sensitivity Concentration change per 0.010 Abs change
431 (ULR)	30 mg/L COD	28.8–31.2 mg/L COD	0.5 mg/L COD
430 (LR)	80 mg/L COD	77–83 mg/L COD	3 mg/L COD
435 (HR)	800 mg/L COD	785–815 mg/L COD	23 mg/L COD
435 (HR Plus)	8000 mg/L COD	7850–8150 mg/L COD	230 mg/L COD

Summary of method

The results in mg/L COD are defined as the milligrams of O_2 consumed per liter of sample under the conditions of this procedure. The sample is heated for 2 hours with sulfuric acid and a strong oxidizing agent, potassium dichromate. Oxidizable organic compounds react, reducing the dichromate ion ($Cr_2O_7^{2-}$) to green chromic ion (Cr^{3+}).

When the 0.7–40.0 or the 3–150 mg/L colorimetric method is used, the amount of Cr^{6+} that remains is measured. When the 20–1500 mg/L or 200–15,000 mg/L colorimetric method is used, the amount of Cr^{3+} that is produced is measured. The COD reagent also contains silver and mercury ions. Silver is a catalyst, and mercury is used to complex chloride interferences.

Test results are measured at the wavelengths that are specified in Table 3.

Table 3 Range-specific test wavelengths

Range in mg/L COD	Wavelength
0.7 to 40.0 mg/L	350 nm (for applicable instruments)
3 to 150 mg/L	420 nm
20 to 1500	620 nm (610 nm for colorimeters)
2000 to 15,000 mg/L	620 nm (610 nm for colorimeters)

Pollution prevention and waste management

Reacted samples contain mercury, silver and chromium and must be disposed of as a hazardous waste. Dispose of reacted solutions according to local, state and federal regulations. Users in the United States can use the ez COD Recycling Service for disposal of COD vials. Refer to Consumables and replacement items on page 7.

Consumables and replacement items

Required reagents

Description	Quantity/test	Unit	Item no.
COD, Ultra Low Range, 0.7 to 40 mg/L	1-2 vials	25/pkg	2415825
COD, Low Range, 3 to 150 mg/L	1-2 vials	25/pkg	2125825
COD, High Range, 20 to 1500 mg/L	1-2 vials	25/pkg	2125925
COD, High Range Plus, 200 to 15,000 mg/L	1-2 vials	25/pkg	2415925
Water, deionized	varies	4 L	27256

Alternate reagents and package sizes

Description	Quantity/test	Unit	Item no.
COD2, Low Range, 0 to 150 mg/L COD	1-2 vials	25/pkg	2565025
COD2, High Range, 0 to 1500 mg/L COD	1-2 vials	25/pkg	2565125
COD2, High Range, 0 to 1500 mg/L COD	1-2 vials	150/pkg	2565115
COD2, High Range Plus, 0 to 15,000 mg/L COD	1-2 vials	25/pkg	2834325
COD Digestion Reagent Vials, 3 to 150 mg/L COD	1-2 vials	150/pkg	2125815
COD Digestion Reagent Vials, 200 to 1500 mg/L COD	1-2 vials	150/pkg	2125915
COD Digestion Reagent Vials, ULR 0.7-40.0 mg/L	1-2 vials	150/pkg	2415815
COD Digestion Reagent Vials, HR plus,200-25,000 mg/L	1-2 vials	150/pkg	2415915

Required apparatus

Description	Quantity/test	Unit	Item no.
Blender, 2-speed, 120 VAC	1	each	2616100
OR			
Blender, 2-speed, 240 VAC	1	each	2616102
DRB200 Reactor, 110 V, 15 x 16 mm	1	each	LTV082.53.40001
OR			
DRB200 Reactor, 220 V, 15 x 16 mm	1	each	LTV082.52.40001
Pipet filler, safety bulb	1	each	1465100
Pipet, volumetric, Class A, 2.00-mL	1	each	1451536

Recommended standards and apparatus

Description	Unit	Item no.
Beaker, 250-mL	each	50046H
COD Standard Solution, 300-mg/L	200 mL	1218629
COD Standard Solution, 300-mg/L	500mL	1218649
COD Standard Solution, 800-mg/L	200 mL	2672629
COD Standard Solution, 1000-mg/L	200 mL	2253929
Oxygen Demand Standard (BOD, COD, TOC), 10-mL ampules	16/pkg	2833510
Pipet, TenSette®, 0.1–1.0 mL	each	1970001
Pipet tips for TenSette Pipet 1970001	50/pkg	2185696
Pipet tips for TenSette Pipet 1970001	1000/pkg	2185628
Potassium Acid Phthalate, ACS	500 g	31534
Stir bar, octagonal	each	2095352
Stirrer, electromagnetic, 120 VAC, with electrode stand	each	4530001
Stirrer, electromagnetic, 230 VAC, with electrode stand	each	4530002
Test tube rack	each	1864100
Wipes, disposable	70/pkg	2096900

Optional reagents and apparatus

Description	Unit	Item no.
Balance, analytical, 80 g x 0.1 mg 100-240 VAC	each	2936701
Flask, volumetric, Class A, 1000-mL	each	1457453
Flask, volumetric, Class A, 100-mL	each	1457442
Mercuric Sulfate	28 g	191520
Pipet, volumetric, Class A, 3-mL	each	1451503
Pipet, volumetric, Class A, 10-mL	each	1451538
Sulfuric Acid, ACS	500 mL	97949
Wastewater Influent Standard, Mixed Parameter, for NH_3-N, NO_3-N, PO_4, COD, SO_4, TOC	500 mL	2833149

Consumables and replacement items (continued)

Description	Unit	Item no.
EZ COD™ Recycling Service with 5-gal bucket-mail back option (For US customers only. 20 and 55 gallon sizes are also available.)	each	2895405
EZ COD™ Recycling Service with 5-gal bucket- pick up option. (For US customers only. 20 and 55 gallon sizes are also available.)	each	2895405P
Finger cots	2/pkg	1464702
Gloves, chemical resistant, size 9-9.5	pair	2410104[1]
Paper, for weighing, 100 x 100 mm	500/pkg	1473885
Safety goggles, vented	each	2550700
Wastewater, Effluent Inorganics, for NH_3-N, NO_3-N, PO_4, COD, SO_4, TOC	500 mL	2833249

[1] Other sizes available

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04/2013, Edition 8

Appendix B

Experimental Data Tables

Table B-1 Raw data from concrete compression tests

carbon/ cementitious	side of sample on top during test	Test	dia (in)	dia (in)	load (lb)	avg. dia (in)	avg. radius (in)	Area (in^2)	psi
0	Uncertain	3-day	4.0328	4.0425	15,620	4.0377	2.0188	12.8040	1220
0	Uncertain	3-day	4.0455	4.0389	18,250	4.0422	2.0211	12.8329	1422
0	Uncertain	3-day	4.0337	4.0538	15,510	4.0438	2.0219	12.8428	1208
0	Uncertain	3-day	4.0457	4.0419	18260	4.0438	2.0219	12.8431	1422
0	Uncertain	7-day	4.0252	4.0412	16,920	4.0332	2.0166	12.7758	1324
0	Bot	7-day	4.0479	4.0423	17,800	4.0451	2.0226	12.8513	1385
0	Bot	7-day	4.0389	4.0288	21,680	4.0339	2.0169	12.7800	1696
0	Top	28-day	4.0484	4.0391	21,340	4.0438	2.0219	12.8428	1662
0	Top	28-day	4.0479	4.0368	19,740	4.0424	2.0212	12.8339	1538
0	Bot	28-day	4.0673	4.0182	20420	4.0428	2.0214	12.8364	1591
0.05	Top	3-day	4.0311	4.0468	13,890	4.0390	2.0195	12.8123	1084
0.05	Top	3-day	4.0162	4.0361	12,090	4.0262	2.0131	12.7312	950
0.05	Top	3-day	4.0232	4.0386	13,490	4.0309	2.0155	12.7613	1057
0.05	Top	3-day	4.0305	4.0414	14000	4.0360	2.0180	12.7933	1094
0.05	Top	7-day	4.025	4.0349	14,740	4.0300	2.0150	12.7553	1156
0.05	Top	7-day	4.0316	4.0316	17,550	4.0316	2.0158	12.7657	1375
0.05	Top	7-day	4.0363	4.0326	16,550	4.0345	2.0172	12.7838	1295
0.05	Top	28-day	4.053	4.0209	19,300	4.0370	2.0185	12.7996	1508
0.05	Top	28-day	4.0211	4.0437	18,900	4.0324	2.0162	12.7708	1480
0.1	Top	3-day	4.0261	4.0372	13,020	4.0317	2.0158	12.7660	1020
0.1	Top	3-day	4.0391	4.0284	12,060	4.0338	2.0169	12.7793	944
0.1	Bot	3-day	4.0283	4.0269	10,870	4.0276	2.0138	12.7404	853
0.1	Uncertain	7-day	4.0459	4.0298	11,500	4.0379	2.0189	12.8053	898
0.1	Top	7-day	4.0296	4.0316	10,640	4.0306	2.0153	12.7594	834
0.1	Bot	7-day	4.0371	4.0361	12,930	4.0366	2.0183	12.7974	1010
0.1	Top	7-day	4.0249	4.0244	11,650	4.0247	2.0123	12.7217	916
0.1	Top	28-day	4.0301	4.0318	11,120	4.0310	2.0155	12.7616	871
0.1	Top	28-day	4.0397	4.0299	13,950	4.0348	2.0174	12.7860	1091
0.1	Top	28-day	4.0248	4.0424	15060	4.0336	2.0168	12.7784	1179

Table B-2 Raw data from 28-day concrete tension tests

Test Date	carbon/ cementitious	dia (in)	dia (in)	dia (in)	length (in)	length (in)	length (in)	load (lb)	Tensile stength (psi)
12/18/2012	0	4.042	4.0336	4.0373	7.96875	8.0125	7.9375	14260	282
	0	4.0322	4.0418	4.0382	8.075	8.05625	8.05625	15090	295
	0	4.0397	4.0297	4.0279	8.075	8.075	8.05625	15840	310
2/20/2013	0.05	4.0302	4.0339	4.0242	8	8.025	8	12,970	256
	0.05	4.027	4.0433	4.0396	8.0375	8.025	8.05625	13,500	265
	0.05	4.0422	4.0311	4.0247	8.025	7.975	8.0375	12,910	254
1/9/2013	0.1	4.0266	4.0289	4.0187	8.0375	8	7.96875	10,560	209
	0.1	4.0349	4.0287	4.0326	8.0375	8.05625	7.975	10,290	203
	0.1	4.0338	4.0208	4.0171	8.0125	8.025	8.025	10,250	202

Table B-3 Raw data from concrete porosity tests

	carbon/ cementitious	dia (in)	dia (in)	dia (in)	length (in)	length (in)	length (in)	H2O (lb)	avg. volume (ft^3)	volume H2O	% voids
12/13/2012	0	4.0398	4.0320	4.0300	8.0625	8.0625	8.0000	0.7565	0.0595	0.0121	20.4
	0	4.0340	4.0412	4.0340	8.0313	8.1063	8.0500	0.6870	0.0597	0.0110	18.5
	0	4.0274	4.0428	4.0379	8.0688	8.0938	8.0125	0.6870	0.0597	0.0110	18.5
2/18/2013	0.05	4.0399	4.0347	4.0421	8.0250	8.0313	7.9688	0.6850	0.0594	0.0110	18.5
	0.05	4.0382	4.0380	4.0208	8.0438	7.9688	8.0500	0.6670	0.0593	0.0107	18.1
	0.05	4.0348	4.0289	4.0356	7.9938	8.0750	8.0063	0.7085	0.0593	0.0114	19.2
1/8/2013	0.1	4.0287	4.0316	4.0220	8.0125	8.0563	8.0125	0.8185	0.0592	0.0131	22.2
	0.1	4.0152	4.0421	4.0273	8.0688	8.0375	8.0313	0.8010	0.0593	0.0129	21.7
	0.1	4.0129	4.0419	4.0203	8.0563	8.0125	8.0063	0.8335	0.0591	0.0134	22.6

Table B-4 Raw data from concrete permeability tests

	carbon/ cementitious	time (s)	volume (mL)	time (min)	volume (gal)	avg. area (in^2)	avg. area (ft^2)	rate (gal/(min*ft^2)
12/13/2012	0	6.03	800	0.101	0.211	12.780	0.089	23.7
	0	8.34	800	0.139	0.211	12.796	0.089	17.1
	0	7.94	800	0.132	0.211	12.794	0.089	18.0
2/18/2013	0.05	10.7	800	0.178	0.211	12.812	0.089	13.3
	0.05	10.88	800	0.181	0.211	12.770	0.089	13.1
	0.05	10.38	800	0.173	0.211	12.775	0.089	13.8
1/8/2013	0.1	7.69	800?	0.128	0.211	12.739	0.088	18.6
	0.1	7.34	800?	0.122	0.211	12.744	0.089	19.5
	0.1	6.81	800?	0.114	0.211	12.724	0.088	21.1

Appendix C

Water Quality Results

Table C-1 Plain PC influent and effluent water concentrations from runoff tests

Contaminant	Condition	Sample ID/ Item								
		P-A-1	P-A-2	P-A-3	P-B-1	P-B-2	P-B-3	P-1 avg.	P-2 avg.	P-3 avg.
Cu (µg/L)	I	15	15	**15**	9	10	9	12	12.5	12
	E	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Pb (µg/L)	I	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5
	E	1.7	4.6	10.2	13.3	< 1	8.3	7.5	< 2.8	9.25
Zn (µg/L)	I	170	170	**170**	170	150	150	170	160	160
	E	< 1	9.4	< 1	< 1	< 1	< 1	< 1	< 5.2	< 1
Oil (mg/L)	I	53	53	53	–	–	–	53	53	53
COD (mg/L)	E	20.5	11.67	8	–	–	–	20.5	11.667	8
COD (mg/L)	I	–	–	–	46	43.2	46	46	43.2	46
	E	–	–	–	46.2	43	47	46.2	43	47
pH	I	5.0 - 5.5	5.0 - 5.5	**5.0 - 5.5**	6.1	5.83	6.09	5.675	5.54	5.67
	E	11 - 11.5	11.5 - 12	9.5 - 10	11.5 - 12	12.1	11.85	11.5	11.925	10.8
TP (mg/L)	I	0.32	0.31	**0.315**	0.3	0.3	0.31	0.31	0.305	0.3125
	E	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
TSS (mg/L)	I	78	78	78	78	78	78	78	78	78
	E (acidified)	–	–	–	< 5	< 5	< 5	< 5	< 5	< 5
	E(non-acidified)	–	–	–	35	122	100	35	122	100

Bold entries indicate values that were not tested, but averaged from the two other days of testing in the sequence.

I: Influent

E: Effluent

Table C-2 Five percent PC influent and effluent water concentrations from runoff tests

Contaminant	Condition	Sample ID/Item								
		5-A-1	5-A-2	5-A-3	5-B-1	5-B-2	5-B-3	5-1 avg.	5-2 avg.	5-3 avg.
Cu (μg/L)	I	10	10	10	9	10	9	9.5	10.0	9.5
	E	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Pb (μg/L)	I	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5
	E	15.9	12.0	5.5	9.4	13.5	< 1	12.7	12.8	3.3
Zn (μg/L)	I	140	160	150	170	150	150	155	155	150
	E	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Oil (mg/L)	I	53	53	53	–	–	–	53	53	53
COD (mg/L)	E	19.1	11.67	14.5	–	–	–	19.1	11.67	14.5
COD (mg/L)	I	–	–	–	46	43.2	46	46	43.2	46
	E	–	–	–	40.00	41.00	49.00	40.00	41.00	49.00
pH	I	5.0-5.0	5.0-5.0	5.0-5.0	6.1	5.83	6.09	5.675	5.54	5.67
	E	10-10.5	10-10.5	9.5-10.5	11.5-12	11.75	11.9	11	11	10.95
TP (mg/L)	I	0.31	0.33	0.3	0.3	0.3	0.31	0.31	0.32	0.31
	E	< 0.03	< 0.03	0.3613	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.1957
TSS (mg/L)	I	78	78	78	78	78	78	78	78	78
	E (acidified)	–	–	–	< 5	< 5	< 5	< 5	< 5	< 5
	E(non-acidified)	–	–	–	49	82	62	49	82	62

I: Influent

E: Effluent

Table C-3 Ten percent PC influent and effluent water concentrations from runoff tests

Contaminant	Condition	Sample ID/Item								
		10-A-1	10-A-2	10-A-3	10-B-1	10-B-2	10-B-3	10-1 avg.	10-2 avg.	10-3 avg.
Cu (µg/L)	I	15	15	**15**	9.5	11	12	12.3	13.0	13.5
	E	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Pb (µg/L)	I	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5
	E	< 1	1.4	1	13.8	5.6	< 1	< 7.4	3.5	< 1
Zn (µg/L)	I	170	170	**170**	140	160	170	155	165	170
	E	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Oil (mg/L)	I	53	53	53	–	–	–	53	53	53
COD (mg/L)	E	18	16.95	16	–	–	–	18	16.95	16
COD (mg/L)	I	–	–	–	44	47	48	44	47	48
	E	–	–	–	46	48	46	46	48	46
pH	I	5.0 - 5.5	5.0 - 5.5	**5.0 - 5.5**	5.65	5.6	5.75	5.45	5.425	5.5
	E	11.5 - 12.	9.5 - 10.0	9.5 - 10.0	12.05	11.88	12.06	11.9	10.82	10.91
TP (mg/L)	I	0.32	0.31	**0.315**	0.29	0.31	0.33	0.305	0.31	0.3225
	E	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
TSS (mg/L)	I	78	78	78	78	78	78	78	78	78
	E (acidified)	–	–	–	< 5	< 5	< 5	< 5	< 5	< 5
	E(non-acidified)	–	–	–	52	69	46	52	69	46

Bold entries indicate values that were not tested, but averaged from the two other days of testing in the sequence.

I: Influent

E: Effluent

Table C-4 Compiled analysis results from Utah State University Analytical Labs

USU ID	Identification	Al	As	B	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Se	Si	Sr	Zn
		---mg/L---																						
3978	P-A-1	0.56	<	0.03	0.21	345	<	<	0.005	<	<	16.5	0.03	<	0.001	26.0	<	<	0.002	5.05	0.06	7.65	1.11	<
3979	P-A-2	1.02	<	0.03	0.25	321	<	<	0.003	<	<	18.9	0.04	<	<	20.4	<	<	0.005	3.62	0.05	6.83	1.33	0.01
3980	P-A-3	1.22	<	0.05	0.24	261	<	<	<	<	<	13.0	<	<	<	14.1	<	<	0.010	3.13	<	5.84	1.12	<
3981	P-B-1	0.81	<	0.02	0.14	264	<	<	0.007	<	0.01	18.8	0.01	<	<	42.1	<	<	0.013	9.49	<	16.6	1.04	<
3982	P-B-2	0.85	<	0.01	0.26	361	<	<	0.004	<	0.03	17.6	<	<	<	41.9	<	<	<	4.18	<	6.64	1.28	<
3983	P-B-3	1.23	0.010	0.01	0.21	268	<	<	0.001	<	0.02	12.8	<	<	<	34.6	<	0.03	0.008	4.20	<	9.00	1.10	<
3984	DI-1	1.40	<	0.10	0.03	61.1	<	<	0.006	<	0.85	13.7	0.10	<	<	28.0	<	0.23	0.045	17.1	0.06	45.4	0.20	<
4410	1 (DI-1)	1.24	<	0.10	0.05	61.9	<	<	0.010	<	0.784	10.9	0.06	<	0.004	25.1	<	0.33	0.003	17.7	<	42.1	0.18	<
4415	6 (DI-1)	1.22	0.003	0.10	0.02	60.4	<	<	0.011	<	0.008	10.9	0.05	<	0.004	25.0	<	<	0.002	17.0	0.04	41.1	0.17	<
3985	DI-2	1.59	<	0.05	0.02	72.4	<	<	<	<	0.04	15.7	<	<	<	21.0	<	<	0.033	4.26	<	34.1	0.37	<
4411	2 (DI-2)	1.41	<	0.05	0.03	72.3	<	<	0.004	<	0.049	12.3	<	<	<	18.7	<	<	0.004	4.32	<	30.8	0.33	<
3986	DI-3	1.79	<	0.05	0.02	75.0	<	<	<	<	<	13.4	0.06	<	<	13.2	<	<	0.036	3.83	<	30.5	0.41	<
4412	3 (DI-3)	1.57	<	0.04	0.04	75.1	<	<	0.002	<	0.001	10.5	<	<	<	12.0	<	<	0.002	3.85	<	27.4	0.36	<
3987	5-A-1	1.11	<	0.05	0.10	254	<	<	0.003	<	<	24.9	<	<	0.001	39.0	<	<	0.016	9.70	<	18.9	0.67	<
3988	5-A-2	1.63	<	0.03	0.13	173	<	<	<	<	<	28.0	<	<	<	30.4	<	<	0.012	3.77	<	15.3	0.86	<
3989	5-A-3	1.25	<	0.04	0.11	164	<	<	<	<	<	18.1	0.29	0.01	<	18.8	<	0.36	0.010	2.57	<	13.4	0.69	<
4088	3 (≈5-A-3)	1.06	<	0.02	0.109	160	<	<	0.002	<	0.006	14.1	0.06	<	0.002	17.4	<	<	<	2.50	<	11.7	0.586	0.003
3990	5-B-1	0.86	<	0.03	0.12	254	<	<	0.003	<	<	20.9	<	<	0.001	46.2	<	<	0.018	9.86	<	19.1	0.69	<
4086	1 (5-B-1)	0.74	0.004	0.03	0.123	248	<	0.001	0.008	<	0.020	17.2	0.13	<	0.008	41.9	<	<	<	9.88	<	17.3	0.607	<
3991	5-B-2	0.98	<	0.03	0.15	158	<	<	<	<	<	20.6	0.05	<	<	42.9	<	<	0.014	3.37	0.04	19.1	0.79	<
4414	5 (5-B-2) no acid	0.45	0.001	0.04	0.30	120	<	<	0.002	<	<	22.3	<	<	0.003	45.6	<	<	<	3.70	<	11.3	0.77	<
3992	5-B-3	1.19	<	0.02	0.17	209	<	<	<	<	<	13.4	<	<	<	34.4	<	<	<	3.34	<	9.68	0.78	<
3993	10-A-1	0.76	<	0.04	0.12	331	<	<	<	<	<	15.6	<	<	0.002	27.6	<	<	<	6.42	0.03	9.57	0.63	<
3994	10-A-2	1.18	<	0.04	0.16	247	<	<	<	<	<	16.2	<	<	<	19.5	<	<	0.001	3.99	<	7.46	0.70	<
4087	2 (10-A-2)	1.17	<	0.04	0.156	243	<	<	0.003	<	0.012	15.9	0.09	<	0.005	19.5	<	<	0.001	4.08	0.10	7.25	0.645	<
3995	10-A-3	1.26	<	0.04	0.18	254	<	<	<	<	<	15.3	0.10	<	<	16.0	<	<	0.001	3.60	<	6.38	0.77	<
3996	10-B-1	0.55	<	0.03	0.10	291	<	<	0.003	<	<	14.5	<	<	0.005	37.5	<	<	0.014	10.8	<	17.2	0.60	<
4413	4 (10-B-1) no acid	0.21	<	0.03	0.27	225	<	<	0.008	<	<	12.8	<	<	0.012	35.4	<	<	<	10.6	<	1.78	0.54	<
3997	10-B-2	0.82	0.001	0.02	0.13	215	<	<	<	<	<	17.3	<	<	<	38.3	<	<	0.006	3.58	0.05	14.6	0.67	<
3998	10-B-3	0.87	<	0.01	0.15	298	<	<	<	<	<	9.71	0.06	<	<	28.3	<	<	<	3.73	<	4.87	0.56	<
3999	RA51	<	<	0.04	0.07	0.24	<	<	<	<	<	<	0.06	<	<	3.85	<	0.19	<	0.18	0.04	0.20	0.00	0.09
4089	Runoff A	<	<	0.02	0.001	0.14	<	<	<	0.006	0.004	<	0.09	<	<	17.8	<	0.27	0.058	0.05	<	<	0.003	0.124
4090	R5 A2	<	<	0.03	<	0.17	<	<	<	0.001	<	0.08	0.07	<	<	3.88	<	0.28	0.004	0.18	<	0.18	0.001	0.113
4091	R5/P3 Acid	<	<	0.02	<	0.09	<	<	<	0.007	<	<	0.01	<	<	19.1	<	0.26	0.049	0.06	0.08	0.01	0.002	0.130
Detection Limits:		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.005	0.001	0.001	0.001	0.001	0.001	0.03	0.001	0.01	0.025	0.001	0.001	0.001

Appendix D

Calculated Data

Table D-1 Standard deviation values for concrete compressive strength tests

Day	Plain	5%	10%
3	120.28	80.75	83.45
7	263.07	na	72.93
28	87.34	19.74	217.22

Table D-2 Standard deviation values for concrete tensile strength tests

Mixture	Standard deviation
Plain	9.22
5%	5.95
10%	na

Table D-3 Standard deviation values for concrete porosity tests

Mixture	Standard deviation
Plain	1.12
5%	0.56
10%	0.49

Table D-4 Standard deviation values for concrete permeability tests

Mixture	Standard deviation
Plain	0.61
5%	0.44

Table D-5 Standard deviation values for influent and effluent concentrations

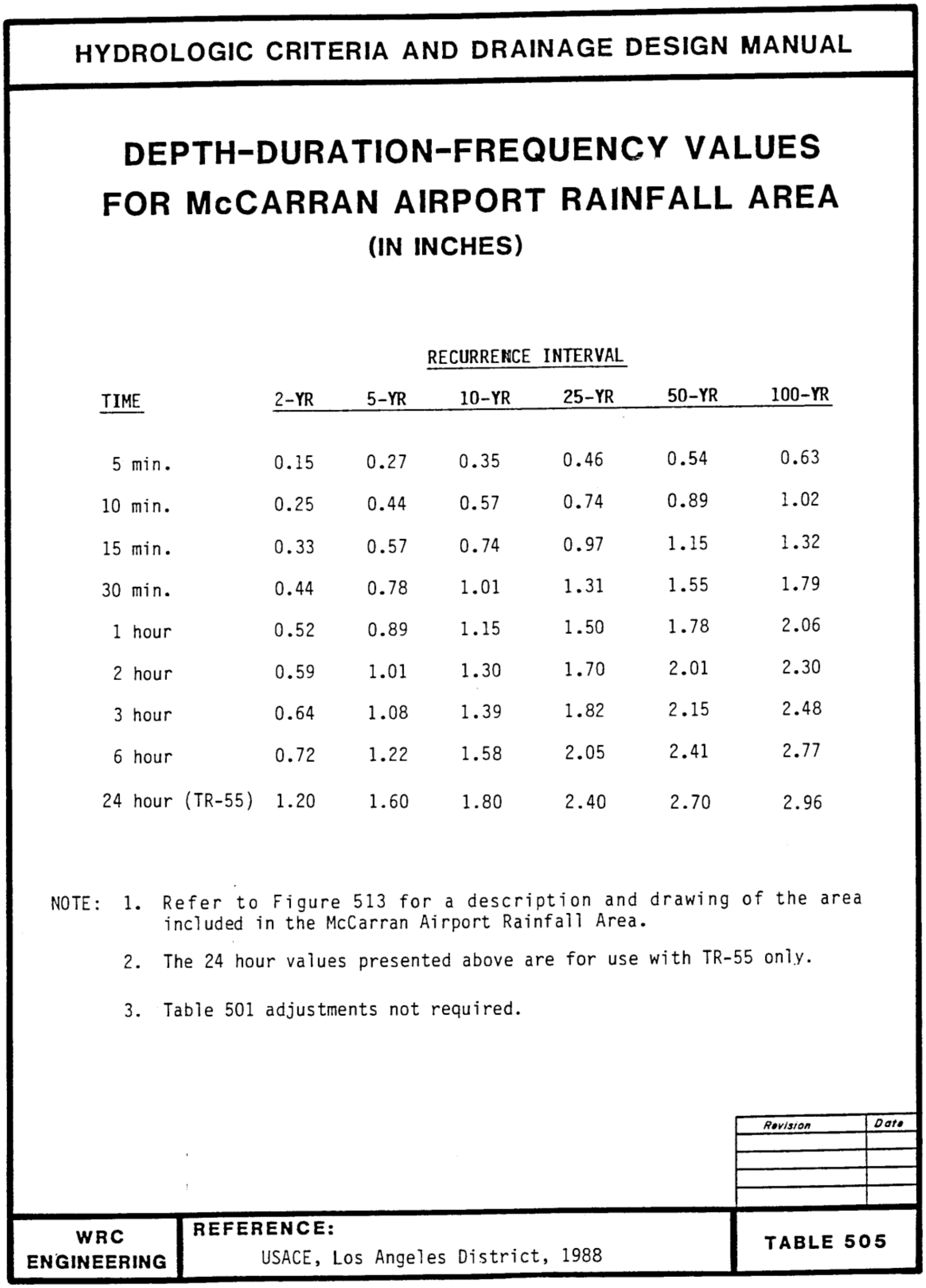
Sample	Contaminant	Standard deviation					
		day 1		day 2		day 3	
		Influent	Efflluent	Influent	Efflluent	Influent	Efflluent
Plain Concrete	Cu (μg/L)	4.243	0.000	3.536	0.000	4.243	0.000
	Pb (μg/L)[a]	0.000	8.202	0.000	2.546	1.344	0.000
	Zn (μg/L)	0.000	0.000	14.142	5.940	14.142	0.000
	Oil/COD (mg/L)	–	–	–	–	–	–
	COD (mg/L)	–	–	–	–	–	–
	pH	0.601	0.354	0.410	0.247	0.594	1.485
	TP (mg/L)	0.014	0.000	0.007	0.000	0.004	0.001
	TSS (mg/L)[b]	0.000	–	0.000	–	0.000	–
5% Concrete	Cu (μg/L)	0.707	0.000	0.000	0.000	0.707	0.000
	Pb (μg/L)[a]	0.000	4.596	0.000	1.061	0.000	3.182
	Zn (μg/L)	21.213	0.000	7.071	0.000	0.000	0.000
	Oil/COD (mg/L)	–	–	–	–	–	–
	COD (mg/L)	–	–	–	–	–	–
	pH	0.601	1.061	0.410	1.061	0.594	1.344
	TP (mg/L)	0.007	0.000	0.021	0.000	0.007	0.234
	TSS (mg/L)[b]	0.000	–	0.000	–	0.000	–
10% Concrete	Cu (μg/L)	3.889	0.000	2.828	0.000	2.121	0.000
	Pb (μg/L)[a]	0.000	9.051	0.000	2.970	0.000	0.000
	Zn (μg/L)	21.213	0.000	7.071	0.000	0.000	0.000
	Oil/COD (mg/L)	–	–	–	–	–	–
	COD (mg/L)	–	–	–	–	–	–
	pH	0.283	0.212	0.247	1.506	0.354	1.633
	TP (mg/L)	0.021	0.000	0.000	0.000	0.011	0.000
	TSS (mg/L)[b]	0.000	–	0.000	–	0.000	–

[a] Influent lead was calculated

[b] Influent TSS was weighed and placed on the surface of the concrete samples

Appendix E

Hydrologic Reference



HYDROLOGIC CRITERIA AND DRAINAGE DESIGN MANUAL

DEPTH-DURATION-FREQUENCY VALUES FOR McCARRAN AIRPORT RAINFALL AREA

(IN INCHES)

	RECURRENCE INTERVAL					
TIME	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
5 min.	0.15	0.27	0.35	0.46	0.54	0.63
10 min.	0.25	0.44	0.57	0.74	0.89	1.02
15 min.	0.33	0.57	0.74	0.97	1.15	1.32
30 min.	0.44	0.78	1.01	1.31	1.55	1.79
1 hour	0.52	0.89	1.15	1.50	1.78	2.06
2 hour	0.59	1.01	1.30	1.70	2.01	2.30
3 hour	0.64	1.08	1.39	1.82	2.15	2.48
6 hour	0.72	1.22	1.58	2.05	2.41	2.77
24 hour (TR-55)	1.20	1.60	1.80	2.40	2.70	2.96

NOTE:
1. Refer to Figure 513 for a description and drawing of the area included in the McCarran Airport Rainfall Area.
2. The 24 hour values presented above are for use with TR-55 only.
3. Table 501 adjustments not required.

Revision	Date

WRC ENGINEERING

REFERENCE:
USACE, Los Angeles District, 1988

TABLE 505

REFERENCES

ACPA (2006) or American Concrete Pavement Association (2006). Stormwater management with pervious concrete pavement. Retrieved from http://www.dep.wv.gov/WWE/Programs/stormwater/MS4/green/Documents/SW%20Mgmt%20with%20pervious%20concrete.pdf

Ahmad, A. L., Sumathi, S., Hameed, B. H., (2005). Residual oil and suspended solid removal using natural adsorbents chitosan, bentonite and activated carbon: A comparative study. *Chemical Engineering Journal, 108*, 179-185.

Armenante, P. M. (1997). Precipitation of Heavy Metals from Wastewaters. New Jersey Institute of Technology. Retrieved from http://cpe.njit.edu/dlnotes/CHE685/Cls06-2.pdf

Ashley, E. (2008). Using Pervious Concrete to Earn LEED Points. *Concrete InFocus* (Winter 2008). Retrieved from http://www.nrmca.org/research/cif%20winter%2008%20perv%20conc%20leed.pdf

ASTM (2010). C496/C496M – 04. *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.* Retrieved from http://www.rangson.com/pdf/astm%20material/Mat008_C496.PDF

Ayoub, G. M., Hamzeh, A., Semerjian. L., (2011). Post treatment of tannery wastewater using lime/bittern coagulation and activated carbon adsorption. *Desalination, 273*, 359-365.

Brown, D., (2003). Pervious Concrete Pavement: A Win-Win System. *Concrete Technology Today, 24* (2). Retrieved from http://www.secement.org/PDFs/CT032Pervious.pdf

Calgon Carbon (2012). Filtrasorb ® 400 Product Bulletin. Retrieved from http://www.calgoncarbon.com/media/images/site_library/25_Filtrasorb_400_1019web.pdf

CCRFCD (1999) or Clark County Regional Flood Control District (1999). Depth-Duration-Frequency Values for McCarran Airport Rainfall Area. *Hydrologic Criteria and Drainage Design Manual*, Table 505. http://gustfront.ccrfcd.org/pdf_arch1/hcddm/Current%20Manual%20by%20Section/Section%20500.pdf

CCRFCD (2009) or Clark County Regional Flood Control District (2009). *Las Vegas Valley NPDES Municipal Stormwater Discharge Permit Annual Report 2008-2009*, p. 13. Retrieved from http://gustfront.ccrfcd.org/pdf_arch1/NPDES/Las%20Vegas%20Valley%20NPDES%20Municipal%20Stormwater%20Discharge%20Permit%20-%20Annual%20Report%20-%202008-2009.pdf

City of Andrews, TX (2011). *Driveways/Sidewalks.* Retrieved from http://www.cityofandrews.org/departments/community_services/building_inspection/driveways_sidewalks.html

City of Sanford NC (n.d.). *Technical specifications concrete sidewalks, driveways and curb and gutter*. Retrieved from http://www.sanfordnc.net/public_works/engineering/Specifications/CONCRETE

%20SIDEWALKS,%20DRIVEWAYS%20AND%20CURB%20AND%20GUTTER.pdf

Dabek, L. (2003). Sorption of zinc ions from aqueous solutions on regenerated activated carbons. *Journal of Hazardous Materials, B101*, 191-201.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C. (2001). Laboratory study of biological retention for urban stormwater management. *Water Environment Research, 73*, 1.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C.,Winogradoff, D. (2003). Water Quality Improvement through Bioretention: Lead, Copper, and Zinc Removal. *Water Environment Research, 75*.

Dias, J. M., Maria C.M. Alvim-Ferraz, M. C. M., Almeida, M. F., Rivera-Utrilla, J., Sanchez-Polo, M. (2007). Waste materials for activated carbon preparation and its use in aqueous-phase treatment: A review. *Journal of Environmental Management, 85*, 833–846.

EPA (1996). Overview of the Storm Water Program. Retrieved from http://www.epa.gov/npdes/pubs/owm0195.pdf

EPA (1999). 40 CFR Parts 9, 122, 123, and 124. *Federal Register, 64* (235), 68724. Retrieved from http://nepis.epa.gov/EPA/html/DLwait.htm?url=/Exe/ZyNET.exe/20004GNY.PDF?ZyActionP=PDF&Client=EPA&Index=1995 Thru 1999&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C95THRU99%5CTXT%5C00000016%5C20004GNY.txt&Query=&SearchMethod=1&FuzzyDegree

=0&User=ANONYMOUS&Password=anonymous&QField=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&Docs=

EPA (2000). *Protocol for Conducting Environmental Compliance Audits of Public Water Systems under the Safe Drinking Water Act*, p. H4. Retrieved from http://www.epa.gov/oecaerth/resources/policies/incentives/auditing/apcol-sdwa.pdf

EPA (2002). *Federal Water Pollution Control Act*, pp. 15-16. Retrieved from http://epw.senate.gov/water.pdf

EPA (2005a). Extension of National Pollutant Discharge Elimination System (NPDES) Permit Deadline for Storm Water Discharges for Oil and Gas Activity That Disturbs One to Five Acres (2005). *Federal Register*, *70* (45). Retrieved from http://www.epa.gov/npdes/regulations/sw_oil_gas_final_rule.pdf

EPA (2005b) Stormwater Phase II Final Rule: An Overview. Retrieved from http://www.epa.gov/npdes/pubs/fact1-0.pdf

EPA (2006a). Amendments to the National Pollutant Discharge Elimination System (NPDES) Regulations for Storm Water Discharges Associated With Oil and Gas Exploration, Production, Processing, or Treatment Operations or Transmission Facilities (2006). *Federal Register*, *71* (112). Retrieved from http://www.epa.gov/npdes/regulations/final_oil_gas_rule.pdf

EPA (2006b). Amendments to the NPDES Regulations for Storm Water Discharges Associated with Oil and Gas Exploration, Production, Processing, or Treatment Operations, or Transmission Facilities. Retrieved from http://www.epa.gov/npdes/regulations/final_rule_QA.pdf

EPA (2009a). Pervious Concrete Pavement. *National Pollutant Discharge Elimination System NPDES.* Retrieved from http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=137&minmeasure=5

EPA (2009b). Regulation of Oil and Gas Construction Activities. *National Pollutant Discharge Elimination System (NPDES).* Retrieved from http://cfpub.epa.gov/npdes/stormwater/oilgas.cfm

EPA (2013a). Best Management Practices (BMPs). Retrieved from http://www.epa.gov/nrmrl/wswrd/wq/stormwater/bmp.html

EPA (2013b) History of the Clean Water Act (April 2013). Retrieved from http://www2.epa.gov/laws-regulations/history-clean-water-act

EPA (2013c) *Proposed National Rulemaking to Strengthen the Stormwater Program*. Retrieved from http://cfpub.epa.gov/npdes/stormwater/rulemaking.cfm

EPA (2014). *Watershed Assessment, Tracking & Environmental Results*. Retrieved from http://ofmpub.epa.gov/waters10/attains_nation_cy.control

Galiatsatou, P., Metaxas, M., Kasselouri-Rigopoulou,V., (2002). Adsorption of zinc by activated carbons prepared from solvent extracted olive pulp. *Journal of Hazardous Materials, B91*, 187-203.

Goel, J., Kadirvelu, K., Rajagopal, C., Garg, V. K. (2005). Removal of lead(II) by adsorption using treated granular activated carbon: batch and column studies. *Journal of Hazardous Materials, B125*, 211-220.

Goyal, M., Rattan, V. K., Aggrawal, D., Bansal, R. C. (2001). Removal of copper from aqueous solutions by adsorption on activated carbons. *Colloids and Surfaces A: Physiochem. Eng. Aspects, 190*, 229-238.

Hong, E., Seagren, E. A., Davis, A. P. (2006). Sustainable oil and grease removal from synthetic stormwater runoff using bench-scale bioretention studies. *Water Environment Research, 78*, 2. doi:10.2175/106143005X89607

Horst, M., Welker, A., L., Traver, R., G. (2010). Multi year performance of a pervious concrete infiltration basin BMP. *Journal of Irrigation and Drainage Engineering.* doi:10.1061/(ASCE)IR.1943-4774.0000302

Hsieh, C., Davis, A. P. (2003). Multiple-event study of bioretention for treatment of urban storm

water runoff. *Diffuse Pollution Conference Dublin 2003.* Retrieved from http://psparchives.com/publications/our_work/stormwater/lid/bio_docs/Bioretention%20WQ%20Treatment-Davis%202003.pdf

Hsieh, C., Davis, A. P. (2005). Evaluation and optimization of bioretention media for treatment of urban storm water runoff. *Journal of environmental engineering © ASCE.* doi: 10.1061/(ASCE00733-9372(2005)131:11(1521)

Hydraulic Conductivity (n.d.) *Environmental Assessment Division Argonne National Laboratory*. Retrieved from http://web.ead.anl.gov/resrad/datacoll/conuct.htm

Issabayeva, G., Aroua, M. K. (2011). Removal of copper and zinc ions onto biomodified palm shell activated carbon. *World Academy of Science, Engineering and Technology, 76*, 259-262

James, R. J., Wilbon, P., DiVicenzo, J.P. (2010). Pervious and Impervious Urban Stormwater Runoff in a Rapidly Urbanizing Region: Occurrence of Fluoranthene and Pyrene. *Bulletin of Environmental Contamination and Toxicology, 85,* 32-36.

Kang, I. S., Park, J. I., Singh, V. P. (1998). Effect of urbanization on runoff characteristics of the On-Cheon Stream watershed in Pusan, Korea. *Hydrological Processes, 12*, 351-363.

Kevern, J., Wang, K., Suleiman, M. T., Schaefer, V. R. (2006). Pervious Concrete Construction: Methods and Quality Control. *NRMCA Concrete Technology Forum: Focus on Pervious Concrete*, May 24-25, 2006, Nashville, TN

Kwiatkowski, M., Welker, A. L., Traver, R.G., Vanacore, M., Ladd, T. (2007). Evaluation of an infiltration best management practice utilizing pervious concrete. *Journal of the American Water Resources Association 43*, 1208-1222

Luck, J. D., Workman, S. R., Coyne, M. S., Higgins, S. F. (2008). Solid material retention and nutrient reduction properties of pervious concrete mixtures. *Biosystems Engineering 100,* 401-408.

Luck, J. D., Workman, S. R., Coyne, M. S., Higgins, S. F. (2009). Consequences of manure filtration through pervious concrete during simulated rainfall events. *Biosystems Engineering 102*, 417-423.

Madrid, G. A., (n.d.). *ACI 330R-08 Concrete Parking Lot Design*. Retrieved from http://www.engr.nmsu.edu/13_concrete/madrid.pdf

Mannion, B. (2013). *National Trends & EPA's New Stormwater Rule*. ACWA Stormwater Summit. Retrieved from http://www.oracwa.org/documents/NationalTrendsStormwaterUtilities-BrennaMannion.pdf

McLeod, S.M., Kells, J.A., Putz, G. J., (2006). Urban Runoff Quality Characterization and Load Estimation in Saskatoon, Canada. *Journal of Environmental Engineering, 132* (11), 1470-1481.

MWH (2005). *Water Treatment: Principles and Design* (2nd ed.). Hoboken, NJ: John Wiley & Sons, 1252.

NOAA (2014) National Oceanic and Atmospheric Administration. Total Monthly and Annual Precipitation at Las Vegas. http://www.wrh.noaa.gov/vef/climate/LasVegasClimateBook/Total%20Monthly%20And%20Annual%20Precipitation%20At%20Las%20Vegas.pdf

NRMCA (2004) or National Ready Mixed Concrete Association (2004). Concrete in practice: What, why and how? www.nrmca.org

Obla, K. (2010). Pervious concrete – An overview. *The Indian Concrete Journal, 9-18.* Retrieved from http://www.nrmca.com/Research_Engineering/Documents/Pervious_Concrete_Overview_paper_KObla_Aug2010.pdf

Periasamy, K., Namasivayam, C. (1996). Removal of copper(II) by adsorption onto peanut hull carbon from water and copper plating industry wastewater. *Chemosphere, 32*, 769-789.

Quiroz, O. (2011). *Recycling Waste Latex Paint in Overlays, Rigid Pavements, and Pervious Concrete.* ProQuest Dissertations and Theses. Retrieved from http://ezproxy.library.unlv.edu/login?url=http://search.proquest.com/docview/900864307?accountid=3611

Regional Transportation Commission of Southern Nevada (RTCSN). *The Uniform Standard Specifications for Public Works Construction* (third edition). Retrieved from http://www.rtcsnv.com/mpo/streets/Files/CompleteSets/Specifications%20Set.pdf

Roesner, L. A., Bledsoe, B. P., Brashear, R. W. (2001). "Are best-management-practice criteria really environmentally friendly?" *Journal of Water Resources Planning and Management 127* (3), 150-154.

Shen, S., Burton, M., Jobson, B., Haselbach, L., (2012). Pervious concrete with titanium dioxide as a photocatalyst compound for a greener urban road environment. *Construction and Building Materials 35*, 874–883.

Smullen, J.T., Shallcross, A.L., Cave, K. A., (1999). Updating the U.S. Nationwide Urban Runoff Quality Data Base. *Water Science and Technology, 39* (12), 9-16.

Ten Essentials of a Good Road (2008). Tech Transfer. Retrieved from http://www.techtransfer.berkeley.edu/newsletter/08-3/ten-essentials-of-a-good-road.php

Tennis, P. D., Leming, M., Akers, D. J. (2007). *Pervious Concrete Pavements*, 1-28. Portland Cement Association, Skokie, IL and National Ready Mixed Concrete Association, Silver Spring, MD.

The Engineering Toolbox (n.d.) Densities and Specific Weight of Water in Imperial Units. Retrieved from http://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html

The University of Rhode Island Cooperative Extension and the Rhode Island Department of Health Source Water Protection Program (n.d.). *Porous Pavement and*

Groundwater Quality Technical Bulletin Retrieved from http://www.uri.edu/ce/wq/nemo/Publications/PDFs/PP.GWQuality.pdf

United States Court of Appeals for the Ninth Circuit (2008). *Natural Resources Defense Council vs. United States Environmental Protection Agency*. Retrieved from http://www.epa.gov/npdes/regulations/oilandgas_nrdc_v_epa.pdf

USGS (2014), U.S. Geological Survey. Water Density. Retrieved from http://water.usgs.gov/edu/density.html

Wang, J., Zhang, Y., Feng, C., Wang, H., Wang, L. (2010). Adsorption Capacity Comparison Among Three Filter Media for Phosphorus. *Beijing University of Civil Engineering and Architecture.*

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