

The Declining pH of Waters Exposed to Pervious Concrete

By

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Abstract

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The focus of this study is on the pH changes over time in various stormwaters in contact with pervious concrete that has aged under varying ambient air restrictions. Elevated pH levels may be a concern if exfiltrated directly to sensitive waters. This study was conducted to aid designers by determining the rate of pH decline under various conditions. For this study, laboratory prepared pervious concrete specimens exposed to three different levels of ambient air restriction, were periodically tested for pH using four different testing methods; infiltrating either deionized water or tap water through the specimens, or soaking the specimens in either deionized water or tap water. Obvious trends in pH decline were observed. Greater exposure to ambient air significantly increased the rate of pH decline. The tap water tests represented more typical stormwaters and had much lower pH readings than the deionized water tests. The pH of samples representative of typical, in-place conditions, declined sufficiently in well under a year for most typical field conditions. In addition, this study also includes the declining pH of water in contact with pervious concrete exposed to carbonate laden waters. The increased rate of carbonation is desired in many primary and secondary life applications of concrete in order to make the life cycle of concrete structures more carbon neutral. Most carbonation rate studies focus on concrete exposed to ambient air or air enhanced with increased levels of carbon dioxide under various conditions. A possible

alternative mechanism for accelerated carbon sequestration in concrete was investigated in this research based on the pH change of waters in contact with pervious concrete. The results indicate that the pH of water in contact with pervious concrete exposed to carbonate species laden waters declined more quickly than when exposed to ambient air, which may indicate an increased rate of carbonation. It is theorized that the proposed alternative mechanism reduces the limiting rate effect of carbon dioxide dissolution in water and diffusion into the micro pores of the cement paste.

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1 Introduction

1.1 Thesis format

The following section, Section 1.2 is a brief literature review that includes a short introduction to pervious concrete, its uses, and concerns related to the research topic, as well as summarizing pervious concrete research associated with pH and other water quality issues. In addition, section 1.2 summarizes the process of carbonation, which may contribute to pH changes in concrete.

The goals and objectives of this research are listed in Section 1.3. The main goal is broken up into objectives. These objectives are referenced throughout this thesis.

Laboratory methods are described in detail in Section 2. This section covers the procedure used to prepare pervious concrete specimens, the procedure for obtaining the pH by various methods related to the objectives. Section 2 also describes the procedure for measuring the porosity and infiltration rate of the pervious concrete specimens.

Section 3 covers the pH of older pervious concrete specimens based on age that were cored from field placements in South Carolina and Oregon (Objective 1.1). This section covers details about the pervious concrete placements and mixtures, a summary of the methods used to measure the pH of water in contact with these specimens, the results obtained by measuring the pH, a discussion of these results and conclusions.

The declining pH of waters exfiltrated through pervious concrete, which may be caused by exposure to atmospheric carbon dioxide, in a laboratory setting, is analyzed in Section 4. This section identifies the rate of pH decline of deionized and tap water exposed to pervious concrete aged under three levels of ambient air restriction (Objectives 1.1). This section also identifies

differences in pH caused by small and large simulated storms (Objective 1.2). Section 4 is written as a technical paper and includes a consolidated literature review for background on the topic, a discussion of the theory behind the change in pH levels, a summary of the methods used to obtain representations of the pH and difference in pH due to varying atmospheric exposure, corresponding results, discussion of the results and conclusions.

Section 5 discusses the change in pH of pervious concrete exposed to varying concentrations of dissolved carbonate in a laboratory setting (Objective 2). This section, written as a technical paper, includes a consolidated literature review and a proposed theory for why submersion in solutions containing varying concentrations of sodium bicarbonate might accelerate a decline in pH in pervious concrete. Section 5 also gives a background on the topic, a discussion of the theory behind the change in pH levels, a summary of the methods used to obtain representations of the pH and difference in pH due to exposure to varying concentrations of carbonate species, corresponding results, discussion of the results and conclusions.

A detailed discussion of possible causes for variation in pH, calcium leaching from submerged specimens, deionized versus tap water, small storm events versus large storm events and statistics used to confirm a significant difference between slopes of pH decline are located in Section 6. Sections 6.1-6.3 discuss variations such as water temperature, quality of deionized water, blocked micro pores, and portlandite production. Leaching from submerged specimens exposed to varying levels of bicarbonate is presented in Section 6.4. Section 6.5 discusses variations in pH caused by the use of tap water versus deionized water. Section 6.6 discusses the effects of simulating a small storm versus a larger storm event (Objective 1.2). Also, the statistics used to confirm differences in slopes between specimens exposed to varying levels of carbon dioxide are discussed in Section 6.7.

The overall conclusions and recommendation for future research is discussed in detail in Section 7. After Section 7, there is a Reference section and Appendices, which include supporting information that may be helpful for future studies.

1.2 Literature review

The main focus of this literature review is on the pH of water in contact with pervious concrete. Although the main focus is on pH, this literature review will first introduce pervious concrete, summarizing what it is, why it is used, and the potential concerns associated with its pH level. It also identifies various representative water quality tests on pervious concrete to show some of the work that has already been done on pervious concrete. In addition, this literature review describes water quality studies, which address pH as related to this research as well as providing an overview of carbonation studies, which are thought to be the main mechanism resulting in pH drops in runoff from pervious concrete systems.

1.2.1 Background

Pervious concrete is a remarkable pavement material that allows stormwater to infiltrate by replacing impervious material with the highly permeable substitute. Just like traditional concrete, pervious concrete is a mixture of Portland cement, aggregate, water, and admixtures; however, its permeability is made possible by using an open graded aggregate, little to no sand material and less water. The intention is to coat the aggregate with paste, but not to fill in the voids with additional paste and smaller aggregate that would inhibit water passage. The difference between the mixture of pervious concrete and traditional concrete is that the water to cement ratio of pervious concrete ranges from 0.27 to 0.34 compared to traditional concrete with a water to cement ratio of 0.42. The coarse aggregate to cement ratio in pervious concrete ranges from 4 to 4.5, and is higher than in traditional concrete that has an aggregate to cement ratio of

approximately 3. Usually there is no sand (fines) added to pervious concrete mixes, but occasionally some may be added for extra strength (Tennis et al. 2004).

Pervious concrete, under the name “No Fines Concrete”, was originally used in building construction, and became more widely used during a material shortage in Europe after World War II (Ghafoori and Dutta 1995b). One of the first pervious concrete pavement applications in the United States was used in a parking lot in Sarasota, Florida in 1979 (Ghafoori and Dutta 1995a). Since then, the use of pervious concrete pavement has grown. Pervious concrete is mainly used to reduce or eliminate runoff from large parking lots. It has also been used in many driveways, sidewalks, pathways and streets with light traffic. As suburban areas expand the need for stormwater best management practices (BMPs), to reduce runoff will increase. The extra surface water from road and parking lot runoff is currently overloading and eroding the banks of natural channels in areas with a high percentage of imperviousness (Booth and Jackson 1997; U.S. EPA. 2003). As people become more aware of the positive environmental impacts and benefits of pervious concrete it can be expected to become more widely used in future pavement design.

The use of pervious concrete has many benefits over traditional concrete. The American concrete institute’s (ACI) document on pervious concrete, ACI 522R-10 (2010), lists the following as the advantages of pervious concrete over traditional concrete:

- Reduces stormwater runoff
- Controls pollutant sources
- Increases parking area that would otherwise be used for water retention ponds
- Reduces hydroplaning on roadways
- Adds to aircraft lift at takeoff

- Reduces wet roadway glare at night
- Reduces road noise
- Reduces the need for stormwater facilities
- Permits water and air to reach root systems of nearby trees

Despite the numerous advantages of pervious concrete, if certain counter measures are not taken it could cause water quality problems in areas sensitive to high alkalinity. Newly placed concrete and also pervious concrete may have a high pH that may be potentially damaging to adjacent sensitive water bodies.

In structural applications of traditional concrete a high pore water pH is important to maintain because it preserves the reinforcing steel (Neville and Brooks 1987); however, in pavement, it may not be necessary because reinforcement is not always added. Therefore reduced alkalinity in pavements may be a preferred alternative.

For traditional concrete pavement there may be some interaction between freshly placed concrete and stormwater that increases the pH in runoff to surface waters. Usually this is not a concern in pervious concrete, as the water is infiltrated and does not runoff. However pervious concrete has more exposed surface area than traditional concrete. As a result, water, passing through newly placed pervious concrete may reach a high pH (Setunge et al. 2009). If this water does not infiltrate, but perhaps runs off during large storm events, it may be a concern to adjacent sensitive bodies of water.

When manufacturing concrete, the reaction of portland cement and water forms calcium hydroxide, which is a strong base that buffers the pH of water to ~12.5 (Siqueira and Lopes 1999). However, as concrete ages, the pH drops due to molecular changes within the concrete's crystalline structure (Pade and Guimaraes 2007). This pH drop is mainly due to the replacement

of calcium hydroxide with calcium carbonate as carbon dioxide is absorbed from the air or other carbonate sources (calcium carbonate buffers water to a pH of around 9) (Steffens et al. 2002; Huet et al. 2005). In order to design appropriately for sensitive conditions under excessive flow, it is necessary to know how long it takes for the pH of pervious concrete exfiltrate to drop to more ecologically favorable conditions.

For most surface water, the pH is in a more neutral range from 6-9. Lower or higher pH levels may put a strain on some of the aquatic species living in surface water, which can alter the ecosystem. For the most stringent regulations, streams and rivers should not have a man made change from the pH range of 6.5-8.5, and or 0.2 pH units (U.S. EPA 1988; WSDOE 2007). This change is after dilution of the influent with the natural waters. Understanding the pH of pervious concrete exfiltrate over time will aid designers in providing a temporary buffer between a concrete placement and a stream if there is overflow and insufficient dilution. There are many factors that play a role in how the pH from pervious concrete runoff will affect a stream. If the amount of runoff is small and the stream has a high volume, the effect could be negligible, but if the stream has a low volume, the runoff could affect the pH levels. Also, if the runoff travels a greater distance before it reaches the stream, the pH may drop from contact with soils, vegetation, and atmospheric carbon dioxide.

1.2.2 Water quality studies on pervious concrete

Roadways and parking lots are large contributors to non-point source pollution. Suspended solids, heavy metals, and hydrocarbons are distributed over pavement surfaces by automobile exhaust and crankcase leakages (Mangani et al. 2005). Automobile pollutants accumulate on road surfaces until a precipitation event carries these pollutants away in runoff that eventually enters waterways or groundwater (Frumkin 2002; Arnold and Gibbons 1996). These pollutants

can potentially damage sensitive ecosystems in nearby bodies of water or enter the water supply through wells and surface water withdrawals, which can be detrimental to human health.

Various water quality studies of permeable concrete pavement systems report pollutant removal in stormwater. According to these studies, permeable concrete pavement systems may filter out, trap, and biodegrade oil (Newman et al. 2002a; Newman et al. 2004).

The addition of oil degrading bacteria is not necessary for bacterial utilization of oil; the indigenous bacteria are capable of degrading the oil on their own. Also the diversity needed to optimize degradation can naturally populate pervious pavement systems without inoculation of the pavement (Newman et al. 2002b; Coupe et al 2003).

In some cases where oil was efficiently degraded, nutrients were needed to promote the oil degrading activity of the bacteria. As the nutrient level declined so did carbon dioxide levels, which indicate bacterial activity (Pratt et al. 1999; Newman et al. 2002b). Before claims can be made that oil is sufficiently degraded in pervious pavement, a feasible method of slowly releasing nutrients into the pervious pavement might need to be developed that will last the lifetime of the pavement. Research has been started to implement slow release phosphate beads into designs (Spicer et al. 2006), but field testing should also be performed to verify laboratory results.

As microorganism diversity increases in pavement structures so does the utilization rate of oil. This phenomenon is not well understood and more research is needed to determine why the optimum oil degrading activity occurs with higher diversity even though the oil is only observed to be degraded by bacteria (Newman et al. 2002a).

Permeable concrete pavements such as pervious concrete have also been reported to remove heavy metals from infiltrating water without the danger of mobilization (Dierkes et al. 2002).

The alkalinity in concrete raises the pH of infiltrating water, which may cause most heavy metals to precipitate as metal hydroxides and remain in or around the concrete layer or in the base material (Dyer et al. 2009). Studies have also reported that heavy metals sorption to calcium silicate hydrate may retain metals such as cadmium, cobalt, copper, nickel, and zinc with greater than 99.5 percent retention (Pellegrini et al. 2006).

In a number of studies, pervious concrete has been considered as a media to grow biofilms for the removal of nutrients. Pervious concrete systems were reported to have reduced the amount of total nitrogen by 37-95 percent as well as reduce the total phosphorous by 66-95 percent (these results are from both laboratory tests and test sites) (Horst et al. 2008; Jianming et al. 2008; Park and Tia 2003). Also in some systems, suspended phosphorous was reported to have precipitated out of solution as calcium or magnesium phosphates (Luck et al. 2008).

1.2.3 Water quality studies that include pH

Four studies that report the pH of waters in contact with pervious concrete. The first, Collins (2007), evaluates a pervious concrete system, which is pervious concrete and the aggregate storage layer below. The second, Luck et al. (2008), reports the pH of pervious concrete at one point in time. The third, Park and Tia (2003), evaluates the pH of laboratory prepared pervious concrete specimens that were immersed in river water. The fourth, Kwiatkowski et al. (2007), evaluates an infiltration best management practice utilizing pervious concrete. These four studies do not focus on pH, but include pH data.

The study with the most data is Collins (2007). This study reports the pH of water exfiltrated through a pervious concrete system in a Kinston, NC parking lot. The pervious concrete system in this study consists of a 15 cm pervious concrete layer over a 5 cm washed No. 78 stone gravel layer, and a 23 cm additional sub layer of washed No. 5 stone gravel. An impermeable

membrane and an under drain were used to collect the water exfiltrated through the system. The pH data collected from this study started 70 days after the pervious concrete placement and ended 525 days after placement (see Figure 1.1). Although there are large variations in pH, it is important to notice the trend as the pH drops with the age of concrete. The highest recorded pH value (~11.4) drops after aging 1.4 years to a highest pH value of ~9.

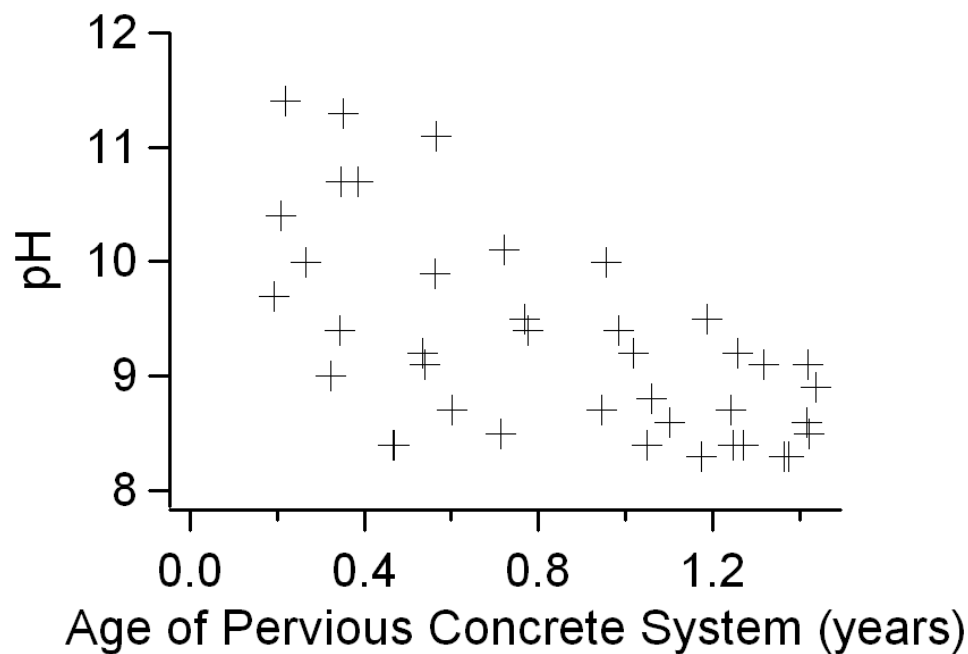


Figure 1.1. pH of exfiltrate from a pervious concrete system at various ages from data in (Collins 2007).

Kwiatkowski et al. (2007) used pervious concrete to transport runoff that comes from buildings, walkways and grassy areas down to a storage area where the water eventually infiltrated. The pervious concrete was placed over a layer of limestone aggregate, used as a water storage volume. For this study sensors were used to measure copper, nutrients, chloride, total and suspended solids, pH and conductivity. The pH of water from different storms was measured at five locations. One measured the rain water pH, another measured the water in the storage area after the water passed through the pervious concrete (port), and the other three

locations were buried under the subgrade. One was buried at 0.3 meters below the subgrade (IN0.3), another at 0.6 meters below the subgrade (IN0.6), and the other at 1.2 meters below the subgrade (IN1.2). The pH from these locations can be seen in Figure 1.2. The pervious concrete used for this study was placed in August 2002, several months before the first samples are taken. In the Figure 1.2 the first two data points show a much higher pH for the port.

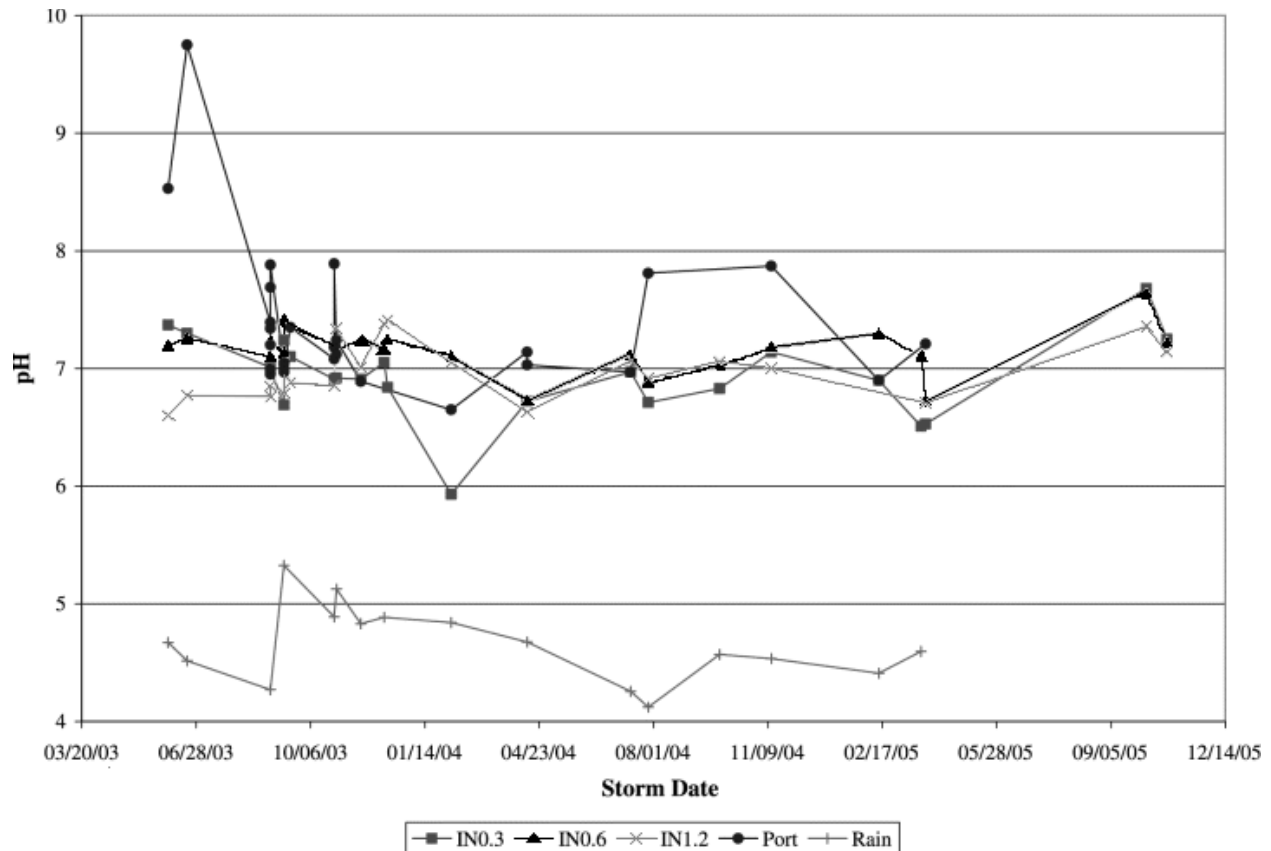


Figure 1.2. pH for All Sampled Storms, which is taken directly from (Kwiatkowski et al. 2007).

The first point is approximately 305 days (0.84 years) after placement and the second point is approximate 325 days (0.89 years) after placement. After these two points the pH at the port remains close to neutral. The higher pH from these two points may be caused by pH buffering from the pervious concrete, but may have dropped as the buffering capacity of the concrete dropped. The pH values are never greater than 10, which suggests that other factors also played

a role in lower pH values. Dissolved compounds in the runoff may have also decreased the effect the alkalinity of the concrete may have had on raising the pH of infiltrating waters. Another point of interest from Kwiatkowski et al. (2007) is that the higher pH from the first two storms did not affect the pH after the water passed through the soil. The soil and lime stone aggregate material in the storage area may have buffered the pH to values close to neutral.

Another study that reported a pH value from pervious concrete exfiltrate was Luck et al. (2008). For this test, water was filtered through composted beef cattle manure and straw bedding that was placed on top of pervious concrete specimens. This laboratory test focused mainly on solid material retention and nutrient reduction, but the pH was also measured. The pH of the pervious concrete exfiltrate in this study was reported to be 9.3. The age of pervious concrete specimens used were 8 months old, but were not actually reported in the study. The age was acquired by a researcher contacting one of the authors of Luck et al. (2008). The Park and Tia (2003) study on the water purification properties of pervious concrete also reported the pH of pervious concrete specimens that were eventually used as a media to grow biofilms. For this study, specimens were soaked in river water for 90 days, and tested for pH every 7 days. The results from this laboratory test are summarized in Table 1.1, where CB indicates that 30 percent blast furnace slag was used instead of 30 percent of the Portland cement; SF indicates that an additional 10 percent silica fume was used instead of Portland cement, and FA indicates that an additional 20 percent fly ash was used instead of Portland cement. The mineral composition of the river water was not given.

Table 1.1. pH results from pervious concrete soaked in river water (Park and Tia 2003).

Age (days)	CB I	CB+SF I	CB+FA I
	pH		
7	10.81	10.21	11.16
14	10.75	10.19	11.28
21	10.60	10.21	11.13
28	10.49	9.95	10.88
35	10.26	9.75	10.75
42	9.80	9.38	10.18
49	9.53	9.04	9.71
56	9.15	8.90	9.49
63	9.01	8.88	9.25
90	8.70	8.70	8.60

As seen in Table 1.1, the pH for all the specimens dropped over time. Note that the pH of water exposed to the pervious concrete in Park and Tia (2003) dropped more rapidly than the pH of the stormwater exfiltrated through the pervious concrete in Collins (2007). The pervious concrete pavement system in Collins (2007) was aged under ambient air conditions with rainwater exposure, and the pervious concrete specimens in Park and Tia (2003) were aged in river water under submerged conditions.

An additional study, Horst et al. (2008), includes a change in pH from water flowing horizontally through pervious concrete, but this study did not report any specific pH data.

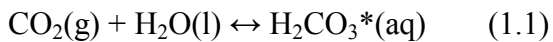
Many studies on pervious concrete are related to properties such as infiltration rates and acoustics (Bean et al. 2007; Marolf et al. 2004). Several have some water quality information, but only a few include pH and none of these studies specifically focuses on pH levels. The studies that do include pH show a trend that the pH declines as pervious concrete ages.

1.2.4 The carbonation process and pH

In many applications, reduction in the pH of pervious concrete exfiltrate occurs with exposure to ambient air. The same phenomenon that causes this drop in pH in pervious concrete

also occurs on the surface of traditional concrete. The drop in pH of concrete is caused by a chemical replacement reaction within the cement paste that is usually thought to replace the hydroxide anion associated with portlandite (calcium hydroxide) with a carbonate anion to form calcite (calcium carbonate). This chemical process is called carbonation. There are two different proposed theories about how carbonation takes place in concrete. Some researchers model the mechanism as a direct reaction between solid calcium hydroxide or calcium oxide and carbon dioxide gas. The most widely accepted hypothesis is that carbonation takes place in dissolved phases and will be summarized herein (Ishida and Maekawa 2000; Engelsen et al. 2005). The dissolution theory of carbonation is a series of complex reactions that replaces the hydroxide anions in calcium hydroxide with a carbonate anion.

One step in this process is the dissolution of carbon dioxide in water, which forms carbonic acid (Equation 1.1). The dissolution of carbon dioxide is governed by a Henry's Law constant (H_{CO_2}) of 0.033363 mol/L*atm at 25°C, which varies with temperature and partial pressure (Masters and ELA 2008).



Where,

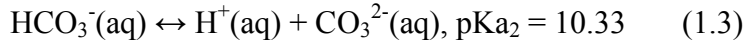
(g) is gaseous phase;

(l) is liquid phase;

(aq) is aqueous.

Carbonic acid further dissociates into first a proton and bicarbonate (Equation 1.2) and second a proton and carbonate. The reversible reactions for the equilibrium of carbonate species are summarized in Equation 1.2-1.3 with the associated negative log of the reaction rate coefficient (pKa), which only gives relative information. Carbonic acid, bicarbonate and

carbonate all exist together in equilibrium, but at different concentrations depending on the pH (Ishida and Maikawa 2000).

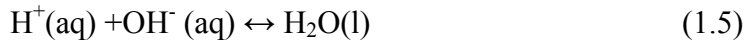


Additional associated reactions include calcium hydroxide dissociation with the introduction of uncarbonated concrete in an aqueous system, and the standard equilibrium reaction between the free proton and hydroxide in water (Equation 1.4 + 1.5).



Where,

(s) is solid phase.



The carbonate ion in the system may react with the free Ca^{2+} to form calcium carbonate completing the carbonation process as in Equation 1.6.



The rate that carbonation occurs in concrete depends on the moisture content of the concrete, the relative humidity in the ambient air, the partial pressure of carbon dioxide in the atmosphere and the surface area of the concrete specimen, etc (Neville 1981). Pade and Guimaraes (2007) looked at the surface area of concrete and estimated that the rate of carbonation of concrete is significantly faster when more of the surface area is exposed to air. According to Engelson et al. (2005), the carbonation rate is usually a maximum at a relative humidity of 50-60%, and increases with higher porosity, higher temperature, increased surface area, higher partial pressure of carbon dioxide, and with added pozzolan, which is defined by Mehta and Monteiro (1993) “as a siliceous or siliceous and aluminous material which in itself possesses little or no cementing

property but will in a finely divided form and in the presence of moisture chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties”.

Concrete carbonation in concrete structures has been widely studied for many decades, and is usually a very slow process, with significant carbonation on outer surfaces, and a *carbonation front*, slowly progressing inward at typically decreasing rates of millimeters or less annually. The *rate of carbonation* commonly refers to the rate of progression of this carbonation front and the depth of this front of carbonation (D_c) for these traditional applications it is traditionally modeled as a function of the square root of time (t) as in Equation 6, where k_c is the carbonation front coefficient.

$$D_c = k_c * t^{(1/2)} \quad (1.6)$$

It is theorized that in traditional concrete, water from a high relative humidity (>60%) may block the capillary system, and make it difficult for carbon dioxide gas to diffuse into concrete (see Figure 1.3).

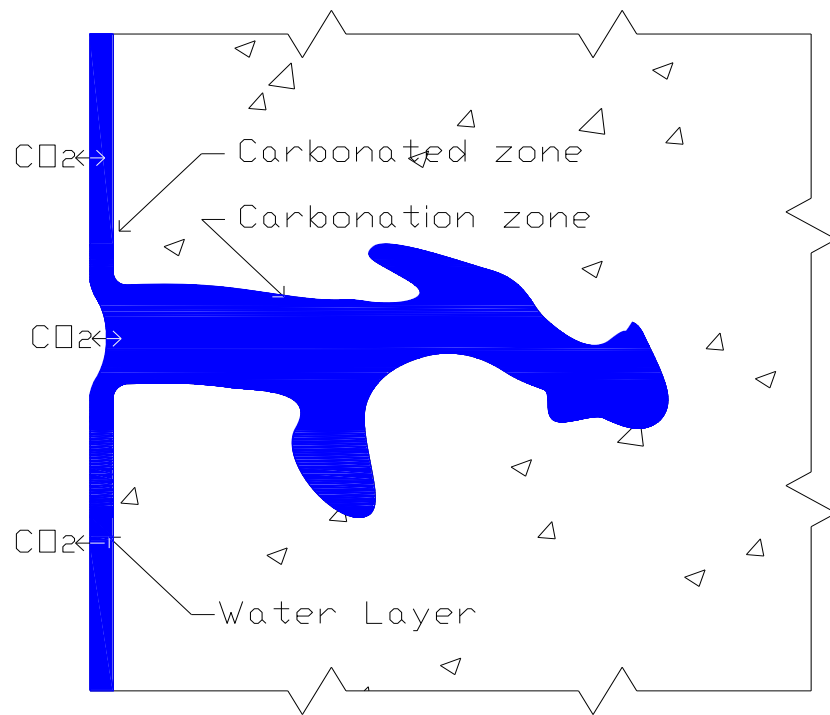


Figure 1.3. Reduced carbonation rate at 100 percent relative humidity due to reduced surface area from the pore filling up with water.

Other researchers theorize that carbon dioxide gas may use convection as a transport method for surface carbonation, instead of diffusion (McPolin et al. 2008). As stated earlier, the carbonation rate is dependent on the optimum moisture content and relative humidity for traditional concrete exposed to ambient air. At a low relative humidity, there is not enough water in the shallow pores of concrete to support carbonation. Thus, the carbonation rate is slow in low relative humidity conditions. If the relative humidity is too high, water blocks the pores, limiting carbon dioxide diffusion. In both cases the carbonation process is more gradual. For traditional concrete the surface may carbonate quickly, but extensive interior carbonation takes decades, if not centuries. The theorized optimum carbonation rate with ambient air exposure can be seen in Figure 1.4, which shows a shallow pore at 55 percent relative humidity.

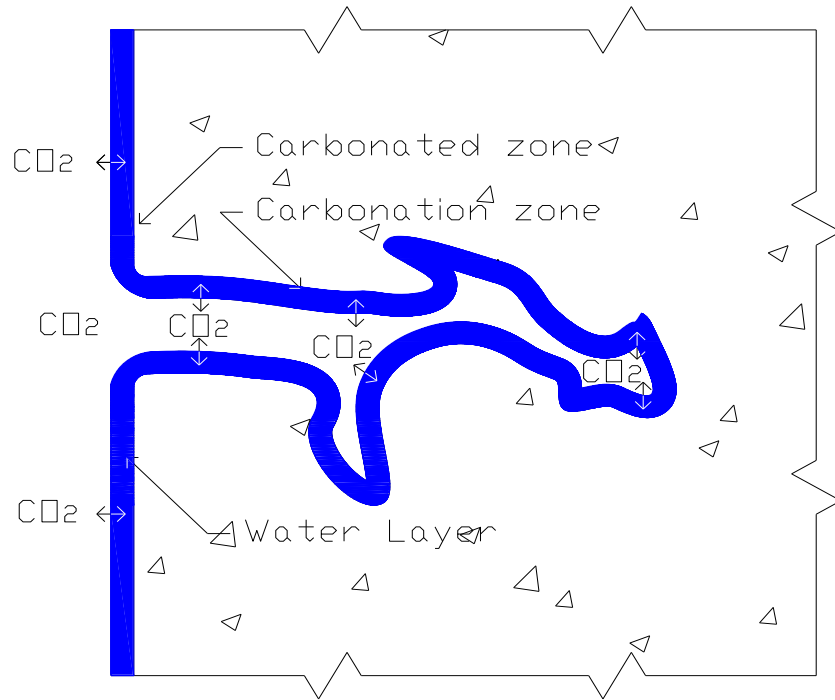


Figure 1.4. Optimum ambient air carbonation at ~55 percent relative humidity. Increased surface area of pore water.

McPolin et al. (2009) is a study on carbonation and pH in mortars manufactured with supplementary cementitious materials. In this study pore fluid pH was measured using phenolphthalein, thermo gravimetric analysis and pore fluid extraction. Surface pH was lower than that measured in the concrete pores. Other compounds such as potassium and sodium oxide also play a factor in pH levels. This study also helps confirm that larger pore size plays a factor in carbonation depth. Larger pores allow a carbonation front to go deeper because there are fewer restrictions. The carbonation depth is defined by industry as the depth at which a phenolphthalein indicator turns from red to colorless (NT-Build 357 1989). However, McPolin et al. (2008) concludes that the use of phenolphthalein for measuring actual carbonation depth is not accurate because of the limited range of pH detection. McPolin et al. (2008) also states that the value of ‘uncarbonated’ concrete (i.e. carbonation front) pH is a function of the mix design. Mixes with 10% pozzolan and 90% portland cement had an uncarbonated concrete pH of 12.8-

13.0, and mixes with 30-50% pozzolan and 70-50% Portland cement had an uncarbonated Concrete pH of 12.6-12.7. The lower pH in cement containing pozzolan is thought to be due to a lower concentration of calcium hydroxide. In the concrete industry, ‘carbonated’ concrete is usually assumed to be the portions behind the carbonation front, while ‘uncarbonated’ concrete portions are beyond the carbonation front. In actuality there are varying levels of carbon dioxide adsorption with depth of carbonation (Pade and Guimaraes 2007).

In summary, carbonation in pervious concrete exposed to ambient air should be very different than in traditional concrete. The carbonation rate in pervious concrete is expected to increase because of its extensive pore structure. The pore structure may allow increased carbon dioxide diffusion into the micro pores of the cement paste as well as increase overall carbonation within pervious concrete. If more overall carbonation occurs, pervious concrete’s life cycle can be considered more carbon neutral.

In addition to ambient air exposure, it is hypothesized herein that the rate of pH decline of water in contact with pervious concrete may increase if submerged in carbonate species laden water, based on Park and Tia (2003) and Lagerblad (2007). The submersion of pervious concrete in water with increased carbonate species may allow carbonate into the micro pores at a faster rate because of the greater concentration gradient of carbonate species outside the pores and the absence of the limitation caused by the dissolution of carbon dioxide in pore water.

1.3 Goals and objectives

The goal is to determine the rate of pH decline of waters exposed to aging pervious concrete. This information will aid designers in the use of preventive measures in reducing the risk of possible damage to sensitive waters.

The main objectives of this study are the following:

1. Study the rate of pH decline based on testing with deionized water (i.e. pore pH) and tap water (simulated clean runoff) under the following conditions.
 - 1.1 pH decline when exposed to varying levels of carbon dioxide in a laboratory setting.
 - 1.2 pH variation with respect to simulated small storm events versus large storm events in a laboratory setting.
2. Study the pH decline of water exposed to pervious concrete aged in carbonate laden waters.

2 Laboratory Methods

The laboratory methods section explains various laboratory procedures. First, it explains how the laboratory pervious concrete specimens were prepared. Then it gives details on the various pH tests used such as: the pH infiltration test (small storms), the pH immersion test (larger storm events, or more representative of pore pH) for both the deionized water (pore pH) and tap water (runoff). The submersion testing procedure for specimen aging for Objective 2 is also outlined. Finally, some ancillary procedures such as porosity tests and infiltration rate tests are discussed.

2.1 Pervious concrete specimen preparation

Five separate batches of pervious concrete were made, each for the purpose of investigating the change in pH from the time of placement. The WA, WB, WC, WD, and WF were specimens made in the Washington State Universities concrete laboratory. The dimensions and mixing specifications for each batch are shown in Table 2.1. They were all made using 8 inch by 4 inch diameter cylindrical molds (Deslauriers Inc. CAT # TC-4). The following is the procedure used to make one batch of pervious concrete.

- The mixer was wetted using 2 lbs of water and 2 lbs of Commercial Grade, type I/II, Portland cement (for WD's 25% of Portland cement was replaced with fly ash). The mixer ran for about $\frac{1}{2}$ a minute until the mixer was fully wetted. Then, the water and cement mixture was dumped out of the mixer and appropriately disposed of.
- One hundred twenty pounds of #8 aggregates (all fines removed except in WA batch, which was also pre-wetted and drained) were poured into the mixer.
- The mixer was turned on and run for $\frac{1}{2}$ a minute. All cementitious materials were added and $\frac{1}{2}$ of the 8 lbs of water were added; the mixer was turned on for 4 minutes.
- The sides of the mixer were scraped using a long metal bar. This was to ensure that the batch was mixed properly. Half of the rest of the water ($\frac{1}{4}$ of the 8 lbs of water) was added and the mixer was run for 3 minutes.
- The ball test was performed (ACI 522R-10 2010). In the ball test, a handful of material was taken from the mixer and if the material stuck together in a ball pressed together by hand, enough water was added and the material was adequately mixed. If it fell apart, more water and mixing was required. Also before mixing, the sides of the mixer were scraped using a long metal bar. $\frac{1}{2}$ of the leftover water was added and the mixer was run for another 3 minutes. This was repeated until the material stuck together in a pressed ball, which was usually about 5 times.
- Once all of the 8 lbs of water was added and the material didn't pass the ball test a small amount of water was added in about $\frac{1}{4}$ of a pound increments and mixer was run for an additional 3 minutes. The sides of the mixer were scraped using the long metal bar between each mixing. If at any time the ball in the ball test dripped water, then there was

too much water in the mix and the procedure would need to be restarted with fresh materials.

- When the material passed the ball test, it was poured out into a wheelbarrow and covered with plastic until it was put into cylinders molds. The top of each cylinder mold was scraped using a masonry knife to remove excess.
- WA's were the first batch prepared and after curing some lower mass specimens had pockets void of concrete, so a minimum mass was established for placement in the cylinders molds. The rest of the specimens were weighed to be sure a minimum mass of 2900 grams was achieved.
- A concrete tamper sized to fit the molds was placed over the opening. Then a rubber mallet was used to tap the concrete tamper until 9-10% compaction was achieved. This is representative of typical field compaction levels (Haselbach and Freeman 2006).
- After the specimens were compacted in the cylinder molds, they were sealed. Tape was used for additional sealing on caps that did not fit correctly. Once all cylinders molds were filled, tamped and sealed they were left to cure for 7 days, which is typical of covered pervious concrete curing in the field (ACI 522R-10 2010).

After the WA, WB, WC, WD and WF specimens were cured for 7 days before the mass was measured with the covers off, but without removing the cylinder. Then the cylinders were removed and infiltration pH test was performed on the WA, WB, WC and WD specimens (see Section 2.2.2).

The WA, WB, WC and WD specimens were used to research Objective 1, and then compared to the results of Objective 2 using the WF specimens. The WA through WD specimens were immediately shrink wrapped after curing on the sides to simulate in-situ conditions by

limiting the air exposure of the sides of the specimens (WA specimens were allowed to air dry before being shrink wrapped). For the WA, WB, WC, and WD batches caps were put on both ends of 6 of each batch of specimens as well as on the bottom of 6 other specimens of each batch. The rest of the specimens were left uncapped. The WA through WD specimens with the three different levels of ambient air exposure can be seen in Figure 2.1.

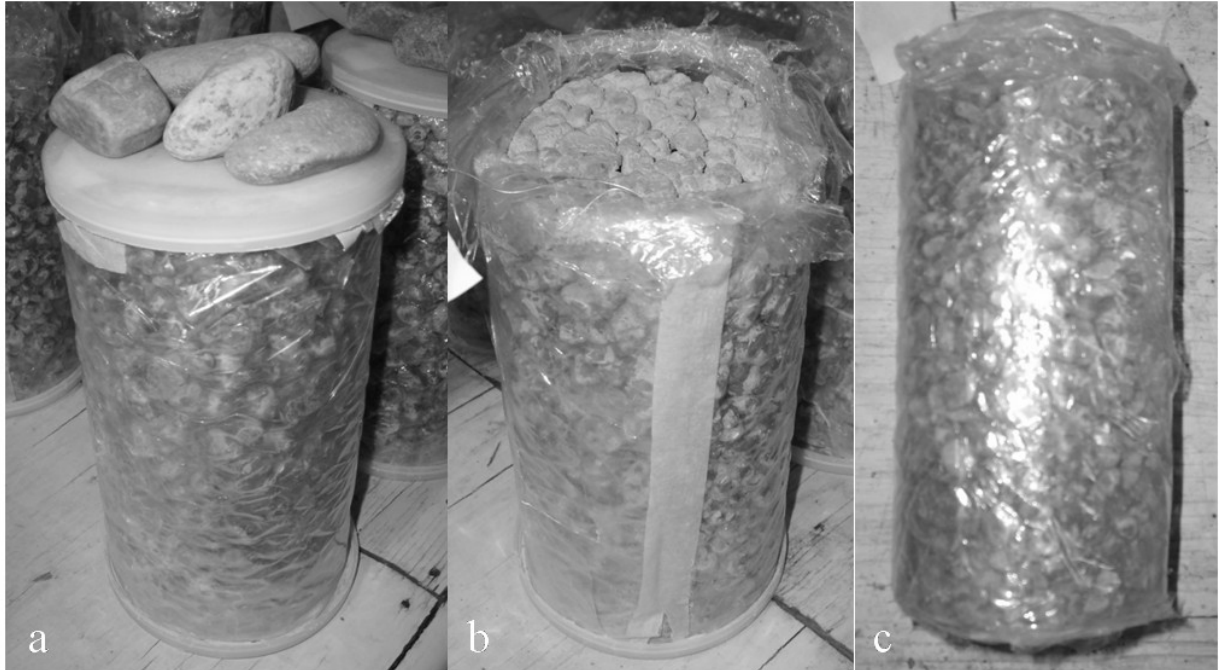


Figure 2.1. Specimens with different levels of ambient air exposure, which are (a) capped on top and bottom, (b) capped on the bottom, and (c) not capped.

After WF specimens cured for 7 days the caps and cylinders were removed and the pH immersion test was performed (see Section 2.2.5). Immediately after the pH immersion test, the submerged mass of the specimens were taken for the porosity test. Then the sides of the specimens were plastic wrapped prior to the exfiltration test (see Section 2.3). Finally, the plastic was removed and the WF specimens used in the submersion test for Objective 2.

Table 2.1. Dimensions and variations of specimens made from different concrete batches.

Batch	Number of specimens	Length	Diameter	Aggregate
WA	18	17.8 cm (7 in)	10.2 cm (4 in)	#8
WB	18	17.8 cm (7 in)	10.2 cm (4 in)	#8*
WC	17	17.8 cm (7 in)	10.2 cm (4 in)	#8*
WD**	17	17.8 cm (7 in)	10.2 cm (4 in)	#8*
WF	20	17.8 cm (7 in)	10.2 cm (4 in)	#8*

*All Fines specially removed from aggregate

** Replaced 25 percent of Portland cement with fly ash

2.2 pH testing procedures

The following procedures include calibration of the pH measuring instrument, the pH infiltration test procedure, the pH immersion test procedures of both the new pervious concrete specimens (WA-WD) that were prepared in the laboratory and older pervious concrete specimens (B, C, TP, J, and E) that were cored from pavement placed in South Carolina and Oregon, as well as additional details of the pH submersion procedure.

2.2.1 pH calibration

For calibration of the Oakton pH S10 Series two buffered solutions from Fisher Scientific were used. One with a pH of 7.00 that was buffered with potassium monobasic and potassium hydroxide (SB 108-1) and the other with a pH of 10.00 that was buffered with potassium carbonate, potassium borate and potassium hydroxide (SB 116-1). Fifteen milliliters of each buffer were poured into separate 25 milliliter beakers. After turning on the pH meter the Cal/Mea button was pressed to put the meter in calibration mode. The sensor for the Oakton pH meter was pat dried, and then placed in a holder over the 25 milliliter beaker with the blue tip of the sensor placed just under the surface of the buffered water. The sensor was placed so that it did not touch the sides of the beaker. Under the pH value it showed the pH 7.00 correction value. Once “ready” was displayed on the screen, the enter button was pressed, which corrected

the pH value. The sensor was rinsed in deionized water and pat dried, and then the sensor was placed in the holder again over the 25 milliliter beaker containing the water buffered to pH 10. The blue tip of the sensor was placed just under the surface of the buffered water. The sensor was placed so that it did not touch the sides of the beaker. Under the pH value it showed the pH 10.00 correction value. Once “ready” was displayed on the screen, the enter button was pressed, which corrected the value. The Cal/Mea button was pressed to return the meter to the measure mode. This calibration procedure was performed prior to each series of pH infiltration, pH immersion, or pH river water tests.

2.2.2 pH infiltration test

Tests were performed with either deionized water or tap water. Deionized water was used for this test to show the worst case scenario for pH values, and is more representative of pore water pH values. Also since deionized water was used more calcium hydroxide was expected to dissociate, which resulted in higher concentrations of hydroxide anion and higher pH values. Tap water was used in some tests instead of deionized water to show that the pH will be buffered if ions are already present as will be under natural conditions.

After calibration (Section 2.2.1), each specimen was held over a 2 liter plastic Nalgene container, and 75-100 milliliters of deionized water was poured over the top of that specimen. The Nalgene container was then used to catch approximately 20 milliliters of exfiltrated water. Fifteen to twenty milliliters of infiltrated water was poured into a 25 milliliter beaker. After the sensor for the Oakton pH meter was pat dried, the sensor was placed in a holder over the 25 milliliter beaker with the blue tip of the sensor placed just under the surface of the exfiltrated water. Also the sensor was not touching the sides of the beaker. When the pH value leveled off the pH was recorded for that sample. Each Nalgene container and 25 milliliter beaker was

carefully rinsed with tap water and dried using a paper towel between each use. This procedure was repeated for all six randomly selected specimens in each specimen group.

After the pH infiltration test, each specimen of pervious concrete was placed in a separate plastic container for the pH immersion test (new specimens) as performed in Section 2.2.4. The dates of each pH infiltration test can be seen in Table 2.2 and 2.3.

2.2.3 *pH immersion test (aged specimens)*

The old specimens were tested about once a month from October 17, 2008 to July 2, 2009. Initially a pH infiltration test was used as well as the pH immersion test, but pH infiltration tests were stopped. On July 2, 2009 a final pH was taken on the old specimens using the pH immersion test. Deionized water was used for this test to show the worst case scenario for pH levels. Since deionized water was used more calcium hydroxide was expected to dissociate, which may have resulted in higher concentrations of hydroxide anion and higher pH values.

Cored specimens collected from various in place pavements were immersed in deionized water for 30 minutes. Thirty minutes was chosen for this test because it was estimated in Montes et al. (2005) that 30 minutes was sufficient for water to reach most of the pore structure of the pervious concrete specimens (Montes et al. (2005) mainly focuses on measuring porosity and concludes that additional time past 30 minutes is negligible for porosity calculations).

The older specimens were placed in 2000 milliliter graduated cylinders or 5 inch square plastic containers and deionized water was poured over them until the specimens were completely covered. The specimens were left immersed in the deionized water for 30 minutes. After the 30 minutes the deionized water in which the pervious concrete specimens were soaking was manually stirred for about 10 seconds with the specimens still immersed. A 25 milliliter beaker was rinsed twice using the immersion water before the beaker was filled with

approximately 25 milliliters of the immersion water. After the sensor for the Oakton pH meter was pat dried, the sensor was placed in a holder over the 25 milliliter beaker with the blue tip of the sensor placed just under the surface of the infiltrated water. Also the sensor was not touching the sides of the beaker. When the pH value leveled off the pH was recorded for that sample. Each 25 milliliter beaker was carefully rinsed with tap water and dried using a paper towel between each use. The 2000 milliliter graduated cylinders and plastic containers were rinsed with tap water and then rinsed with deionized water between each use.

2.2.4 *pH immersion test (new specimens)*

Deionized and tap water pH immersion tests were performed on the new specimens. Deionized water was also used for the immersion test to show the worst case scenario for pH, but tap water with moderate hardness (116 mg/l five year average) (City of Pullman 2009) was used in some tests instead of deionized water to simulate relatively clean runoff from adjacent areas or more realistic conditions.

The immersion test was performed on six specimens at a time after the infiltration test was completed. For this test all six of the specimens were placed in individual plastic containers and approximately 2 liters of deionized water was poured into the container, which completely immersed each of the pervious concrete specimens. The specimens were left immersed in the deionized water for 30 minutes for the same reason discussed in Section 2.2.3. After the 30 minutes each specimens was lifted up over the plastic containers that they had been immersed in and drained for about 10 seconds. Then the specimens were returned to the table and covers were placed on specimens that had them before. The water in which the pervious concrete specimens were soaking was manually stirred in the plastic containers for about 10 seconds. The 25 milliliter beaker was rinsed twice using the immersion water before the beaker was filled with

approximately 25 milliliters of the immersion water. After the sensor for the Oakton pH meter was pat dried, the sensor was placed in a holder over the 25 milliliter beaker with the blue tip of the sensor placed just under the surface of the infiltrated water. Also the sensor was not touching the sides of the beaker. When the pH value leveled off the pH was recorded for that sample. Each 25 milliliter beaker was carefully rinsed with tap water and dried using a paper towel between each use. The plastic containers were rinsed with tap water and then rinsed with deionized water between each use. This procedure was repeated for all six randomly selected specimens of each specimen type and treatment.

The infiltration and immersion tests were performed two more times until all 18 specimens were tested in each group (WC and WD had 17 specimens each). From June 3, 2009 to June 12, 2009 the immersion water was not properly mixed. The data between these dates were excluded because they were considered outliers.

Tap water was used instead of deionized water on the following days May 18, 2009, May 27, 2009, July 22, 2009, Aug 5, 2009. Tap water was used to show that other compounds in solution can significantly impact the pH level. Deionized water is thought to dissociate more calcium hydroxide resulting in higher observed pH's, and might also be more sensitive to minor levels of contaminants in the deionized water. Tap water is thought to be a better representation of runoff from other areas that might infiltrate through pervious concrete.

The pH infiltration and immersion procedures were performed approximately twice a month from February 28, 2009 to June 3, 2009 with the WA and WB specimens on the same day and WC and WD on other days. After June 3, 2009 these procedures were performed more frequently. Before June 26, 2009 specimens were tested in numerical order. After June 26, 2009 the specimen order was chosen at random using a list of random numbers. The same order of

random numbers was used on each type of specimen per test date. The infiltration and immersion test were all done simultaneously in sets of six (WC and WD only have 17 specimens so the last set only has five). The dates that the pH infiltration and immersion (new specimens) test procedures were performed can be seen in Table 2.2 and 2.3.

Table 2.2. WA and WB specimen testing dates.

WA			WB		
Date	pH Infiltration	pH immersion	Date	pH Infiltration	pH immersion
11/7/2008	DI Water		12/18/2008	DI Water	
12/19/2008	DI Water		1/16/2009	DI Water	
1/16/2009	DI Water		2/28/2009		DI Water
2/28/2009		DI Water	3/15/2009	DI Water	
3/15/2009	DI Water		3/20/2009		DI Water
3/20/2009		DI Water	3/29/2009	DI Water	DI Water
3/29/2009	DI Water	DI Water	4/19/2009	DI Water	DI Water
4/19/2009	DI Water	DI Water	5/3/2009	DI Water	DI Water
5/3/2009	DI Water	DI Water	5/18/2009	Tap Water	Tap Water*
5/18/2009	Tap Water	Tap Water*	6/3/2009	DI Water	DI Water*
6/3/2009	DI Water	DI Water*	6/17/2009	DI Water	DI Water
6/15/2009	DI Water	DI Water	6/28/2009	DI Water	DI Water
6/26/2009	DI Water	DI Water	7/9/2009	DI Water	DI Water
7/9/2009	DI Water	DI Water	7/22/2009	Tap Water	Tap Water
7/22/2009	Tap Water	Tap Water	7/29/2009	DI Water	DI Water
7/28/2009	DI Water	DI Water	8/5/2009	Tap Water	Tap Water
8/5/2009	Tap Water	Tap Water	8/18/2009	DI Water	DI Water
8/18/2009	DI Water	DI Water	8/27/2009	Tap Water	Tap Water
8/27/2009	Tap Water	Tap Water	9/3/2009	DI Water	DI Water
9/3/2009	DI Water	DI Water	9/17/2009	DI Water	DI Water
9/17/2009	DI Water	DI Water	9/30/2009	DI Water	DI Water
9/30/2009	DI Water	DI Water	10/14/2009	DI Water	DI Water
10/14/2009	DI Water	DI Water	10/28/2009	DI Water	DI Water
10/28/2009	DI Water	DI Water	11/13/2009	DI Water	DI Water
11/12/2009	DI Water	DI Water	12/3/2009	DI Water	DI Water
12/3/2009	DI Water	DI Water	12/17/2009	DI Water	DI Water
12/17/2009	DI Water	DI Water	1/15/2010	DI Water	DI Water
1/15/2010	DI Water	DI Water	1/29/2010	Tap Water	Tap Water
1/29/2010	Tap Water	Tap Water	2/10/2010	DI Water	DI Water
2/10/2010	DI Water	DI Water			

* Data omitted due to testing errors

Table 2.3. WC and WD specimen testing dates

WC			WD		
Date	pH Infiltration	pH immersion	Date	pH Infiltration	pH immersion
1/2/2009	DI Water		1/2/2009	DI Water	
1/31/2009	DI Water		1/31/2009	DI Water	
3/22/2009		DI Water	3/23/2009		DI Water
4/18/2009	DI Water	DI Water	4/18/2009	DI Water	DI Water
4/26/2009	DI Water	DI Water	4/26/2009	DI Water	DI Water
5/10/2009	DI Water	DI Water	5/10/2009	DI Water	DI Water
5/27/2009	Tap Water	Tap Water*	5/27/2009	Tap Water	Tap Water*
6/10/2009	DI Water	DI Water*	6/12/2009	DI Water	DI Water*
6/22/2009	DI Water	DI Water	6/24/2009	DI Water	DI Water
7/1/2009	DI Water	DI Water	7/1/2009	DI Water	DI Water
7/15/2009	DI Water	DI Water	7/15/2009	DI Water	DI Water
7/22/2009	Tap Water	Tap Water	7/22/2009	Tap Water	Tap Water
7/31/2009	DI Water	DI Water	7/31/2009	DI Water	DI Water
8/5/2009	Tap Water	Tap Water	8/5/2009	Tap Water	Tap Water
8/19/2009	DI Water	DI Water	8/20/2009	DI Water	DI Water
8/28/2009	Tap Water	Tap Water	8/28/2009	Tap Water	Tap Water
9/8/2009	DI Water	DI Water	9/10/2009	DI Water	DI Water
10/1/2009	DI Water	DI Water	10/1/2009	DI Water	DI Water
10/15/2009	DI Water	DI Water	10/15/2009	DI Water	DI Water
10/29/2009	DI Water	DI Water	10/29/2009	DI Water	DI Water
11/13/2009	DI Water	DI Water	11/12/2009	DI Water	DI Water
12/4/2009	DI Water	DI Water	12/4/2009	DI Water	DI Water
12/18/2009	DI Water	DI Water	12/18/2009	DI Water	DI Water
1/15/2010	DI Water	DI Water	1/15/2010	DI Water	DI Water
1/29/2010	Tap Water	Tap Water	1/29/2010	Tap Water	Tap Water
2/17/2010	DI Water	DI Water	2/17/2010	DI Water	DI Water

* Data omitted due to testing errors

2.2.5 pH submersion test

The following is the method of testing used to determine if submersion in a bicarbonate solution accelerates the carbonation process as per Objective 2.

The 20 cylindrical WF specimens of pervious concrete were exposed to four different sodium bicarbonate solutions, as well as a control of de-ionized water. Each solution contained four pervious concrete specimens. The volume of each solution was 80 liters (21.1 gal). The concentration of sodium bicarbonate that was in each solution and other testing parameters is shown in Table 2.4.

All of the five, 80 liter baths were open systems. Equilibrium with atmospheric carbon dioxide was expected to be reached in each bath. Test frequency was every two weeks. For this test, specimens were removed from their sodium bicarbonate bath and rinsed in de-ionized water. The specimens were placed in individual plastic containers and de-ionized water was poured over the specimens until they were completely covered (approx. 2000mL or 33.81 oz). The specimens remained immersed in de-ionized water for 30 minutes before removal.

After the specimens were removed from the water, the water samples were manually stirred for about 10 seconds. A 25 mL beaker was rinsed twice using the immersion water before the beaker was filled with approximately 25 mL (0.85 oz) of the immersion water. After the sensor for the Oakton pH meter was pat dried, the sensor was placed in a holder over the 25 mL beaker with the blue tip of the sensor placed just under the surface of the water. The sensor was not touching the sides of the beaker.

When the pH value leveled off, the pH was recorded for that sample. Each 25 mL beaker was carefully rinsed with tap water and dried using a paper towel between each use. The plastic containers were also rinsed with tap water between each use.

Table 2.4. Dimensions and variations of specimens made from different concrete batches.

Containers	Specimens	concentration (mg/l)	Conc. Replenishment
1	1,6,11,16	0	yes
2	2,7,12,17	20	yes
3	3,8,13,18	100	yes
4	5,9,13,18	250	yes
5	4,10,15,20	100	no

Before the specimens were placed back in their original sodium bicarbonate solutions three of the four solutions were replenished to the original concentration of sodium bicarbonate, and one of the 100 mg/l solutions was not replenished.

The concentration of each basin was replaced approximately every two weeks by dumping out the basins. The basins were then washed with tap water to remove any residue on the sides of the basins. After cleaning the basins, solid calcium bicarbonate was weighed using a scale (OHAUS Adventurer Pro AV213) and put into the corresponding basins. The mass of sodium bicarbonate put in the 20, 100, and 250 mg/L basins was 1.6, 8, and 20 grams, respectively. The basins with submerged pervious concrete specimens can be seen in Figure 2.1.

2.3 Exfiltration test procedure

The exfiltration test was performed on just the WF specimens to show how quickly water infiltrates through the specimens. The exfiltration test gives similar results to in-situ infiltration tests, but is more representative of the exfiltration rate available to the storage bed or soil below, counting storage or uptake within the pervious concrete. The procedure and apparatus (Figure 2.2) used for this test is the following:

- The sides of the specimens were plastic wrapped with about a 2 inch lip of plastic wrap overlapping each edge.
- The specimens were set on top of a large funnel that was placed on top of a 2000 mL graduated cylinder.
- A 5 gallon bucket was used to pour water over the specimen. As water was poured over the specimen, the water level of ~2 cm over the top of the specimen was maintained.
- The timer started as water started to come out of the bottom of the funnel and was stopped when the water reached the 2000 mL mark.
- This procedure was repeated for all WF specimens.



Figure 2.2. Apparatus for exfiltration test.

The results of the exfiltration test can be seen in Appendix E.

2.4 Porosity measuring procedure

The following procedure is the measurement of the void space within the pervious concrete specimens. This procedure has three main steps: measure the mass, measure the submerged mass, and measure the volume. These three parameters are used to then calculate the porosity.

The dry mass of each specimen was first measured on an open scale (OHAUS Adventurer Pro AV213). Once the specimens were all weighed, they were soaked for at least 30 minutes as suggested in Montes et al. (2005). The same scale was set up over a water tank, where a basket was hung from a hook on the bottom of the scale. The basket was lowered to a depth that would allow the specimen to become fully submerged. Tare was pressed on the scale to zero it out once the water had settled. The specimens were removed from the water where they were soaking one at a time and submerged in the larger water tank with the basket. The pervious concrete specimen was then rotated until all directions have faced the water's surface and tapped on the side of the tank to allow trapped air to escape. The pervious concrete specimen was set in the basket and weighed once the water settled. The specimen was removed and set aside for drying. This procedure was repeated for all specimens.

The volume of the cylinders were calculated from the average of 3 height measurements using a micrometer and the diameter, which was measured with a diameter tape. The porosity was measured using Equation 2.1 from Montes et al. (2005).

$$\text{Porosity, } P (\%) = [(1 - ((W_d - W_s) / \rho_w) / V_t)] \times 100 \quad (2.1)$$

Where,

W_d is the dry mass.

W_s is the submerged mass.

ρ_w is the density of water.

V_t is the total volume of the specimen.

The measurements for calculating the porosity were performed at different times for each batch of specimens. The WAs were measured for calculating the porosity on November 10, 2008, 10 days after batch mixing. The WBs were measured for calculating the porosity on December 18, 2008, 10 days after batch mixing. The WCs were measured for calculating the porosity on January 2, 2009, 9 days after batch mixing. The WDs were measured for calculating the porosity on January 3, 2009, 10 days after batch mixing. The aged specimens EA, B, C, TP, and J were tested for porosity at an unknown date. The results of the porosity testing done on all specimens used for other pH infiltration and immersion tests are given in Appendix F.

3 Aged Specimens

Several pervious concrete specimens were taken from five separate locations that are shown in Table 3.1.

Table 3.1. Aged pervious concrete specimens with placement dates and locations.

Specimens	Date of Placement	Location
B	1/6/04	Spartanburg, SC
C	4/1/04	Charleston, SC
J	5/15/06	Georgetown, SC
TP	4/28/05	Greenville, SC
EA1-2	2/12/07	Salem, OR
EA3-4	2/16/07	Salem, OR

These specimens were exposed to ambient air carbon dioxide in laboratory conditions. Carbon dioxide restrictions may have occurred from lack of air exchange in the laboratory, but there is no way to verify any such restrictions.

3.1 Background on aged specimens

The B specimens came from pervious concrete placed January 6, 2004 in Spartanburg South Carolina and a few weeks later were saw cut and sent to the laboratories at the University of South Carolina. The B specimens are 3 inch diameter specimens cored out of the saw cut blocks later in 2004. Five B specimens were pH tested. These specimens have a low porosity with an average of about 14.7 percent. The mixture used to make these concrete specimens is shown in Table 3.2.

Table 3.2. Pervious concrete mix of Spartanburg, South Carolina placement (B specimens).

Portland Cement	692 kg	1530 lb
Aggregate (#789 granite)	2803 kg	6180 lb
Water	692 kg	1526 lb
MLR Admixture	1.7 kg	3.7 lb

The C specimens came from pervious concrete placed April 1, 2004 in Charleston, South Carolina and a few weeks later were saw cut and sent to the laboratories at the University of South Carolina. The C specimens are 3 inch diameter specimens cored out of the saw cut blocks later in 2004. Four C specimens were pH tested. The average porosity of the C specimens is 28.8 percent and ranges from 27.2-34.2 percent. The mixture used to make these concrete specimens is shown in Table 3.3.

Table 3.3 Pervious concrete mix of Charleston, South Carolina placement (C specimens).

Portland Cement	522 lb
Aggregate (#789 granite)	2460 lb
Water	738 lb
Fly Ash	90 lb
WRDA17 Admixture	1.3 lb

The J specimens came from pervious concrete placed May 15, 2006 in Georgetown, South Carolina. The J specimens are 3 inch diameter specimens cored out of in-situ pavement. Three J specimens were pH tested. These specimens have a high porosity with an average of about 30.3% (Gaither 2007). These specimens were mixed with 17.9% fly ash. The mixture of these concrete specimens is shown in Table 3.4.

Table 3.4. Pervious concrete mix of Georgetown, South Carolina placement (J specimens).

Portland Cement	550 lb
Aggregate (#789 granite)	2507 lb
Water	971 lb
Fly Ash	120 lb
Retarder Admixture	2.6 oz
MRA Admixture	20.8 oz

The TP specimens came from pervious concrete placed April 28-29, 2005 in Greenville, South Carolina. Two separate batches were placed over a two day period because of the larger area of placement. The TP specimens are 3 inch diameter specimens cored out of in-situ pavement. Three TP specimens were tested using the pH immersion test. These specimens have a high porosity with an average of about 33.0% (Gaither 2007). These specimens were mixed with 17.9% fly ash. The mixture of these concrete specimens is shown in Table 3.5.

Table 3.5. Pervious concrete mix of Greenville, South Carolina placement (TP specimens).

Portland Cement	550 lb
Aggregate (#789 granite)	2507 lb
Water	971 lb
Fly Ash	120 lb
Retarder Admixture	20.1 oz
MRA Admixture	26.8 oz

The E specimens came from pervious concrete placed February 12, 2007 (EA1-2) and February 16, 2007 (EA3-4) in Salem, Oregon. Two separate batches were placed over a four day

period because of the larger area of placement. The E specimens are 3 inch diameter specimens cored out of in-situ pavement. Eight of the EA1-2 and 6 of the EA3-4 specimens were tested using the pH immersion test. The average porosity of the EA specimens is 22.5 percent and range from 9.2-24.1 percent. No other information was given about the mixture of the E specimens.

3.2 Results and discussion from pH testing of aged specimens

The pH of the immersion water from the pervious concrete specimens declined with additional exposure to ambient air carbon dioxide as shown in Table 3.6.

Table 3.6. Change in pH of aged specimens from ambient carbon dioxide exposure.

Placement	Age at Earliest Testing	Avg. pH	Age at Latest Testing	Avg. pH
Salem, OR	1.7 years	9.70±0.90	2.4 years	8.72±0.06
Georgetown, SC	2.4 years	9.87±0.25	3.1 years	9.11±0.04
Greenville, SC	2.8 years	9.74±0.19	3.5 years	9.22±0.15
Charleston, SC	4.6 years	9.13±0.08	5.3 years	8.94±0.03
Spartanburg, SC	4.8 years	9.66±0.31	5.5 years	8.99±0.11

The drop in pH while in Albrook Laboratory most likely occurred from continued carbonation because of the additional exposure to unrestricted ambient air carbon dioxide. Most of the drop in pH happened before the specimens entered Albrook Laboratory. More detailed results of pH testing from the aged specimens are shown in Appendix A.

3.3 Conclusions

The pH of pervious concrete aged more than one year has a much lower pH level than pervious concrete at initial placement. Even though the specimens were aged, they still were not fully carbonated. This was made evident by the small decline in pH over the time the specimens were exposed in Albrook Laboratory.

4 pH vs. Ambient Carbon Dioxide Exposure

The following section is written as the technical paper Thomle and Haselbach (2010), which was submitted as a manuscript to the Journal of Environmental Engineering under the title “The Declining pH of Pervious Concrete Exfiltrate.” As a technical paper, this section has its own literature review, methods section, results, discussion and conclusion. The research in this section was designed to satisfy Objective 1 listed in Section 1.3.

4.1 Background

Pervious concrete is a remarkable pavement material that allows stormwater to infiltrate by replacing impervious material with the highly permeable substitute. Pervious concrete, like traditional concrete, is a mixture of cementitious material, aggregate, water, and admixtures. However, it allows stormwater to flow through pore spaces that form between its open graded aggregate. The pore spaces are formed by coating the aggregate with paste without filling in the voids with additional paste, smaller aggregate or fine material that would inhibit water passage (Tennis et al. 2004).

One of the first pervious concrete pavements in the United States was used in a parking lot in Sarasota, Florida in 1979 (Ghafoori and Dutta 1995a). Since then, the use of pervious concrete pavement has grown. Pervious concrete is mainly used to reduce or eliminate runoff from large parking lots. It has also been used in many driveways, sidewalks, pathways and streets with light traffic. As suburban areas expand, the need for stormwater best management practices (BMPs) that reduce runoff increases. The extra surface water from road and parking lot runoff is currently overloading and eroding the banks of natural channels in areas with a high percentage of imperviousness (Booth and Jackson 1997; U.S. EPA. 2003). As people become more aware

of the positive environmental impacts and benefits of pervious concrete it can be expected to become more widely used in future pavement design.

The use of pervious concrete has many benefits over traditional concrete. The American Concrete Institute's (ACI) document on pervious concrete, ACI 522R-10 (2010), lists the following as the advantages of pervious concrete over traditional concrete: it reduces stormwater runoff, controls pollutant sources, increases available parking areas that would otherwise be used for water retention ponds, reduces hydroplaning on roadways, adds to aircraft lift at takeoff, reduces wet roadway glare at night, reduces road noise, reduces the need for stormwater facilities, and permits water and air to reach root systems of nearby trees.

Counter measures are usually recommended for freshly placed traditional concrete surfaces contiguous to natural waters sensitive to high alkalinity. Water running off of newly placed concrete and also pervious concrete could have a high pH that may be potentially damaging to adjacent sensitive water bodies (Setunge et al. 2009).

For traditional concrete pavement there may be some interaction between freshly placed concrete and stormwater that increases the pH in runoff to surface waters. Usually this is not a concern with pervious concrete, as the water is infiltrated and does not runoff. However, pervious concrete has more exposed surface area than traditional concrete. As a result, water, passing through newly placed pervious concrete may reach a high pH (Setunge et al. 2009). If this water does not infiltrate, but runs off during large storm events, it may be a concern to adjacent sensitive water bodies.

When manufacturing concrete, the reaction of Portland cement and water forms calcium hydroxide, which is a strong base that buffers the pH of water to about 12.5 (Siqueira and Lopes 1999). However, as concrete ages, the pH drops due to molecular changes within the concrete's

crystalline structure (Pade and Guimaraes 2007). The pH drop is mainly due to the replacement of calcium hydroxide with calcium carbonate as carbon dioxide is absorbed from the air or other carbonate sources (calcium carbonate buffers water to a pH of around 9) (Steffens et al. 2002; Huet et al. 2005). In order to design appropriately for sensitive conditions under excessive flow, it is necessary to know how long it will take for the pH in concrete to drop to more ecologically favorable conditions.

For most surface water, the pH is in a more neutral range from 6-9. Lower or higher pH levels may put a strain on aquatic species and alter ecosystems. For the most stringent regulations, streams and rivers should not have a man made change from the pH range of 6.5-8.5, and or 0.2 pH units (EPA 1988; WSDOE 2007). This change is after dilution of the influent with the natural waters. Understanding the pH of pervious concrete exfiltrate over time will aid designers in providing a temporary buffer between a concrete placement and a stream if there is overflow and insufficient dilution.

4.1.1 Previous water quality studies on pervious concrete

There are various water quality studies on pervious concrete that report pollutant removals in stormwater with its use. According to these studies, pervious concrete systems may filter out, trap, and biodegrade oil (Newman et al. 2002; Newman et al. 2004), as well as remove heavy metals without the danger of mobilization (Dierkes et al. 2002). In a number of studies, pervious concrete has been considered as a media to grow biofilms for the removal of nutrients. In other studies, pervious systems were reported to have reduced the amount of total nitrogen and phosphorous (Horst et al. 2008; Jianming et al. 2008; Park and Tia 2003), and in some systems, suspended phosphorous was reported to have precipitated out of solution as calcium or magnesium phosphates (Luck et al. 2008).

4.1.2 pH

Four previous studies reviewed reported pH measurements, although none of these primarily focused on pH measurements and age. These four studies are Collins (2007), which evaluates a pervious concrete system, Luck et al. (2008), which reports the pH of pervious concrete at one point in time, Park and Tia (2003), which evaluates the pH of laboratory prepared pervious concrete samples that were immersed in river water, and Kwiatkowski et al. (2007), which evaluates an infiltration best management practice utilizing pervious concrete. An additional study, Horst et al. (2008), includes the change in pH from water flowing horizontally through pervious concrete; however, this study did not include any pH data.

The four studies that reported pH data have differences in their methods that may have a role in the variation in pH between the studies. One of the differences is that the data from Collins (2007), Luck et al. (2008), and Kwiatkowski et al. (2007) all may indicate a decline in the pH with age of the concrete exposed to ambient air, but Park and Tia (2003) indicates that this decline in pH was accelerated with exposure to river water. River water most likely contained a substantial amount of the carbonate species (Stumm and Morgan 1996). There were other differences in the studies. The reported pH values from Collins (2007) and Kwiatkowski et al. (2007) are both taken from pervious concrete systems exposed to outdoor weather conditions, where stormwater was exposed to both the pervious concrete and the base materials before they were collected for pH testing. However, Luck et al. (2008) and Park and Tia (2003) performed pH tests on pervious concrete samples in a laboratory (just pervious concrete was tested, not including base materials).

The data reported from all four studies includes the pH and age of pervious concrete, and shows a decline in pH from the typically elevated levels of freshly placed concrete to much lower levels within a year. Data from Collins (2007) shows some of the initial pH measurements

as high as 11.4, but eventually converges to an average pH around 9.1 ± 1.1 within a year of placement (see Figure 4.1).

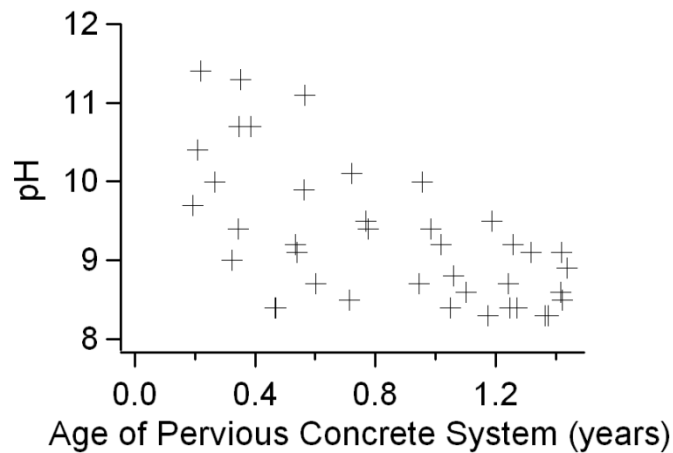


Figure 4.1. pH of exfiltrate from a pervious concrete system at various ages from data in (Collins 2007).

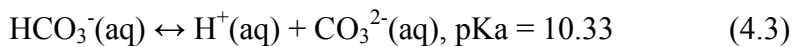
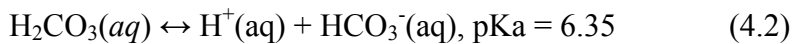
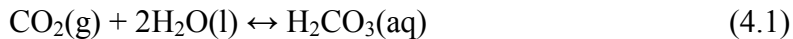
The pH of the exfiltrate from 8 month old pervious concrete in the Luck et al. (2008) study was reported to be 9.3. The age of the pervious concrete in this study was acquired by contacting one of the primary researchers. Kwiatkowski et al. (2007) reports two data points within a year of placement that have a pH above 8, but the rest of the pH data after a year shows a pH close to neutral. The pH values in Kwiatkowski et al. (2007) are much lower than in other studies presumably because of buffering from exposure to lime stone aggregate. Park and Tia (2003) reports pervious concrete specimens soaking in river water to have a pH that dropped from an average of 10.6 to 8.7 in 90 days. Park and Tia (2003) conclude that the low initial pH was due to the use of cement with high pozzolan content. Pozzolan is not cementitious by itself, but is thought to react with calcium hydroxide to form calcium silicate hydrates instead of directly forming them with exposure to water (Mehta and Monteiro 1993).

Many studies on pervious concrete are related to properties such as infiltration rates and acoustics (Bean et al. 2007; Marolf et al. 2004). Several have some water quality information,

but only a few include pH level. None of these studies specifically focuses on pH level. The studies that do include pH show a trend that the pH declines as pervious concrete ages.

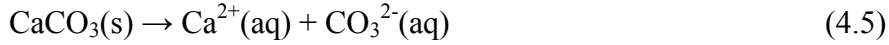
4.1.3 The carbonation process and pH

As shown previously in many applications, reduction in the pH of pervious concrete exfiltrate occurs with exposure to ambient air. The same phenomenon that causes this drop in pH to occur in pervious concrete also occurs on the surface of traditional concrete. The drop in pH of concrete is caused by a chemical replacement reaction within the cement paste that is usually thought to replace the hydroxide anion in calcium hydroxide with a carbonate anion to form calcium carbonate. This chemical process is called carbonation. The model of carbonation that is most widely accepted takes place in dissolved phases (Ishida and Maekawa 2000; Engelsen et al. 2005). The dissolution theory of carbonation is a series of complex reactions that replace the hydroxide anions in calcium hydroxide with a carbonate anion. The following equations summarize the main chemical reactions in the carbonate system:



Depending on the pH, carbon dioxide dissolves in water to form different concentrations of bicarbonate or carbonate ions according to Equations 4.2 and 4.3 (Masters and Ela 2008). The pK_a values listed (negative logarithms of the equilibrium constants) are for dilute aqueous systems. Water in concrete pores may be much more concentrated, but these pK_a values still provide relative equilibrium information. In concrete, bicarbonate dominates the pore water in the carbonated zones while carbonate dominates the uncarbonated zones based on the pH values (Engelsen 2005).

Pore water in cement paste is usually saturated with calcium hydroxide, which can react as in the following secondary chemical reactions of the carbonation process:



As the reactions in Equations 4.1-4.5 continue, with the addition of carbon dioxide more calcium hydroxide will dissolve in order to maintain equilibrium of the system allowing more calcium carbonate to form until essentially all of the calcium hydroxide is converted to calcium carbonate (Engelsen 2005; Ishida and Maikawa 2000).

The rate that carbonation occurs in traditional concrete depends on the moisture content of the concrete, the relative humidity in the ambient air, the partial pressure of carbon dioxide in the atmosphere, depth of the specimen, and the surface area of the concrete specimen, etc (Neville 1981; McPolin et al. 2008; Pade and Guimaraes 2007). Pade and Guimaraes (2007) looked at the surface area of concrete and estimated that the rate of carbonation of concrete is significantly faster when more of the surface area is exposed to air. According to Engelsen et al. (2005), the carbonation rate is usually a maximum at a relative humidity of 50-60 percent, and increases with higher porosity, higher temperature, increased surface area, higher partial pressure of carbon dioxide, and with added pozzolan.

Carbonation depth is also an important factor associated with the surface pH value. The carbonation depth is defined by industry as the depth at which a phenolphthalein indicator turns from red to colorless. The colorless section is considered ‘carbonated’ and the red section ‘uncarbonated’ (NT-Build 357 1989). However, the McPolin et al. (2008) study concludes that the use of phenolphthalein for measuring actual carbonation depth is limited by its range of pH detection. In the concrete industry ‘carbonated’ concrete is usually assumed to be the portions

behind the carbonation front and ‘uncarbonated’ concrete portions are beyond the carbonation front. In actuality there are varying levels of carbon dioxide adsorption within each of these regions (Pade and Guimaraes 2007).

The carbonation rate in pervious concrete is expected to increase because of its extensive pore structure. The pore structure may allow increased carbon dioxide diffusion into the micro pores of the cement paste as well as increase overall carbonation within pervious concrete. If more overall carbonation occurs, pervious concrete can be considered more carbon neutral.

The objectives of this study are to determine the pH of waters in contact with pervious concrete over time. In addition to time, the independent variables will include varying levels of carbon dioxide exposure in a laboratory setting, and the pH of pervious concrete exposed to tap water with moderate hardness, more representative of stormwaters, versus deionized water, which is more representative of concrete pore waters.

4.2 Methodology

Four cylindrical pervious concrete specimen sets (WA, WB, WC, and WD) were made in a Washington State University laboratory. Each set was made from a single batch of concrete. These specimens all were made with a similar mix using number 8 aggregate (fines removed) with the exception of the aggregate in the WAs (aggregate included some fine material) and the use of 25 percent fly ash instead of portland cement in the WDs (see Table 4.1).

Table 4.1. Dimensions and variations of specimens made from different concrete batches.

Batch	Number of specimens	Length	Diameter	Aggregate
WA	18	17.8 cm (7 in)	10.2 cm (4 in)	#8
WB	18	17.8 cm (7 in)	10.2 cm (4 in)	#8*
WC	17	17.8 cm (7 in)	10.2 cm (4 in)	#8*
WD**	17	17.8 cm (7 in)	10.2 cm (4 in)	#8*

*All Fines specially removed from aggregate

** Replaced 25 percent of Portland cement with fly ash

There were 18 WA specimens, 18 WB specimens, 17 WC specimens, and 17 WD specimens. They were all approximately 17.8 centimeters (7 inches) long and 10.2 centimeters (4 inches) in diameter.

The testing procedure for comparing the pH drop with specimen age versus carbon dioxide exposure used three different levels of ambient air carbon dioxide exposure made by limiting air transfer. All of the specimens were wrapped with shrink wrap around their circumference to simulate in place pavement conditions, where continuous slabs are mainly exposed to other environments only at the top and the bottom, as the circumference of the specimen would not be directly exposed to the above ambient air, soils, or base conditions below, but would be imbedded in the pavement. Exposure to ambient air was further limited for approximately one-third of the specimens from each set by adding a cover to the bottom so that ambient air carbon dioxide would be partially restricted. This condition might be representative of slabs with impermeable barriers placed below. Ambient air exposure was even further limited in approximately one-third of the specimens in each set by covering both the top and bottom of the specimens, greatly restricting the ambient air carbon dioxide exposure to these specimens. This condition would be representative of applications such as pervious concrete in interior walls with cladding on both sides. The top and bottom covers were only removed during pH immersion and infiltration testing procedures where the specimens were wetted, approximately every two weeks (Note that the pH immersion and infiltration testing procedures introduced water into the specimens, but also may have introduced limited amounts of additional carbon dioxide). The specific specimens and the specimen numbers given to specimens with no covers (NC), covers

on the bottom (BC), and covers on both the top and the bottom (TBC) is given in Table 4.2 for the WA, WB, WC, and WD batches.

Table 4.2. The specimen numbers of WA, WB, WC, and WD specimens and associated restriction of ambient air carbon dioxide.

Batch	Top and Bottom Covers	Bottom Covers	No Covers
WA	1,2,6,8,9,15	5,7,10,14,16,17	3,4,11-13,18
WB	1-6	7-12	13-18
WC	1-6	7-12	13-18
WD	1-6	7-12	13-18

The pH of water in contact with pervious concrete was tested using four different methods. The four methods can be summarized as follows:

- the pH infiltration test using deionized water;
- the pH immersion test using deionized water;
- the pH infiltration test using tap water; and
- the pH immersion test using tap water.

For the pH infiltration test approximately 75-100 milliliters of either deionized water or tap water was poured through the pervious concrete specimens. The exfiltrate was collected and the pH was measured using an Oakton pH meter. The pH infiltration tests were mainly used to simulate frequent light storm events where a small amount of water might exfiltrate from the concrete. When this test used deionized water, the exfiltrate was more representative of pore water or very clean rain. Additional testing was performed using tap water in the pH infiltration test to show that other dissolved compounds in water may greatly affect the pH of water exposed to pervious concrete, which is more representative of clean stormwater. The infiltration test was expected to have much more variable results than the pH immersion test because the water

randomly travels through the pores of the concrete, and some of the pores are more carbonated than others.

For the pH immersion test, pervious concrete specimens were soaked in either deionized water or tap water for 30 minutes. Thirty minutes was chosen for this test because it was estimated in Montes et al. (2005) that 30 minutes was sufficient for water to reach most of the pore structure of the pervious concrete specimens (Montes et al. (2005) mainly focused on measuring porosity and concludes that additional time past 30 minutes is negligible for porosity calculations). After the 30 minutes the pervious concrete specimens were removed and allowed to drain. The drained water was then mixed and the pH was measured using an Oakton pH meter. The pH immersion test gave a more averaged result over the entire specimen, even partially connected, smaller, interior pores. In the immersion test the deionized water better represented the pore pH, whereas tap water better represented clean stormwater (water containing some minerals picked up from the air or ground that may buffer the pH to a lower level).

Each individual grouping of specimens (WA, WB, WC, and WD) were tested for both the pH infiltration test and the pH immersion test on the same day. The specimens were randomly ordered for most of the testing days during these tests to reduce the affects of errors due to changes in environmental conditions.

In addition to the laboratory prepared sets, a group of much older pervious concrete specimen collected from placements and previous studies were also analyzed with the immersion test using deionized water.

4.3 Results

The pH values from both the infiltration and immersion tests using deionized water indicated a decline in pH as pervious concrete aged; however, the pH of specimens with ambient air restrictions showed less of a decline. The results from these infiltration tests are summarized in Figures 4.2 and 4.3, respectively. The pH data used in Figures 4.4 and 4.5 can be seen in more detail in Appendix B.

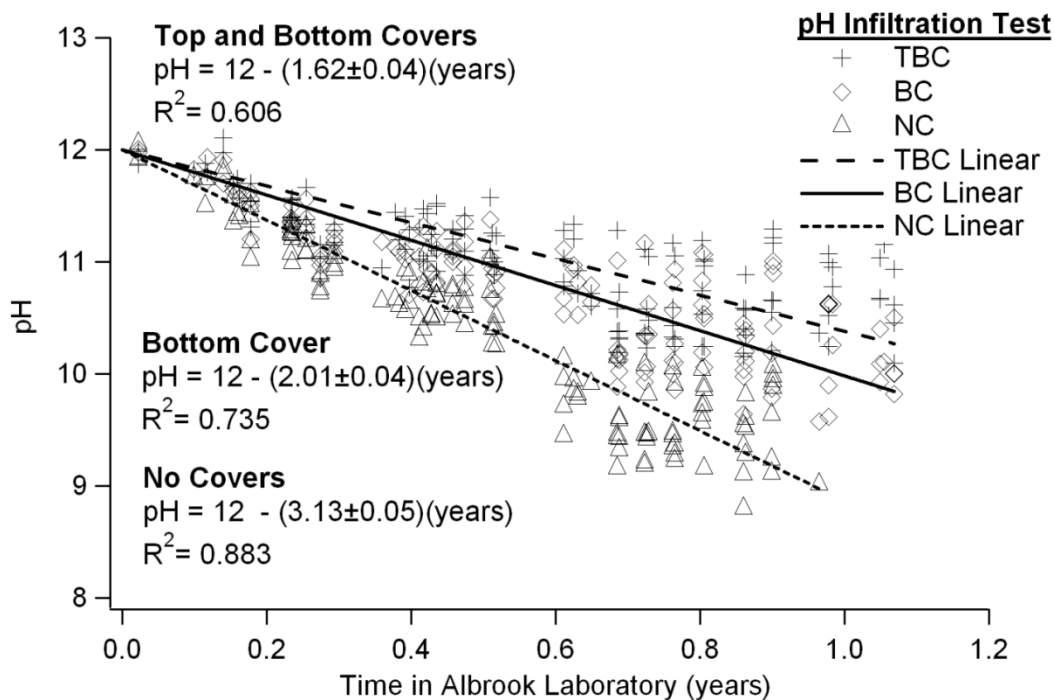


Figure 4.2. The pH infiltration test results from all laboratory prepared pervious concrete specimens (Deionized water).

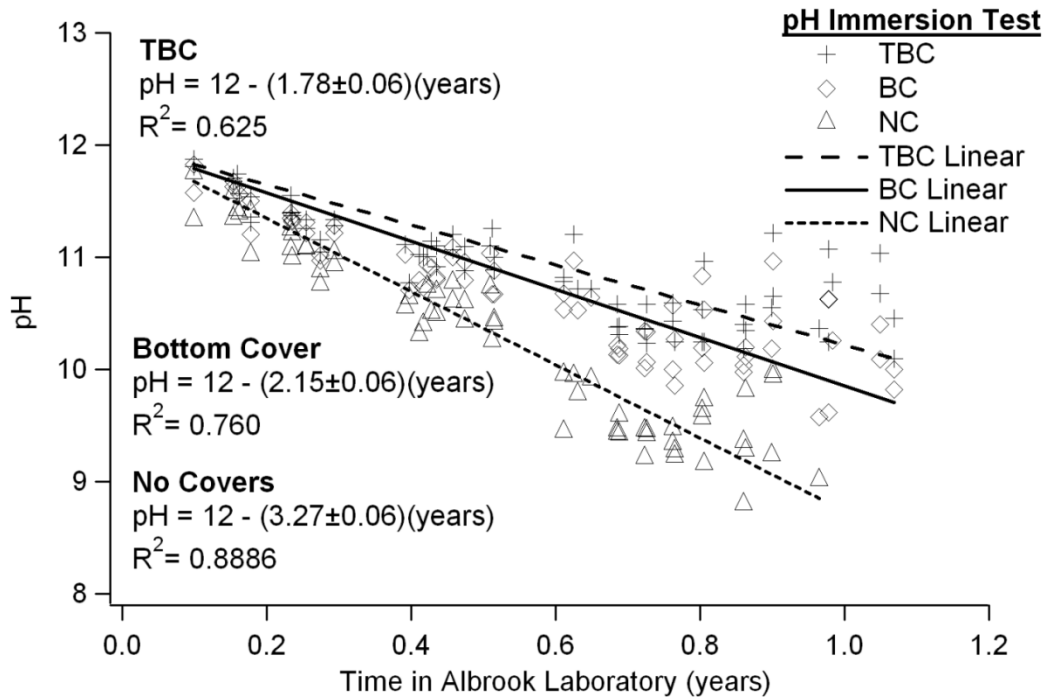


Figure 4.3. The pH immersion test results from all laboratory prepared pervious concrete specimens (Deionized water).

As seen in Figures 4.2 and 4.3, the specimens that had the least amount of ambient air restrictions, the NC set, had the most rapid pH decline, whereas those with the highest amount of ambient air restriction, the TBC set, the pH that declined the least. Linear trend lines are depicted for each set to better visualize these declines.

It is assumed from the results, as expected, that carbon dioxide may have been adsorbed by the concrete in the carbonation process, and was not replenished as rapidly due to carbon dioxide restrictions from the covers in the BC and TBC specimens. The additional air exchange in the BC specimens only showed a slight acceleration from the TBC specimens. Since the air did not have a direct pathway through the tortuous specimens, the fresh ambient air on the outside of the specimen had less of an exchange with the air inside the specimen while the covers were in place. Also the TBC and BC specimens tended to retain water, which may have also restricted airflow.

The vertical-intercepts in Figures 4.2 and 4.3 were forced through a pH value of 12 for three reasons. The first is to compare the slopes of pH decline with pervious concrete age. The second is that these intercepts were all close to 12, even when not forced. The third is that all of the pervious concrete specimens should have had similar pH values on the first day after curing was completed. For these reasons using 12 for the y-intercepts in these figures seemed to be a valid assumption. In actuality, the pH of pure calcium hydroxide is ~12.5, but the pH of water in contact with fresh pervious concrete may be lower because of the interaction of other compounds or other reactions during curing.

The pH values from the laboratory prepared specimens using tap water instead of deionized water also showed declines. These pH values from the infiltration and immersion tests using tap water can be seen in Figures 4.4 and 4.5, respectively. The pH data used in Figures 4.4 and 4.5 can be seen in more detail in Appendix B.

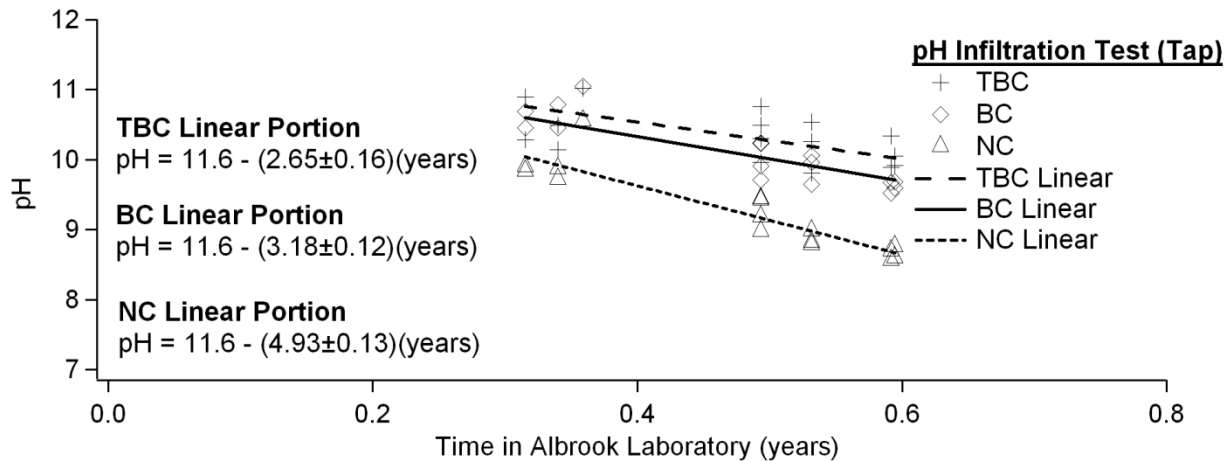


Figure 4.4. The pH infiltration test results from all laboratory prepared pervious concrete specimens (Tap water).

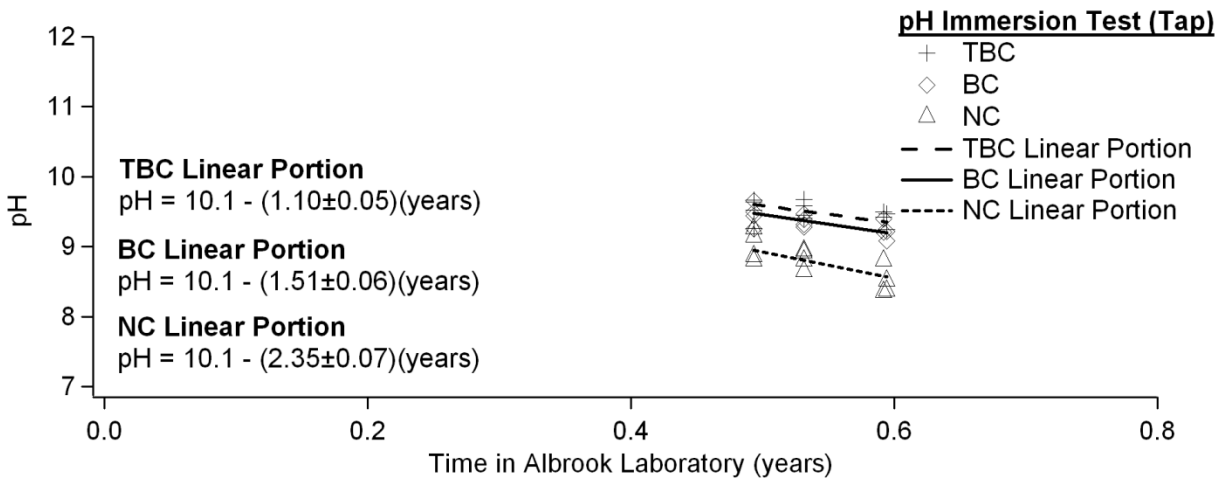


Figure 4.5. The pH immersion test results from all of the pervious concrete specimens (Tap water).

Specimens with carbon dioxide restrictions (TBC and BC) also showed less of a decline than those with no restrictions (NC) and can be seen in Figures 4.4 and 4.5, but the slopes of the pH decline are all closer together than in the deionized water tests. It became apparent that there is a linear section of pH decline and a non-linear section with a rate that may decline more rapidly as it approaches an asymptote. Only the section that is thought to be linear is plotted in Figures 4 and 5.

Comparing Figures 4.2 and 4.3 to Figures 4.4 and 4.5, it is apparent that the tap water tests have a lower pH than the deionized water tests, and may be the result of buffering from carbonate hardness and/or reduced solubility from dissolved minerals already present in tap water, as is also expected in stormwater.

The rate of decline in pH for all four tests were checked using a 95 percent confidence (95% CI) interval to determine if there was any significant differences in the slope from the TBC, BC, and NC specimens. As shown in Figure 4.6 there was a significant difference between the rates of decline of the different levels of carbon dioxide restriction using the immersion test with deionized water.

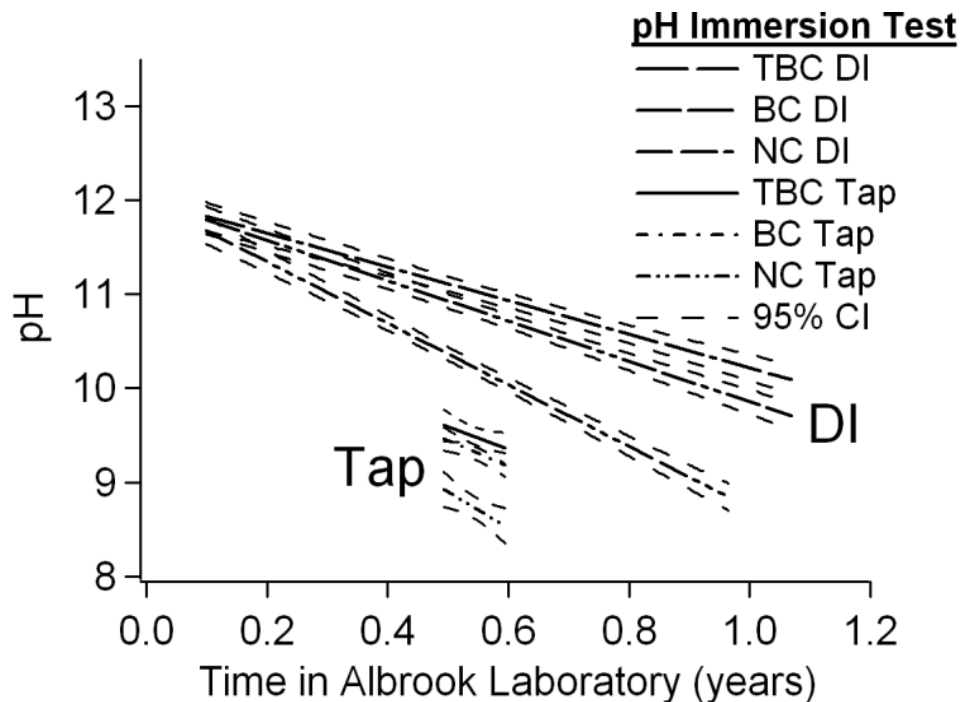


Figure 4.6. The pH immersion test results from both deionized and tap water with a 95 percent confidence interval to show the significant difference between slopes (Laboratory Specimens).

The immersion test data with the tap water also showed a significant difference using a 95% CI between the NC specimens and both the TBC and BC specimens, but there was not a significant difference between the TBC and the BC probably because of the narrow range of data collected. Similar results were obtained in the infiltration tests. The difference in the slopes using the four testing methods listed in Section 4.2 can be seen in Appendix C.

Note that the time given in Figures 4.2, 4.3, 4.4, 4.5 and 4.6 are time from exposure in the Albroom Laboratory. Two of the four sets initially were located in a small room with restricted carbon dioxide availability. As a result, significant carbon dioxide exposure began when the sets were relocated to the large Albroom Laboratory airspace with substantial ambient air exchange.

Other pervious concrete specimens cored from placements in South Carolina and Oregon also indicate that the pH of pervious concrete drops as the specimen's age. Table 4.3 shows the

average pH of cored specimens from 5 different pervious concrete placements verses approximate age.

Table 4.3. The pH of aged specimens cored from test placements in South Carolina and Oregon.

Placement	Age at Earliest Testing	Avg. pH	Age at Latest Testing	Avg. pH
Salem, OR	1.7 years	9.70±0.90	2.4 years	8.72±0.06
Georgetown, SC	2.4 years	9.87±0.25	3.1 years	9.11±0.04
Greenville, SC	2.8 years	9.74±0.19	3.5 years	9.22±0.15
Charleston, SC	4.6 years	9.13±0.08	5.3 years	8.94±0.03
Spartanburg, SC	4.8 years	9.66±0.31	5.5 years	8.99±0.11

These specimens were mainly exposed to air on all sides in a laboratory in South Carolina or in place at a field location in Oregon, prior to the earliest testing. They were then exposed in the Albrook laboratory until later testing.

These cored specimens from different placements all had a pH less than 10. The pH also continued to drop as the specimens continued to age.

4.4 Discussion

The variability in pH among the laboratory specimens that resulted from each of the four different testing methods may best be explained by seasonal differences in temperature, inconsistent exposure in concrete specimens, and inconsistencies in both the tap and deionized water. Other factors may have played a role in pH variations, but these three factors are thought to have affected the pH the most.

Testing occurred over all four seasons. The temperature variations in the Albrook Laboratory may have affected the pH because changes in temperature affect the solubility of the two chemical compounds associated with pH levels. The solubility of calcium hydroxide and calcium carbonate both increase with a decrease in temperature (Yeatts and Marshall 1967;

Johnson and Williams 1916), which is the opposite of most ionic compounds. The solubility of calcium hydroxide controls the high pH because it is much more soluble than calcium carbonate (Silberberg 2003). If the temperature is much lower, more calcium hydroxide will be dissolved causing a higher pH value than if tested at a higher temperature.

Another aspect of the variability in Figures 4.2-4.6 is due to the use of pH, a logarithmic variable. When the concentration of hydroxide ions is plotted instead, the variability is reduced as the pH drops as depicted by hydroxide concentration in Figure 4.7. When comparing the pH infiltration test to the pH immersion test, more variability is seen in the pH infiltration test data. The pH infiltration test only uses a small amount of water, which randomly passes through the concrete specimens. Some of the water may flow through areas which are more carbonated than others, and since the quantity of water used for this test is small compared to the pH immersion test, the pH of the water is greatly affected by variations in levels of carbonation within pervious concrete passages.

During testing, some results from tests using deionized water were found to be extremely low on the same day. The pH values on these days were almost comparable to the pH values from the corresponding tests using tap water. This indicated that the water was not fully deionized. On days that this was an obvious problem the data was omitted. Some other low data points may have had a similar problem with water that was not fully deionized, but were not as drastically affected, making it difficult to determine if this problem played a role in the pH variation.

pH is a logarithmic scale and changes in pH are not necessarily good indicators of variability. This is evident when the concentrations of protons and hydroxides are considered instead of looking at pH levels. The concentration of hydroxide ions has a fairly low variability as the pH drops as can be seen in Figure 7.

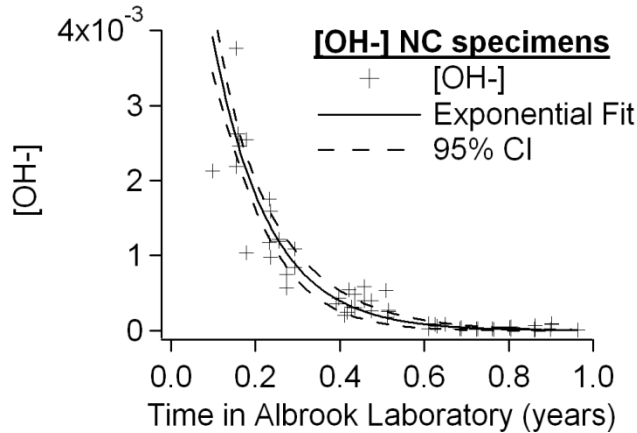


Figure 4.7. Concentration of hydroxide ions from pH immersion test using deionized water for the NC laboratory specimens.

After assessing the properties of pervious pavement systems, the level of ambient air restrictions that best represent in place pavement conditions is thought to be the specimens with no covers (NC) restricting the ambient air exposure. In place pervious pavement conditions would have top surfaces exposed and also usually have air which is free to move through the pavement into the base layers. There is also air in the soil, which may contain elevated levels of carbon dioxide from microbial activity in the soil. On average the concentration of carbon dioxide in soil voids is 10 times greater than in ambient air (Santruckova and Simek 1997). Elevated concentrations of carbon dioxide may increase the rate of carbonation even more than in the NC specimens, allowing the pH of exfiltrated water to drop more quickly as the pervious concrete ages (Engelson et al. 2005). Thus, placements of pervious concrete in the field may actually carbonate faster and have even more rapid pH declines.

4.5 Conclusions

It was confirmed that exfiltrated waters with higher levels of hardness exposed to pervious concrete have a lower pH value. This is consistent with Kwiatkowski et al. (2007) which reported much lower pH values than in Collins (2007) , as the pervious concrete in Kwiatkowski

et al. (2007) mainly exfiltrated runoff from other areas with higher levels of dissolved minerals, but the pervious concrete in Collins (2007) exfiltrated mainly rain water with lower levels of dissolved minerals.

The rate of decline in pH of pervious concrete is related closely to the level of ambient air restriction, and the rate of pH decline is greatly slowed by these restrictions. Engelsen et al. (2005) reported that the carbonation rate, which alters the pH in concrete, is increased with higher carbon dioxide exposure. Thus increased carbon dioxide exposure (decreased ambient air restrictions) should result in decreased pH levels. The results support this observation.

The pH of stormwater exposed to typical pervious concrete placements (NC) drop sufficiently in well under a year, usually in under 6 months. This drop is from the pervious concrete layer alone, without further reductions in pH from base material.

5 pH vs. Water Carbonate levels

This section is written as an extended version of the technical paper Haselbach and Thomle (2010), which was submitted as a manuscript to the Journal of Environmental Science and Technology under the title “An Alternative Mechanism for Accelerated Carbon Sequestration in Concrete.” As a technical paper, this section has its own small literature review, methods, results, discussion, and conclusion sections. The research in this section was designed to satisfy Objective 2 listed in Section 1.3.

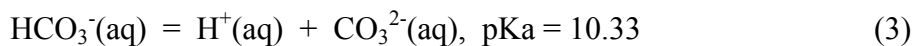
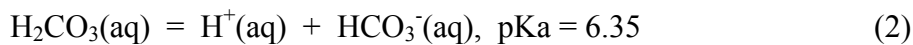
5.1 Background

The concentration of carbon dioxide is thought to have increased considerably since the industrial revolution due to anthropogenic activity and may have an impact on global climate change. The production of portland cement contributes to carbon dioxide emissions through both

energy usage and calcination, the chemical reaction whereby calcium carbonate dissociates into carbon dioxide and calcium oxide, a major component of portland cement. However, a significant portion of the carbon dioxide produced can be re-absorbed by the concrete in the reverse reaction to calcination, commonly referred to as carbonation (Pade and Guimaraes 2007). The carbonation process is generally very slow, taking years if not decades, for most concrete applications. There is interest in accelerating this process for appropriate primary life applications of concrete and for secondary usages of recycled concrete aggregate in order to make the life cycle of concrete structures more carbon neutral with respect to the calcination reaction.

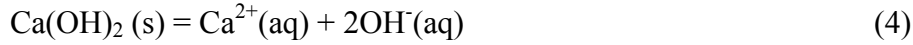
5.1.1 Concrete Carbonation and Carbon Dioxide Exposure in Ambient Air

The carbonation process is frequently modeled as carbon dioxide dissolving in water and then reacting with the portlandite (calcium hydroxide) in the cement paste in concrete to form calcite (calcium carbonate). Equations 1-3 represent chemical equilibriums in a typical aqueous (aq) carbonate system:



Equation 1 represents dissolution of gaseous (g) carbon dioxide into water and the equilibrium is typically represented by Henry's Law (Snoeyink and Jenkins 1980). In the water solution the dissolved carbon dioxide can then further dissociate into bicarbonate and carbonate ions with the equilibrium constants given by the noted pKa values for dilute aqueous systems. Water in concrete pores may be much more concentrated, but these pKa values still provide relative information.

The higher pH of pore water in uncarbonated cement paste is usually caused by the dissociation of solid (s) calcium hydroxide, a major component of hydrated cement, which can then react as in the following chemical reactions of the carbonation process:



The reactions in Equations 1-5 continue over time with the addition of carbon dioxide from the environment, allowing more calcium carbonate to form until theoretically all of the calcium hydroxide could be converted to calcium carbonate (Engelson 2005).

Concrete carbonation in concrete structures has been widely studied for many decades, and is usually a very slow process, with significant carbonation on outer surfaces, and a *carbonation front*, slowly progressing inward at typically decreasing rates of millimeters or less annually. The *rate of carbonation* commonly refers to the rate of progression of this carbonation front and the depth of this front of carbonation (D_c) for these traditional applications is traditionally modeled as a function of the square root of time (t) as in Equation 6, where k_c is the carbonation front coefficient.

$$D_c = k_c * t^{(1/2)} \quad (6)$$

According to researchers of traditional concrete carbonation such as in buildings, k_c increases at optimum ambient air relative humidity (50-60%), and with higher temperatures, higher partial pressures of carbon dioxide, higher porosities, larger surface areas, and higher pozzolan material contents (Neville 1981; Banks and McCabe 1988; Park and Tia 2003; Engelson 2005).

Engelsen et al. (2005) indicates that concrete saturated with water due to a 100 percent relative humidity under ambient air conditions carbonates more slowly than unsaturated concrete. It is theorized that in traditional concrete applications exposed to ambient air, water

from a high relative humidity may block the micro pores common in the cement paste. This may then limit the rate of carbonation by reducing the surface area available for the dissolution of carbon dioxide from the air at the ends of the pores as depicted in Figure 5.1.

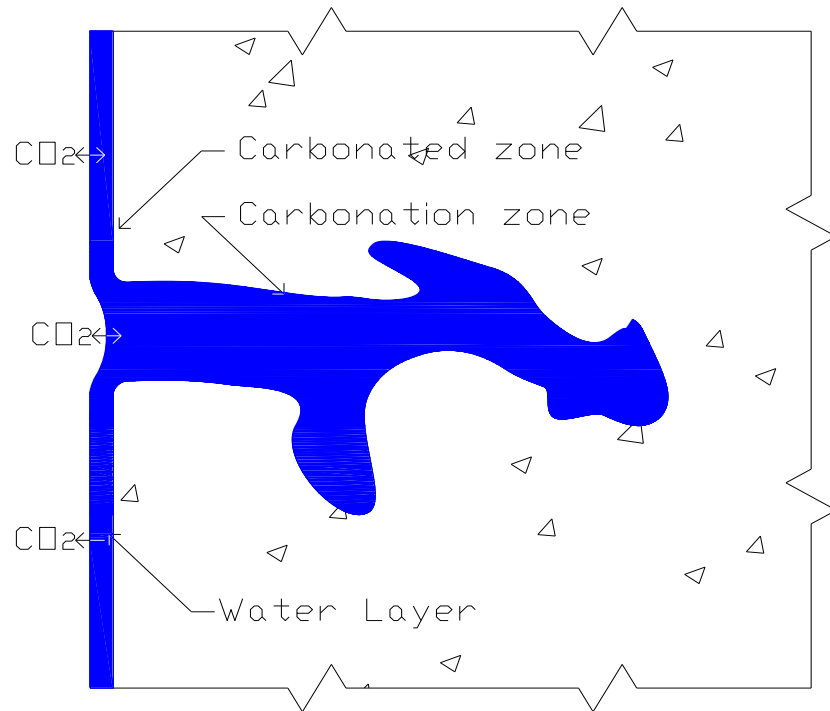


Figure 5.1. Concrete with lower *carbonation rate* at 100 percent relative humidity due to reduced water surface area at the ends of the saturated pores.

Conversely, if the relative humidity is too low, water will not be available in the shallow pores for calcium hydroxide to dissolve and little to no carbonation will occur. The theorized optimum *carbonation rate* based on relative humidity of typical concrete structures such as buildings exposed to ambient air is depicted in Figure 5.2.

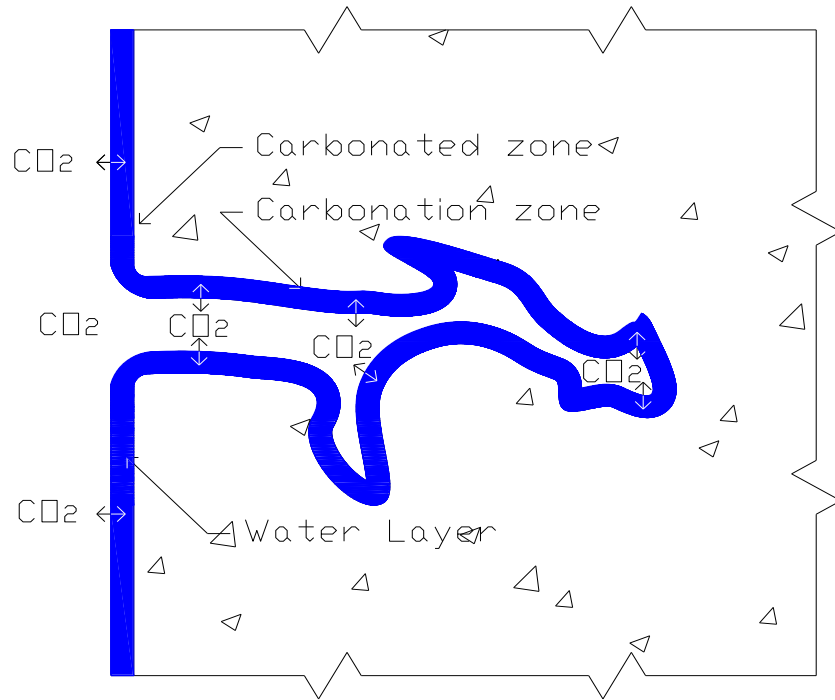


Figure 5.2. Optimum relative humidity for ambient air carbonation of concrete

The primary method for identifying carbonation depth in concrete is by using a pH indicator. The carbonation depth is frequently defined by industry as the depth at which a phenolphthalein indicator turns from red to colorless. A pH indicator, such as phenolphthalein, can be used because the pH decreases with carbonation due to the shift from calcium hydroxide dominance to calcium carbonate dominance (Pade and Guimaraes 2007; Lagerblad 2007; Chang and Chen 2006).

5.1.2 Pervious Concrete and Carbonation

Pervious concrete is a type of concrete with larger interconnected macro pores in addition to the typical cement paste micro pores. It is used for pavements and other structures where it is beneficial for water to be able to flow through. In pervious concrete, carbonation cannot be determined by depth from its outer surface because of the influence of its extensive interconnected pore structure, which allows ambient air and water to more readily reach interior spaces. When water flows through pervious concrete, the pH of the water will change due to the

presence of calcium hydroxide and calcium carbonate in the cement paste, with lower pH values indicating more calcium carbonate, or a higher amount of carbonation. Therefore, the pH of the exfiltrate may be a relative indicator of the amount of carbonation in the pavement over time.

Several previous studies on pervious concrete include information on the pH of water exfiltrated through pervious concrete. Thomle and Haselbach (2010) specifically focused on the declining pH of waters exfiltrated through pervious concrete exposed to ambient air over time. The lower pH of the more carbonated pavement is typically a preferred condition if exfiltrate from the pavement might discharge to sensitive waters. They found that pH decreased with time and that the pH of the exfiltrate from specimens with more outer surfaces exposed to ambient air lowered more rapidly than those with fewer exposed outer surfaces, an indication of increased carbonation with increased exposure to carbon dioxide in the ambient air. Park and Tia (2003) evaluated the pH of laboratory prepared pervious concrete specimens that were immersed in river water in order to study contamination from concrete alkalinity. Park and Tia (2003) only reported that the pH had dropped as their specimens soaked in river water, but no explanation was given for the drop. The other studies did not focus on pH or carbonation but provided some pH information of either pervious concrete or pervious concrete pavement systems, where the pavement systems include an underlying aggregate storage bed for stormwater management (Collins 2007, Luck et al. 2008, Kwiatkowski et al. 2007, and Horst et al. 2008).

Thomle and Haselbach (2010), Collins (2007), and Kwiatkowski et al. (2007) indicate that a decline in pH occurred in pervious concrete exfiltrate when aged with exposure to ambient air. Usually the decline was to a pH of 10 or less in six to 12 months. These studies used various types of waters periodically flowing through the pervious concrete, ranging from deionized water, to rain or stormwater. Collins (2007) reported the highest pH values of exfiltrated rain

water to be ~11.4, which dropped as the pervious concrete aged to ~9 within 1.3 years (see Figure 5.3).

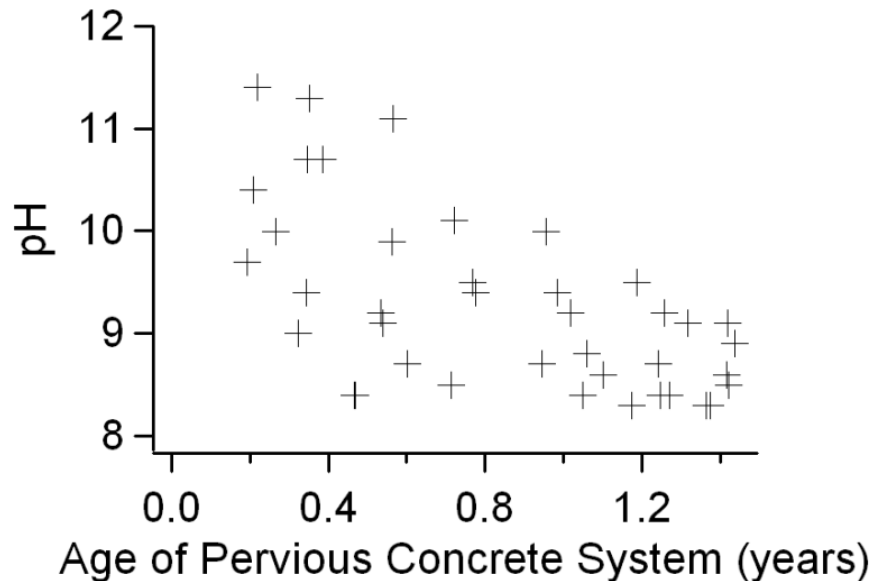


Figure 5.3. pH of pervious concrete system exfiltrate versus time from data in Collins 2007, but taken directly from Thomle and Haselbach (2010).

The pH of exfiltrate from an 8 month old pervious concrete specimen in the Luck et al. (2008) study was reported to be 9.3. The age of the pervious concrete in this study was determined by an author from contacting one of the primary researchers. The Kwiatkowski et al. (2007) study reported two data points within a year of placement that have a pH above 8, but the rest of the pH data after a year shows a pH close to neutral. The pH values in the Kwiatkowski et al. (2007) study were much lower than in other studies presumably because of buffering from exposure to lime stone aggregate.

Some representative data from the Thomle and Haselbach (2010) study is depicted in Figure 5.4. This study focused on pervious concrete independent of other materials in the pervious concrete system such as granular base material and sub-base material. Thomle and Haselbach (2010) focused on rate limiting conditions for carbonation, namely the low relative humidity of

the semi-arid climate in the laboratory, and the specimens were periodically inundated with deionized or tap water, representative of precipitation events with fairly clean rainwater.

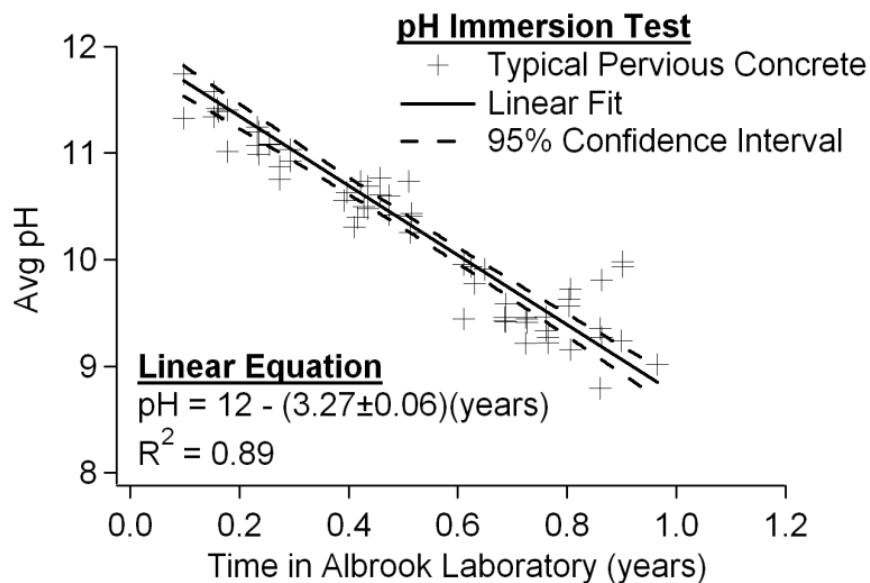


Figure 5.4. Change in pH of pervious concrete specimens exposed to ambient air at both ends (Thomle and Haselbach 2010).

The Park and Tia (2003) study reported pervious concrete specimens soaking in river water to have a pH that dropped from an average of 10.6 to 8.7 in 90 days. The Park and Tia (2003) study concluded that the low initial pH was due to the use of cement with high pozzolan content. Pozzolan is not cementitious by itself, but is thought to react with calcium hydroxide to form calcium silicate hydrates instead of directly forming them with exposure to water (Mehta and Monteiro 1993). The Park and Tia (2003) study indicated that this decline in pH took only a few months when immersed in river water which is contrary to the accepted carbonation rate theories of traditional concrete exposed to ambient air, where saturation due to high relative humidities decreased the rate of carbonation. However, river water contains a substantial amount of carbonate species, generally in the form of bicarbonates (Stumm and Morgan 1996), which may have contributed to the carbonation process. This leads to the hypothesis postulated herein

that concrete immersed in carbonate laden waters may carbonate at a faster rate than concrete exposed to ambient air and that this rate may be through a modified mechanism from the models in Figures 5.1 and 5.2.

The carbonate and bicarbonate levels in the Park and Tia (2003) study were not given. However, river water generally has concentrations of bicarbonate anions from 20 mg/L to 250 mg/L (Stumm and Morgan 1996). In traditional concrete, carbonate species are thought to diffuse more slowly into pores than carbon dioxide because carbonate species are larger molecules (Lagerblad 2007). However, with a higher concentration gradient caused by the additional carbonate species in the river water, the specimens may have carbonated at a higher rate than ambient air carbonation.

Higher carbonate species concentrations are not limited to rivers, but also exist in lakes and sea water. Carbonate species in alkaline lakes such as Hannington in Tanzania and Balangida in Kenya can have concentrations as high as 59,000 mg/L (Hecky and Kilham 1973). Sea water carbonate species concentrations vary depending on depth and latitude, with a typical concentration of ~140 mg/L (Gianguzza et al. 2000).

The primary objective of this study is to identify whether the pH of water exfiltrated through pervious concrete declines more rapidly when the concrete has been submerged in a bicarbonate solution than when exposed to ambient air. If so, then this indicates that concrete structures exposed to carbonate laden waters in their primary life might carbonate faster than indicated by the previous studies on ambient air exposure. It also implies that there may be an alternative accelerated method for secondary life or post disposal carbonation. The concentrations of bicarbonate used for this study directly reflect the range of bicarbonate concentrations found in rivers. If the rate of carbonation increases when the specimens were submerged it may be

attributed to both the breaking of pore water surface tension, allowing ions to exchange more freely, and the higher concentration gradient of dissolved carbonate species which may promote the diffusion of carbonate into the pores where it can react with calcium ions and produce calcium carbonate that precipitates in the concrete pores (Lagerblad 2007).

5.2 Methods

The testing protocol used in this study is based on the range of bicarbonate concentrations in rivers as reported in Stumm and Morgan (1996) and a control of deionized water. The concentrations chosen for this test were 0, 20, 100, and 250 mg/L. There was also a replenishment control with an additional 100 mg/L system with no replenishment of sodium bicarbonate solution for which de-ionized water is added to make up for evaporation. The specimens were submerged in an open bath of water with added sodium bicarbonate. This methodology represents an open system, which assumes that carbon dioxide will dissolve from the air, increasing the concentration of carbonate species, which is representative of an outdoor system. The overall testing design was to submerge pervious concrete specimens in water, and periodically test the pH of the waters in each basin, and also periodically remove the specimens and test the pH of water exfiltrated through the pervious concrete.

5.2.1 Specimen Preparation

The specimens were prepared the same way as the specimens in the Thomle and Haselbach (2010) study by using a mix of 54.4 kg (120 lb) of #8 granite aggregate (most fines removed), 13.6 kg (30lb) of portland cement and 4.1 kg (9 lb) of water. After mixing, 20 specimens were shaped using 10.2cm (4 inch) diameter molds, compacted by approximately 10 percent and covered with lids for curing. Specimens were allowed to cure for 7 days before removal from the cylindrical molds and lids, and dried for another 7 days and weighed before the initial pH

measurement. The material mix design, compaction level and curing period are representative of typical pervious concrete pavement placements.

5.2.2 Specimen Testing

Twenty cylindrical specimens of pervious concrete were submerged in five separate baths and exposed to the same ambient air conditions as in the Thomle and Hasebach (2010) study. Each bath contained four pervious concrete specimens. The volume of solution placed in each basin was 80 liters (21.1 gal). The concentration of sodium bicarbonate that was in each basin and other testing parameters are shown in Table 1.

Table 5.1. Dimensions and submersion bath characteristics of pervious concrete specimens

Containers	Specimens	Conc. NaHCO ₃ (mg/L)	Conc. Replenishment
1	1,6,11,16	0	Yes
2	2,7,12,17	20	Yes
3	3,8,13,18	100	Yes
4	5,9,13,18	250	Yes
5	4,10,15,20	100	No

All five 80 liter baths were open systems. Equilibrium with atmospheric carbon dioxide was expected to be reached in each bath. The pH tests were performed approximately every two weeks. First a sample of water from each basin was taken and tested for pH (*basin pH test*) and then the pH was also tested on each pervious concrete specimen (*pervious concrete pH immersion test*).

For the pervious concrete pH immersion tests, specimens were removed from their sodium bicarbonate bath and rinsed in de-ionized water. The specimens were placed in plastic containers and de-ionized water was poured over the specimens until they were completely immersed (approximately 2000mL or 33.81 oz), and then the pervious concrete specimens were left immersed in de-ionized water for 30 minutes before removal of the specimens. (Thirty minutes

was chosen because Montes et al. (2005) reported that 30 minutes was an appropriate time in which water would reach most of the micro pore structure in pervious concrete for porosity testing purposes.) After the specimens were removed from the pH water test, the remaining immersion solutions in the plastic containers were manually stirred for about 10 seconds and their pH recorded.

Before the specimens were placed back in their original sodium bicarbonate solutions, four of the baths were replenished to the original concentration of sodium bicarbonate, and one of the 100 mg/L solutions was not replenished. After completion of the testing period, the specimens were removed from their baths, air dried for two weeks, weighed and the pervious concrete pH immersion test repeated.

5.3 Results

Figures 5.5 and 5.6 depict the results of the basin pH tests, with pH plotted versus time in Figure 5.5 and the hydroxide concentration plotted versus time in Figure 5.6. The pH of water in each of the basins on average declined over time. The pH of the water with the higher concentrations of sodium bicarbonate declined more rapidly than the basins with a lower sodium bicarbonate concentration. (In Figure 5.5, the corresponding outdoor temperature is plotted to show that the temperature was much colder on the day of testing for the fourth data set, and may explain the increase in pH before 0.2 years as noted in the discussion section.) The hydroxide concentration plots in Figure 5.6 give a more visual representation of the rapid initial decline of the hydroxide ion concentration. The pH data used in Figures 5.5 and 5.6 can be seen in more detail in Appendix D.

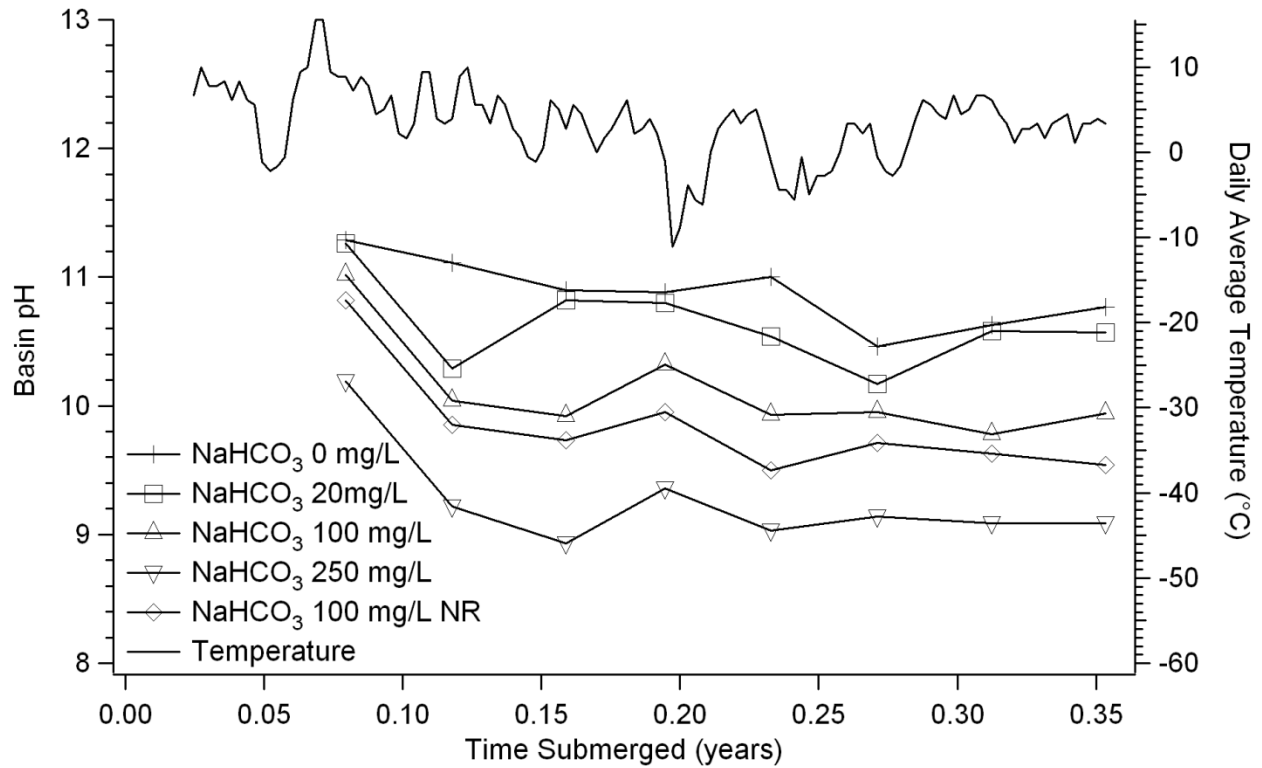


Figure 5.5. Basin water pH levels from the five basins were the pervious concrete specimens were submerged.

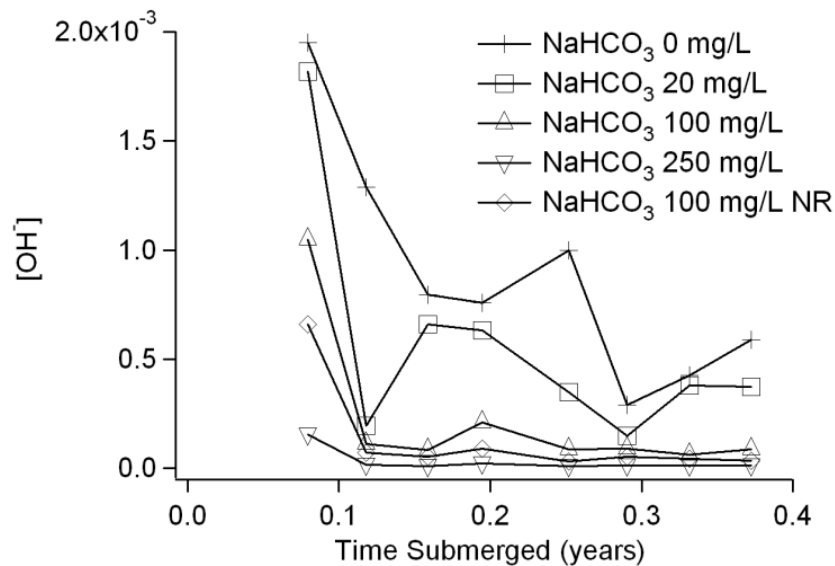


Figure 5.6. Basin water hydroxide concentrations from the five basins were the pervious concrete specimens were submerged.

The average pH of the specimens tested using the pH immersion test also showed a decline in the pH levels of specimens in all five basins. The average pH declined to a much lower level in

the specimens that were submerged in higher concentrations of sodium bicarbonate as can be seen in Figure 5.7. The pH data used in Figure 5.7 can be seen in more detail in Appendix D.

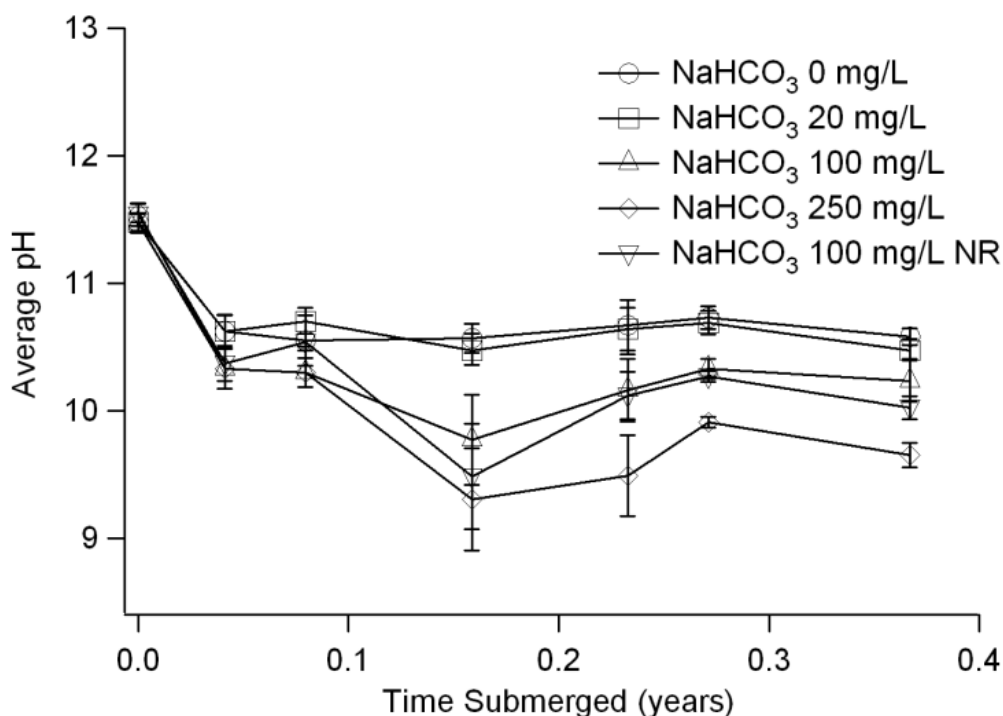


Figure 5.7. Average specimen pH from the specimens submerged in the five basins.

pH immersion tests were performed on the specimens before initial submersion in sodium bicarbonate solutions and after the specimens were allowed to dry for two weeks. All of the pH values dropped significantly as can be seen in Table 5.2. The corresponding difference in mass can also be seen in Table 5.3. The difference in mass is important because it can show if leaching played large role in the decline in pH, or if carbonation played a larger role.

Table 5.2. The change in pH from before submersion in basins with sodium bicarbonate solutions and final pH after drying for two weeks.

Concentration of NaCO ₃ added	Initial Avg pH	Final Avg pH
0 mg/L	11.47±0.09	9.26±0.13
20 mg/L	11.48±0.08	9.38±0.11
100 mg/L	11.47±0.09	9.49±0.10
250 mg/L	11.55±0.09	9.56±0.14
100NR mg/L	11.54±0.10	9.65±0.10

Table 5.3. The percent change in mass from dry specimens before submersion in basins with sodium bicarbonate solutions and final specimen mass after drying for two weeks.

Conc. Of bicarbonate	Avg Percent Change in Mass (%)
mg/L	
0	-0.511
20	-0.502
100	0.150
250	0.325
100NR	0.325

Basins with the same concentrations of sodium bicarbonate but with no concrete specimens were left in the same location as the basins with the submerged concrete for two weeks after completion of the submersion testing period in order to identify the difference in pH caused by the sodium bicarbonate and the environmental conditions of the laboratory. The results from these basins that just had sodium bicarbonate and no concrete are plotted in Figure 5.8 with calculated equilibrium pH values using only sodium bicarbonate solutions, sodium bicarbonate solutions saturated with calcium hydroxide without carbon dioxide exposure, and the calculated sodium bicarbonate solutions saturated with calcium carbonate with carbon dioxide exposure.

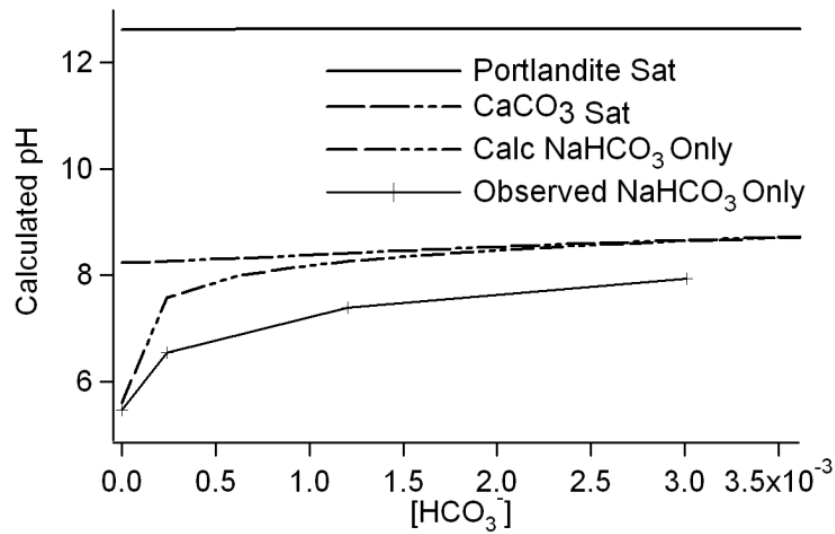


Figure 5.8. Calculated equilibrium pH values to show the affects sodium bicarbonate has on the pH of saturated solutions of portlandite and calcite.

5.4 Discussion

The results indicate that there is a more rapid decrease in the pH when the bicarbonate level of the water is higher. The decrease is not smooth, but the fluctuations of the pH data can be explained by both temperature fluctuations and some variability in the deionized water. The outside temperature is plotted with the basin pH values to show that very low temperatures correlate with a pH spike that can be seen in Figure 5 before 0.2 years. This spike may have been caused by an increase in solubility of calcium hydroxide from low temperatures. Calcium hydroxide is one of the few ionic compounds that are more soluble at lower temperatures (Yeatts and Marshall 1967).

The pH of the pervious concrete from the Thomle and Haselbach (2010) laboratory test declined much more slowly than the pH of pervious concrete submerged in bicarbonate solutions as can be seen in Figure 9. This indicates that there may be a change in the rate limiting step for carbonation. It is postulated that ambient carbon dioxide dissolution is no longer limiting. The

increased concentration gradient of carbonate species in the bicarbonate baths may cause a higher diffusion rate than from only ambient air carbon dioxide dissolution, allowing the carbonation rate to increase (Lagerblad 2007). Higher concentrations of sodium bicarbonate also had higher rates of decline in pH levels. Thus, higher rates of carbonation occur when pervious concrete is submerged in higher concentrations of sodium bicarbonate.

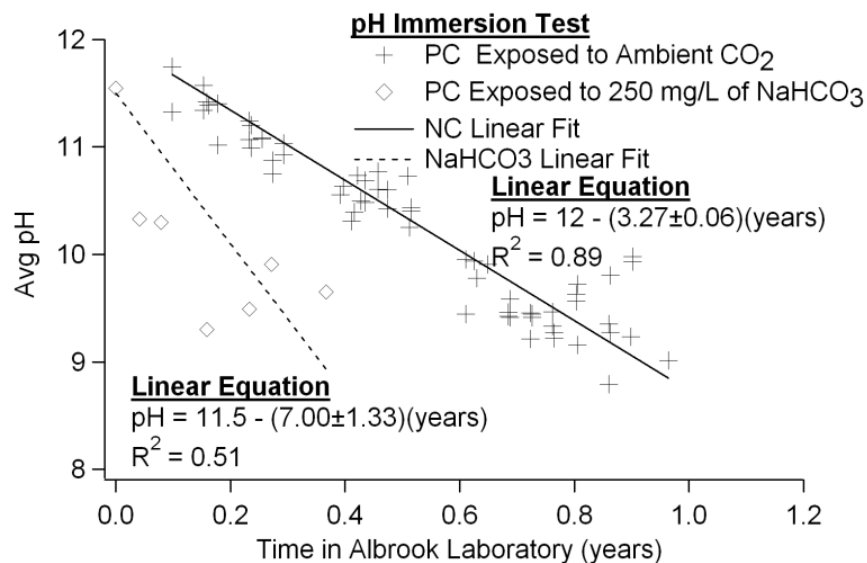


Figure 9. The pH from the pervious concrete (PC) specimens that had no end covers (NC) from the Thomle and Haselbach (2010) study are compared to the specimens immersed in 250 mg/L of sodium bicarbonate solution.

A possible mechanism for the accelerated decline of the pH of pervious concrete when exposed to carbonate laden waters may be the increased availability of dissolved carbonate species combined with the removal of the dissolution surface area restriction for high relative humidities as previously depicted in Figure 5.1. For this accelerated mechanism, the rate of carbonation may no longer be controlled by carbon dioxide dissolution from ambient air as depicted in Figure 10.

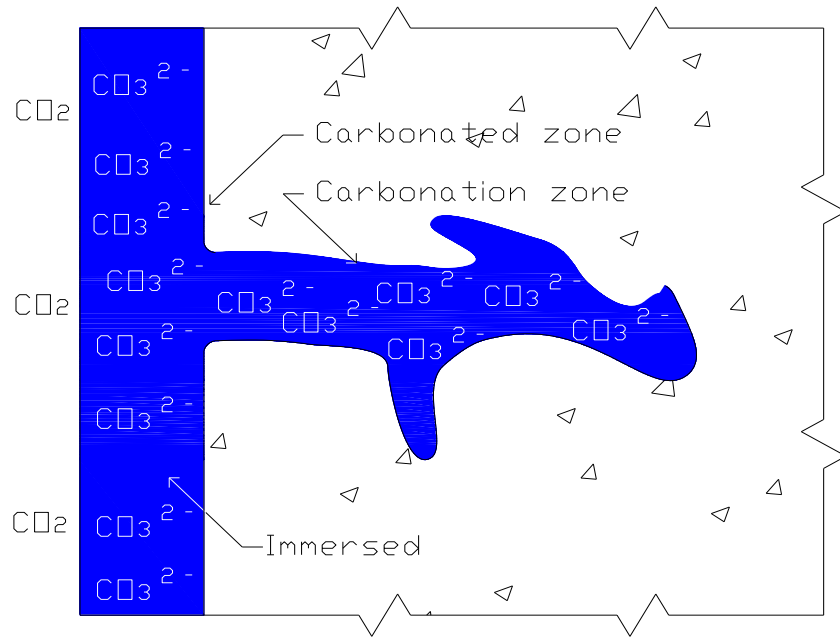


Figure 10. Proposed mechanism for the accelerated carbonation of pervious concrete when exposed to carbonate laden waters with the carbonation rate no longer limited by carbon dioxide dissolution from the air and lower carbonate concentration gradients.

It was also noted that a layer of solids formed in each basin, mostly in the control basin and the basin with less sodium bicarbonate added. These solids are assumed to be from the leaching of calcium hydroxide out of the cement paste. According to Lagerblad et al. (2007), in these cases, the concentration gradient was too low to cause carbonate species to diffuse into the pores of the concrete, instead the calcium hydroxide leached out into the basin water. Carbonation may have occurred, but not in the concrete. This assumption of leaching is further verified by the reduction of mass of the pervious concrete specimens in the basin with zero and 20 mg/L of sodium bicarbonate.

The difference in pH between the replenished and the non-replenished 100 mg/L sodium bicarbonate basins was insignificant, but the mass had more of an increase in the specimens that were submersed in the non-replenished basin. This can be explained by a loss of dissolved

calcium being removed when the basin water was emptied and replenished. A small amount of calcium was removed every time the water was replenished because more would dissolve in the unsaturated water that replenished the basin, but the amount of calcium in the non-replenished basins remained unchanged.

5.5 Conclusions

When pervious concrete specimens were submerged in carbonate species laden water, the pH dropped more rapidly than when exposed to ambient air, which indicates that there may be a change in the rate limiting step for carbonation. It is postulated that ambient carbon dioxide dissolution is no longer as limiting. The pH of immersion water exposed to pervious concrete specimens drops even more rapidly when submerged in baths with higher concentrations of sodium bicarbonate, and may indicate that the increased availability of carbonates dissolved in solution provide a higher concentration gradient and thus react more quickly with calcium hydroxide in concrete.

The significance of this alternative accelerated mechanism for concrete carbonation is two-fold. First, primary applications of concrete with exposure to carbonate species water might carbonate more rapidly than concrete applications only exposed to ambient air. This rate information is important in understanding the life cycle carbon footprint of these primary applications. Secondly, this alternative mechanism may be useful in designing enhanced carbonation processes in concrete post its primary life, either prior to disposal or before or during secondary life applications.

More research is needed to investigate the mechanisms that accelerate the pH reduction in pervious concrete and concrete over time. These mechanisms are important because they may be used in the future to reduce atmospheric carbon dioxide by using concrete as a sink.

6 Discussion

6.1 Variations in pH associated with temperature.

6.1.1 Variation from temperature changes between pH tests of specimens exposed to ambient air carbon dioxide.

The water temperature of both the deionized water and the tap water may have been affected by seasonal variations, which may explain some of the divergence in the pH values from the pH infiltration and pH immersion tests. The solubility of both calcium hydroxide and calcium carbonate increases significantly with decreases in temperature (Yeatts and Marshall 1967; Johnson and Williams 1916). The deionized water or tap water may have been much cooler on testing days that the outside temperature was very low. Testing at lower temperatures using the deionized water or tap water may have caused more calcium hydroxide to dissolve, raising the pH levels. The temperature of the water used for pH infiltration and immersion tests were not actually measured.

6.1.2 Variations in water temperature between pH tests of specimens exposed to carbonate laden waters

As just discussed in Section 6.1.1, the pH varies with temperature due to the solubility of calcium hydroxide and calcium carbonate in water. The effects of these variations were only evident one day when the average outside temperature dropped below negative 11 degrees centigrade. The temperature in Albrook Laboratory would not have dropped below freezing, but may have dropped below 10 degrees centigrade. According to Visual MINTEQ, the change in temperature would be enough to raise the equilibrium pH without carbon dioxide exposure 0.4 pH units, which is just relative information. This temperature change only seemed to affect the pH of the basins. The deionized water seemed cooler, but did not appear to significantly affect the pH immersion test See Figure 5.5. There is a trend with the outside temperature and pH in the basins.

6.2 Variations in pH due to contaminated deionized water

6.2.1 Variations in pH test of specimens exposed to ambient air carbon dioxide due to possible deionized water contamination.

Variation in pH may also be caused by water that has not fully deionized. There were some cases where the pH was observed to decrease significantly for multiple specimen batches and then the pH increased on the next set of tests to almost the values seen before the significant drop in pH levels. Since the same buffering solutions and the same pH meter were used, the deionized water appears to be contaminated and not fully deionized. The pH values from August 18-19, 2009 were omitted, due to suspicion of contamination, from calculations that were used to determine the slope of the rate of pH decline shown in Figures 4.2, 4.3, 4.6, and 4.7.

6.2.2 Variations in pH test of specimens exposed to carbonate laden waters due to possible deionized water contamination.

As stated earlier in Section 6.2.2, there was some suspicion that the deionized water from the Laboratory in Dana 117 was occasionally contaminated. On November 4, 2009, water that was supposed to be deionized had a pH of 4.5, and had a pH below 7 when exposed to pervious concrete specimens that previously had pH level above 10 when exposed to deionized water. When the low pH from the deionized water was realized, testing immediately stopped and the data from specimens that were suspect were not recorded.

6.3 Variations in pH due to blocked micro pores and portlandite production

6.3.1 Variations in pH test of specimens exposed to ambient air carbon dioxide due to potentially blocked micro pores opening up and continued portlandite production.

In some cases, the pH of certain specimens were observed to have slight increases in pH before declining again. These increases may be explained by two separate events or a combination of two events. One hypothesis is that calcium carbonate may dissolve enough in pores to allow previously closed off pockets of portlandite (calcium hydroxide) to dissolve, thus

increasing the pH levels temporarily until that pocket of portlandite has either fully carbonated or the pore is resealed by calcium carbonate precipitation. Pockets of portlandite may exist in partially carbonated zones. As carbonation occurs, calcium carbonate precipitates out of solution in the pores. The larger calcium carbonate molecules may potentially seal off some of the pores, not allowing the pore water to interact and affect water that is exposed to the cement paste (Fernandez Bertos et al. 2004; Lange et al. 1996). The other hypothesis is that more portlandite is formed from continued hydration in cement paste. The hydration reaction that forms calcium silicate hydrate and calcium hydroxide continues for years after the cement is first placed (Wild and Khatib 1997). The production of portlandite after initial hydration according to Wild and Khatib (1997) is depicted in Figure 6.1.

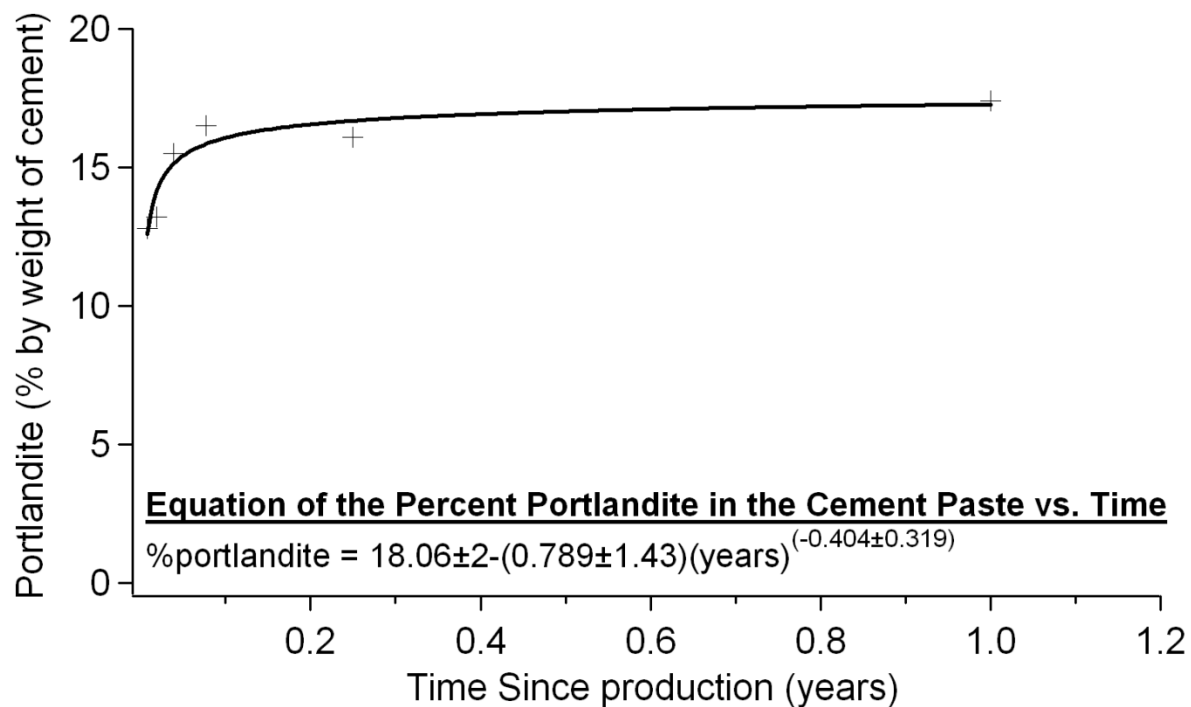


Figure 6.1. Increase in portlandite from the continuation of the hydration reaction.

Although it is likely that continued hydration does occur in the cement paste of pervious concrete, it is possible that continued hydration may be affected by the open pore structure

associated with pervious concrete. In that case the information given by Figure 6.1 is only relative.

6.3.2 Variations in pH test of specimens exposed to carbonate laden water due to potentially blocked micro pores opening up and continued portlandite production.

The same two potential factors in pH variation that were mentioned in section 6.3.1, pores being blocked and re-opened and portlandite production, may be even more significant in pervious concrete specimens submerged in carbonate laden waters.

Calcium leaching will be discussed later in Section 6.4, and may contribute to sealing off pores due to precipitation of calcium carbonate (Lagerblad 2007). The concentration gradient of calcium hydroxide can cause the calcium ion to move toward the entrance of the micro pore. At the same time if carbonate species are abundant in the water outside the micro pore, the free calcium ion and the carbonate may meet in the pore eventually closing it off. Instead of leaching out the calcium hydroxide would stay in equilibrium with the sealed pore. If the calcium carbonate dissolved during later testing, additional calcium hydroxide may be released. If enough of the micro pores are opened up at one time the pH may increase from the added calcium hydroxide in solution.

As also stated in Section 6.3.1, the hydration reaction continues in the cement paste producing more portlandite. This continued production of portlandite could potentially affect the pH of specimens submerged in carbonate laden waters more than specimens exposed to varying levels of carbon dioxide because of the shorter time span of testing from initial production of the concrete specimens. As depicted in Figure 6.1, portlandite production slowly declines as the cement paste ages, but potential increases in portlandite may also cause temporary increases in the pH levels observed.

6.4 Leaching from submerged specimens exposed to varying levels of bicarbonate.

It is evident that carbonation was occurring in all of the five basins with varying concentrations of sodium bicarbonate. During the first few two week periods of testing, as stated in Section 5.4, a layer of crystalline solid formed on the surface of all of the basins. The entire surface of the water in the basins without sodium bicarbonate added and with only 20 mg/L sodium bicarbonate added was covered with a crystalline material believed to be calcium carbonate. The other three basins with higher sodium bicarbonate concentrations only had small patches of the crystalline material floating on the surface. It was not verified that the crystalline material was calcium carbonate, but other studies performed by the Minnesota Department of Transportation in Snyder and Bruinsma (1996) identified precipitated material from crushed concrete leachate as calcium carbonate.

According to Lagerblad (2007), carbonation can occur differently in submerged specimens depending on the speed of carbonate diffusion from the outside of the cement paste and the speed of diffusion of calcium ions from the inside of the cement paste. More leaching occurred in the basin without added sodium bicarbonate, which lead to the hypothesis that more leaching can occur due to the lack of a carbonate concentration gradient to increase carbonate diffusion into the cement paste. The specimens in the basins with higher concentrations of sodium bicarbonate only experienced small amounts of calcium leaching. It is hypothesized that the speed of diffusion of carbonate was greatly increased due to the higher concentration gradient of carbonate on the outside of the cement paste. The two hypotheses are also supported by both Tables 5.2 and 5.3.

The mass of the specimens without sodium bicarbonate and with 20 mg/L sodium bicarbonate decreased in mass over the testing period, which can be explained by calcium

leaching. The specimens that were submerged in the 100 mg/L and 250 mg/L of sodium bicarbonate gained mass. The increase in mass in these specimens can be explained by the higher atomic weight of calcium carbonate over calcium hydroxide. From this we can assume that most of the carbonation and the corresponding precipitation of calcium carbonate occurred in the cement pores of specimens that were submerged in higher concentrations of sodium bicarbonate.

6.5 Deionized versus tap water used for prediction of pH levels.

The pervious concrete specimens were tested with both deionized water and tap water as stated in Section 4.2. The reason for using both deionized water as well as tap water is because deionized water gives a better representation of the pore pH levels in the pervious concrete specimens. The deionized water may also represent very clean rainwater exfiltrated through clean pervious concrete pavement. However, if testing from deionized water alone is used to predict the decline in pH of waters exfiltrated through or exposed to pervious concrete pavement, the prediction may be very conservative. Testing with deionized water is not a good representation of rainwater that exfiltrates through in-place pervious concrete pavement, which can contain dissolved minerals from exposure to soot and dirt on pavement surfaces. Runoff from other areas can also contain minerals from the soil, which can lessen the effects that the concrete has over the pH level of exfiltrated water. Tap water may better represent the pH decline of water exfiltrated through pervious concrete, and in the case of runoff from other areas it too may be conservative. As reported by the City of Pullman (2009), the tap water in Pullman has an average hardness of 116 mg/L (five year average). Runoff exposed to soils may potentially have even more dissolved minerals than the tap water in Pullman.

6.6 Differences in slopes between the pH infiltration test (simulated small storm events) and the pH immersion test (simulated large storm events).

The variation from the pH infiltration test, which simulates smaller storm events, is increased because water may flow through different pathways within the pervious concrete specimen. Some paths through pervious concrete may be more carbonated than others. The larger storm events simulated by the pH immersion test showed more of an average pH throughout the specimens. The equations for the slope of pH decline of all three levels of ambient air restrictions are significantly different using a 90 percent confidence interval between the pH infiltration and immersion tests. The difference can be explained by dilution from larger volumes of water. In the pH infiltration test ~25 mL of water passes through the concrete specimen. In the pH immersion test the specimens are immersed in ~2000 mL of water. Although more surface area within the concrete specimens are in contact with water, in the pH immersion test, the larger amount of water may dilute it and there is also a lack of mixing while the specimen is submerged. Thus, a small amount of dilution may have caused the difference in slopes.

6.7 Statistics used to confirm differences in slopes between specimens exposed to varying levels of carbon dioxide.

In section 4.3, the slope of pH decline was calculated using IGOR Pro 6.1.2.1. This program used the lowest chi squared value to calculate the best fit slope of each line. The associated 95 percent confidence interval was also calculated using IGOR Pro 6.1.2.1, which shows that if an infinite amount of testing was performed 95 percent of the resulting slopes would fall between a certain range that can be seen in Figure 4.6. If the 95 percent confidence intervals from the slope of pH decline between two levels of ambient air exposures do not overlap, than it can be confirmed with 95 percent confidence that the two slopes are significantly different. Equation

6.1 shows the calculations used by IGOR Pro 6.1.2.1 to determine a 95 percent confidence interval.

$$CI = [t_{(n-p, 1-\alpha/2)}][V(\hat{Y})]^{1/2} \quad (6.1)$$

Where,

$t_{(n-p, 1-\alpha/2)}$ is the t-value;

$V(\hat{Y})$ is the variance of a predicted model value and the observed value.

The difference between slopes was also confirmed using an F-test with an alpha value of 0.05. The following is the procedure used for using an F-test to determine if two equations are significantly different.

The error sum of squares (ESS) was calculated using the equation from the first linear fit ($y_1=m_1+b$) and the observed data that was used to make the first linear fit (y_{obs1}). Equation 6.2 is used to calculate the ESS.

$$ESS = \sum (y_1 - y_{obs1})^2 \quad (6.2)$$

From the ESS and the degrees of freedom ($df_{EMS} = n-1$, n = the number of y_{obs1}) the error mean square (EMS) is calculated, as depicted in Equation 6.3.

$$EMS = ESS / (df_{EMS}) \quad (6.3)$$

The hypothesis sum of squares (HSS) was then calculated using the equation from the second linear fit ($y_2=m_2+b$) and the observed data that was used to make the first linear fit (y_{obs1}), as depicted in Equation 6.4.

$$HSS = \sum (y_2 - y_{obs1})^2 \quad (6.4)$$

The conditional mean square (CMS) was then calculated using the HSS and the ESS previously calculated as well as the corresponding degrees of freedom ($df_{CMS} = n-(n-1)$, n = the number of y_{obs1}) as depicted in Equation 6.5.

$$\text{CMS} = (\text{HSS}-\text{ESS})/(\text{df}_{\text{CMS}}) \quad (6.5)$$

The F_{calc} value was then calculated using the values previously determined for CMS and EMS as depicted in Equation 6.6.

$$F_{\text{calc}} = \text{CMS}/\text{EMS} \quad (6.6)$$

The F_{calc} value was then compared to the $F_{0.05, 1, n-1}$ value, which was looked up on an F table. Two F-tests were performed between the three linear equations formed by the pH infiltration test data, which can be seen in more detail in Appendix C. The resulting information shows that the three linear equations depicted in Figure 4.2 are significantly different with 95 percent confidence. This verifies that the 95 percent confidence interval bands used by Igor Pro 6.1.2.1 are correct.

7 Overall Conclusions and Recommendations for Future Research

7.1 Overall Conclusions

The initial primary goal of this research was to determine the rate of pH decline of waters exposed to aging pervious concrete to aid designers in the use of preventive measures in reducing the risk of possible damage to sensitive waters. This goal was met by the early aging linear approximation equations of the decrease in pH for the specimens that can be seen in Figures 4.2-4.5. These drops are from the pervious concrete layer alone, without further reductions in pH from exposure to base material.

The pH of water intermittently in contact with pervious concrete declines more quickly when it is aged with more external area exposed to ambient air, which partially satisfies Objective 1.1 as can be seen in comparing the TBC, BC, and NC data in Figures 4.2-4.5. The TBC specimens had the highest level of ambient air restriction and consistently had a lower overall rate of pH

decline as compared to the BC specimens with moderate exposure. Water exposed to the NC specimens had a faster decline in pH than that of the BC specimens. The level of ambient air exposure that best resembles pavement conditions is the specimens without caps (NC) because of the potential increased exposure to carbon dioxide from the ground, which is produced by the decomposition of soil organic matter by bacteria.

It was confirmed through testing with tap water as compared to deionized water that minerals in exfiltrated water lessens the effect that pervious concrete has on increasing the pH of the exfiltrated water. The equations for the specimens without caps (NC) in Figure 4.2 and 4.3 give an average pH below 10 within 8 months and below 9 within a year, for testing with deionized water, which is considered to be much more conservative (See discussion in Section 6.5). The equations for the specimens without caps (NC) that can be seen in Figures 4.4 and 4.5 are based on tap water, which is a less conservative approach, and give an average pH below 10 within 4 months and below 9 within 7 months. Thus, it is assumed that runoff from other areas that exfiltrates through pervious concrete may have a lower pH value because of the higher concentration of dissolved minerals in the water, which satisfies the rest of Objective 1.1. Also, minerals contained in dirt and soot on the surface of in-place pervious concrete may also decrease the exfiltrate pH of rainwater that falls directly on pervious concrete. The slope of pH decline using tap water may more accurately predict pH values of in-place pervious concrete.

Objective 1.2 is satisfied by using both the pH infiltration test (simulating small storm events) and the pH immersion test (simulating large storm events). Simulated large storm events may cause a dilution effect that reduces the pH level more than small storm events. Although the difference in the slopes of pH decline of deionized water using the pH infiltration and immersion tests are significant using a 95 percent confidence interval. The difference in time that it takes

for the pH of the specimens without caps (NC) to drop below 10 and below 9, are relatively insignificant (less than 0.5 months).

During the research an additional primary goal was hypothesized relating an alternative mechanism for pervious concrete carbonation in carbonate laden waters and became Objective 2. Objective 2 is satisfied, by aging pervious concrete specimens while submerged in water with different concentrations of sodium bicarbonate. The pH of deionized water exposed to the pervious concrete specimens that were submerged in carbonate species laden water declined more rapidly than when exposed to ambient air, which may indicate a change in the rate limiting step for the carbonation process. The pH of deionized water and the basin water, in which the specimens were submerged, declined more quickly when submerged in basins with higher concentrations of sodium bicarbonate. This increased decline in pH may be attributed to a higher concentration gradient of carbonate species outside the cement pores, which may have enhanced the diffusion of carbonate into the cement paste. Leaching and removal of calcium species were also noted as contributing factors to the pH decline in basins with little or no bicarbonate added.

7.2 Recommendations for future research

The research in this thesis was designed to focus on the declining pH of waters exposed to pervious concrete and not carbon sequestration. The methods used in this thesis only give relative information on the amount of carbonation that occurred within the pervious concrete specimens. The amount of carbon dioxide that was retained in the cement of the pervious concrete specimens is unknown. The total change in mass associated with the pervious concrete specimens would not necessarily represent the quantity of carbon dioxide absorbed because of leaching that was observed in both the specimens that were exposed to ambient air and carbonate laden waters. If the testing methods in this study are repeated the mass of the material that was

leached out must be considered in some way to quantify the total carbonation that occurred. Another approach would be to use a thermo gravimetric analysis to determine the extent of carbonation within the pervious concrete specimens as described in McPolin et al. (2009).

In the future, the quantity of carbon that is sequestered within the pervious concrete or crushed concrete should be evaluated using concrete that is submerged in carbonate laden waters. This may be accomplished by using a full speciation analysis of the basin water or other carbonation methods such as thermal gravimetric analysis (TGA) and mass spectrometry. It is also recommended to use even higher concentrations of carbonate species than used in this study to further increase the concentration gradient between the outside water and the pore water. It would also be less difficult to analyze the data from this experiment if the experiment is performed in a closed system instead of in an open system. If a closed system is used, the amount of carbonation that occurred from the carbonate laden water can be directly determined.

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Appendices

Appendix A: pH data from aged specimens exposed to ambient air

The pH values from aged specimens exposed to ambient air carbon dioxide are listed in Table A.1, and are considered supporting information for results of Chapter 3. The water samples from pH immersion tests from the corresponding underlined pH values in Table A.1 may have been contaminated by residue in the 25 mL beakers described in Section 2.2.3. The underlined values are not considered in results of Chapter 3.

Table A.1. pH data from aged specimens exposed to ambient air carbon dioxide.

EA1	Age (yr)	1.68	1.71	1.78	1.89	1.96	2.03	2.24	2.39
	Avg pH	10.06	9.02	<u>9.63</u>	<u>9.43</u>	<u>9.15</u>	<u>9.29</u>	9.19	8.69
EA2	Age (yr)	1.68	1.71	1.78	1.89	1.96	2.03	2.24	2.39
	Avg pH	9.74	8.68	<u>8.88</u>	<u>8.79</u>	<u>8.66</u>	<u>7.88</u>	9.02	8.81
EA3	Age (yr)	1.67	1.70	1.77	1.88	1.95	2.02	2.23	2.38
	Avg pH	9.34	8.99	<u>8.96</u>	<u>8.65</u>	<u>8.56</u>	<u>7.46</u>	9.02	8.85
EA4	Age (yr)	1.67	1.70	1.77	1.88	1.95	2.02	2.23	2.38
	Avg pH	9.97	9.74	<u>9.41</u>	<u>9.13</u>	<u>8.86</u>	<u>8.87</u>	9.02	8.81
B	Age (yr)	4.79	4.81	4.88	4.99	5.06	5.13	5.35	5.49
	Avg pH	9.96	9.49	<u>9.83</u>	<u>9.46</u>	<u>8.98</u>	<u>9.09</u>	9.14	8.99
C	Age (yr)	4.55	4.57	4.65	4.76	4.82	4.92	5.11	5.26
	Avg pH	9.13	9.26	<u>9.03</u>	<u>9.11</u>	<u>8.86</u>	<u>8.55</u>	9.03	8.94
TP	Age (yr)	2.82	2.89	3.00	3.07	3.14	3.36	3.50	
	Avg pH	9.74	10.01	<u>9.61</u>	<u>9.24</u>	<u>8.70</u>	<u>9.39</u>	9.11	
J	Age (yr)	2.43	2.45	2.53	2.64	2.70	2.79	2.99	3.14
	Avg pH	9.87	9.44	<u>9.45</u>	<u>9.28</u>	<u>8.65</u>	<u>8.43</u>	9.28	9.22

Appendix B: pH data from specimens exposed to ambient air

The pH data in this appendix is from specimens exposed to ambient air carbon dioxide, which is summarized in Chapter 4. This data is included as supporting information for Chapter 4, and does not necessarily give any additional information.

As stated in Section 2.1, there are four different batches of pervious concrete. There are some variations within the mixing of each batch of concrete. The following results from the pH

infiltration and immersions tests were originally separated to identify differences in production that may affect pH testing. Separating out the four batches also helped identify days that the deionized water may have been contaminated as discussed in Section 6.2.1.

Shown in Figure B.1 are the average pH values of the WA pervious concrete specimens tested with the pH infiltration test. The specimens are aged under the three levels of ambient air restrictions as described in Section 2.1. One data point was omitted from Figure B.1, Chapter 4 results, and all slope of pH decline equations because of the obvious discrepancy, which is depicted in Figures B.3 and B.4 as well as Table B.1, but is not visible Figure B.2. The discrepancy may have been caused by contaminated deionized water on August 18, 2010 as can be seen in Table 1. In Figures B.2-B.4, the data from approximately the 295th day after production was omitted because possible deionized water contamination.

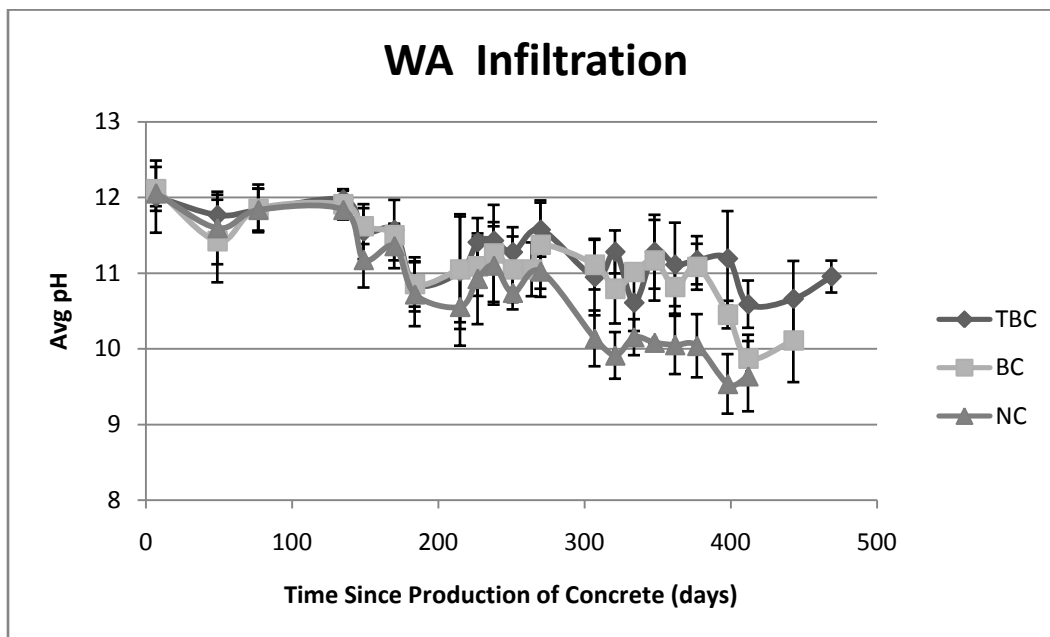


Figure B.1. Averaged pH infiltration test data from the WA batch of pervious concrete (error bars are at a 90 percent confidence interval).

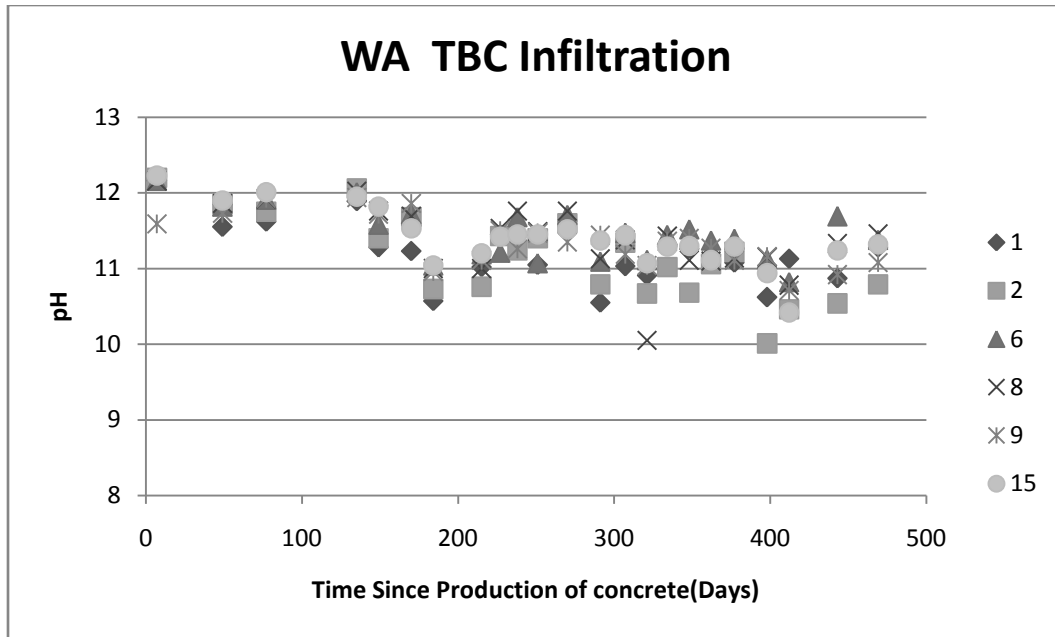


Figure B.2. pH infiltration data from individual WA specimens aged with ambient air restriction on both the top and the bottom (TBC).

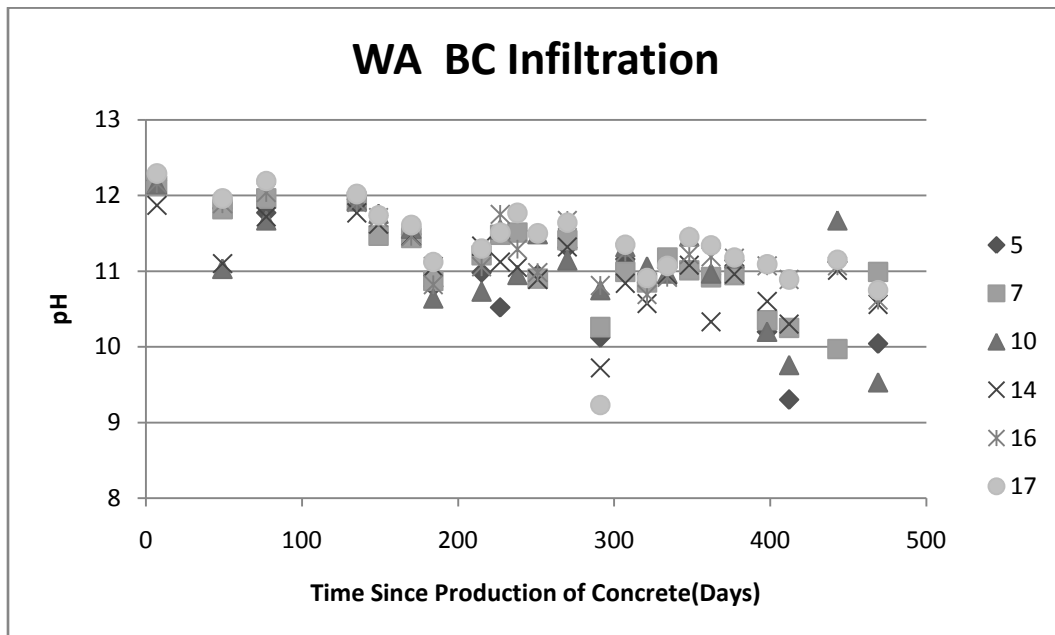


Figure B.3. pH infiltration data from individual WA specimens aged with ambient air restriction on the bottom (BC).

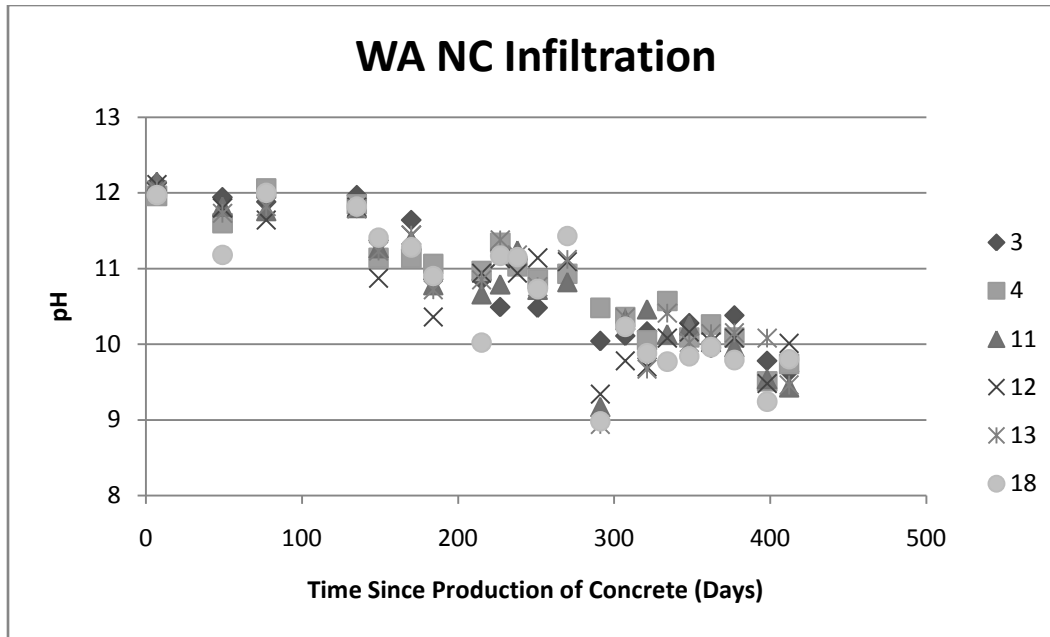


Figure B.4. pH infiltration data from individual WA specimens aged without ambient air restriction on the top or bottom (NC).

Table B.1. pH infiltration test data from the WA specimens (dates underlined used tap water for testing) (Continued).

WA Specimens	1	2	6	8	9	15	5	7	10	14	16	17	3	4	11	12	13	18
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC	NC
11/7/2008	12.2	12.2	12.2	12.2	11.6	12.2	12.2	12.1	12.2	11.9	12.2	12.3	12.1	12	12.2	12.1	12	12
12/19/2008	11.6	11.9	11.8	11.9	11.7	11.9	11.8	11.8	11	11.1	11.9	12	11.9	11.6	11.8	11.8	11.7	11.2
1/16/2009	11.6	11.8	11.9	11.9	11.9	12	11.8	12	11.7	11.7	12	12.2	11.9	12.1	11.8	11.6	11.8	12
3/15/2009	11.9	12.1	12	12	11.9	12	12	11.9	11.9	11.8	11.9	12	12	11.9	11.8	11.8	11.8	11.8
3/29/2009	11.3	11.4	11.6	11.8	11.7	11.8	11.5	11.5	11.8	11.6	11.7	11.7	11.4	11.1	11.3	10.9	11.2	11.4
4/19/2009	11.2	11.7	11.7	11.7	11.9	11.5	11.5	11.4	11.6	11.5	11.5	11.6	11.6	11.1	11.4	11.4	11.4	11.3
5/3/2009	10.6	10.7	11	11	11	11	10.8	10.9	10.6	11.1	10.8	11.1	10.9	11.1	10.8	10.4	10.7	10.9
<u>5/18/2009</u>	10.7	9.6	11.2	11.3	11	10.7	11.2	11.5	10.9	10.1	11.4	11.1	10.6	9.5	10.8	9.86	10.1	9.75
6/3/2009	11	10.8	11.2	11	11.1	11.2	11	11.2	10.7	11.3	11.1	11.3	10.9	11	10.7	10.9	10.9	10
6/15/2009	11.5	11.4	11.2	11.5	11.5	11.4	10.5	11.5	11.6	11.1	11.8	11.5	10.5	11.3	10.8	11.1	11.4	11.2
6/26/2009	11.4	11.2	11.7	11.8	11.3	11.5	11.5	11.5	11	11.1	11.3	11.8	11.1	11	11.2	10.9	11.2	11.2

Table B.1. pH infiltration test data from the WA specimens (dates underlined used tap water for testing) (Continuation).

WA Specimens	1	2	6	8	9	15	5	7	10	14	16	17	3	4	11	12	13	18
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC	NC
7/9/2009	11.1	11.4	11.1	11.5	11.5	11.5	11	10.9	11.5	10.9	11	11.5	10.5	10.9	10.7	11.1	10.8	10.7
<u>7/22/2009</u>	10.4	10.1	10.7	11	10.6	9.91	10.3	10.9	10.2	9.44	9.65	10.7	9.38	9.23	9.24	9.37	9.25	8.87
7/28/2009	11.6	11.6	11.7	11.8	11.4	11.5	11.3	11.4	11.1	11.3	11.7	11.6	11	10.9	10.8	11.1	11.1	11.4
<u>8/5/2009</u>	10.9	9.85	9.98	10.1	10.2	10.1	9.69	9.44	9.72	9.64	10.1	10.3	9.01	8.93	9.24	9.03	8.86	8.67
8/18/2009	10.6	10.8	11.1	11.1	11.4	11.4	10.1	10.3	10.8	9.72	10.8	9.23	10	10.5	9.17	9.34	8.94	8.98
<u>8/27/2009</u>	10.5	10.3	11	9.87	10.5	11	9.24	9.69	9.56	11	10.3	9.81	8.52	8.7	8.96	8.59	9.64	8.51
9/3/2009	11	11.3	11.5	11.4	11.2	11.4	11.2	11	11.3	10.8	11.3	11.4	10.1	10.4	10.3	9.78	10.4	10.2
9/17/2009	10.9	10.7	11.1	10.1	11	11.1	10.9	10.9	11.1	10.6	10.7	10.9	10.2	10.1	10.5	9.7	9.67	9.88
9/30/2009	11.3	11	11.4	11.4	11.4	11.3	11.1	11.2	11	11	10.9	11.1	10.5	10.6	10.1	10.1	10.4	9.77
10/14/2009	11.3	10.7	11.5	11.1	11.4	11.3	11	11	11.5	11.1	11.2	11.5	10.3	10.1	10.3	10.2	10	9.84
10/28/2009	11.2	11.1	11.4	11.1	11.3	11.1	11	10.9	11	10.3	11.2	11.3	9.95	10.3	10	10	10.1	9.96
11/12/2009	11.1	11.2	11.4	11.1	11.1	11.3	11.1	11	11.2	11	11.2	11.2	10.4	10.1	9.96	10.1	10.2	9.79
12/3/2009	10.6	10	11.1	11.2	11.2	10.9	10.2	10.4	10.2	10.6	11.1	11.1	9.78	9.51	9.54	9.48	10.1	9.24
12/17/2009	11.1	10.5	10.8	10.8	10.7	10.4	9.3	10.3	9.76	10.3	10.9	10.9	9.64	9.74	9.43	10	9.46	9.8
1/15/2010	10.9	10.5	11.7	11.3	10.9	11.2	11.1	9.97	11.7	11	11.1	11.2	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	8.91	8.75	9.62	9.47	9.66	9.36	8.69	8.62	7.84	8.91	8.7	9.44	7.78	7.68	7.75	8.02	7.87	7.52
2/10/2010	11.3	10.8	11.4	11.5	11.1	11.3	10	11	9.53	10.6	10.6	10.8	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.

Shown in Figure B.5 are the average pH values of the WA pervious concrete specimens tested with the pH immersion test. One data point was also omitted from Figure B.5, Chapter 4 results, and all slope of pH decline equations because of the obvious discrepancy, which is depicted in Figures B.6-B.8 as well as Table B.2. The discrepancy may have been caused by contaminated deionized water. As can be seen in Figures B.6-B.8, the data from approximately the 295th day after production was omitted because of possible deionized water contamination.

Two other data sets were omitted entirely from Figures B.5-B.8 because of pore mixing of the sample water in the pH immersion test. The testing dates of the omitted data points are highlighted in Table B.2

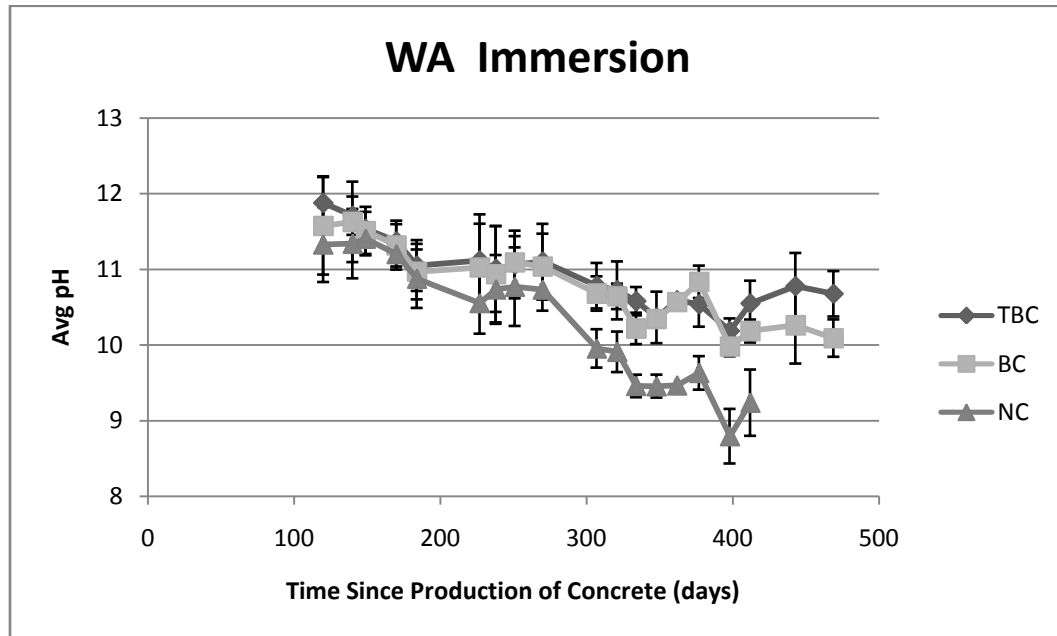


Figure B.5. Averaged pH immersion test data from the WA batch of pervious concrete (error bars are at a 90 percent confidence interval).

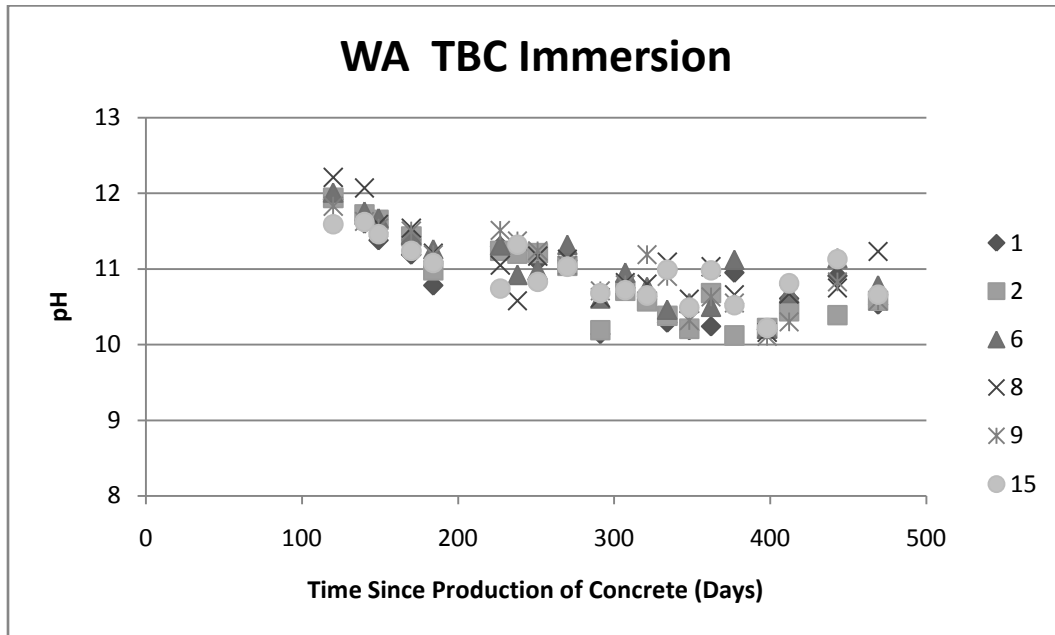


Figure B.6. pH immersion data from individual WA specimens aged with ambient air restriction on both the top and the bottom (TBC).

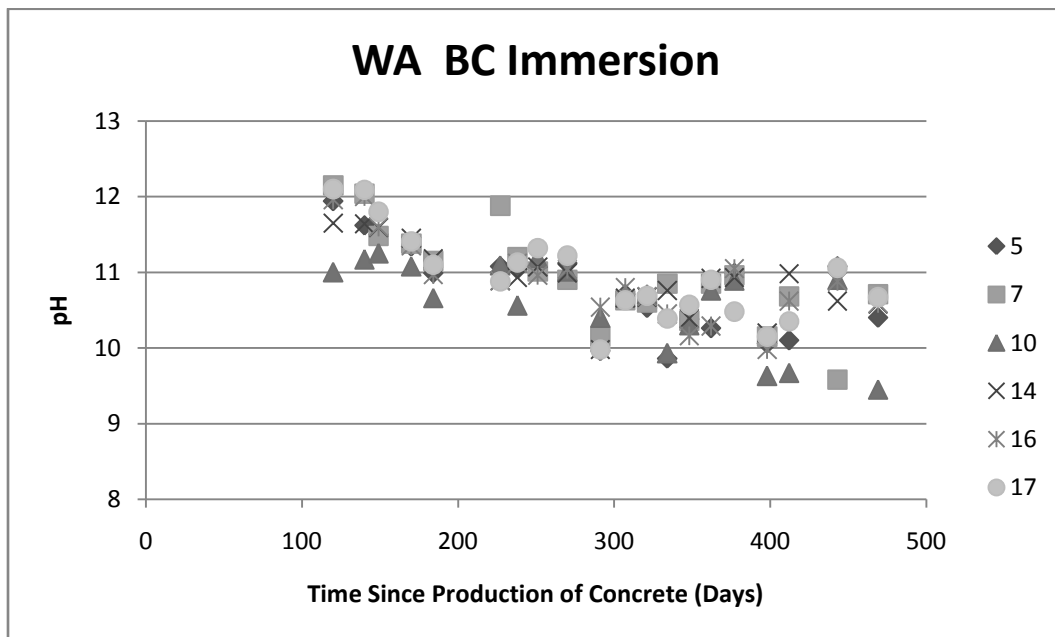


Figure B.7. pH immersion data from individual WA specimens aged with ambient air restriction on the bottom (BC).

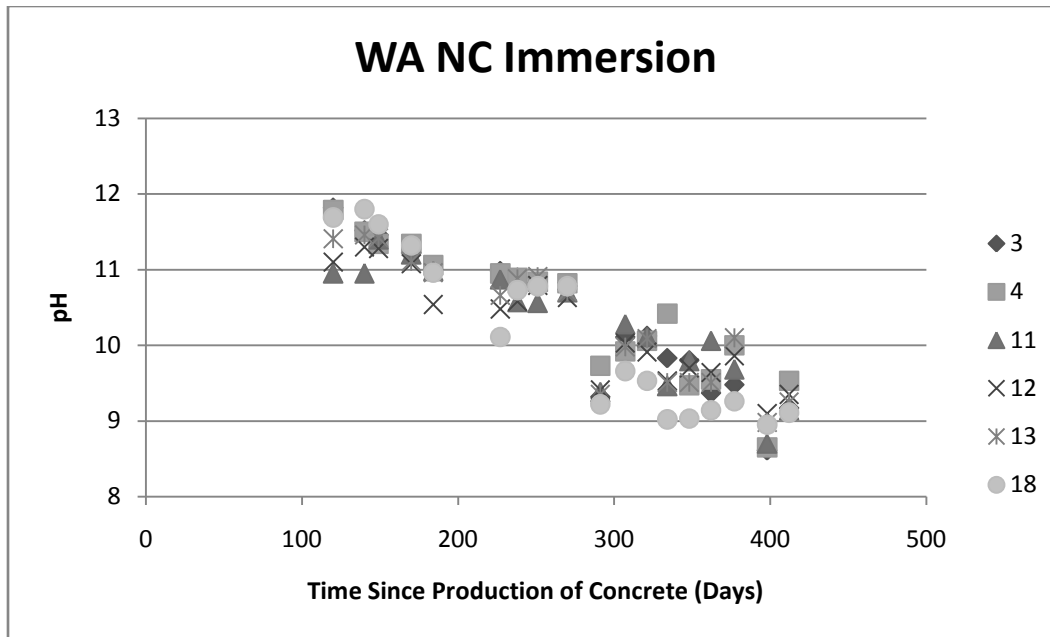


Figure B.8. pH immersion data from individual WA specimens aged without ambient air restriction on the top or bottom (NC).

Table B.2. pH immersion test data from the WA specimens (dates underlined used tap water for testing and highlighted data was omitted due to human error) (Continued).

WA Specimens	1	2	6	8	9	15	5	7	10	14	16	17	3	4	11	12	13	18
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC	NC
2/28/2009	11.9	11.9	12	12.2	11.8	11.6	11.9	12.2	11	11.7	12	12.1	11.8	11.8	11	11.1	11.4	11.7
3/20/2009	11.6	11.7	11.8	12.1	11.6	11.6	11.6	12	11.2	11.6	12	12.1	11.5	11.5	11	11.3	11.5	11.8
3/29/2009	11.4	11.7	11.7	11.6	11.5	11.5	11.5	11.5	11.3	11.6	11.6	11.8	11.5	11.3	11.4	11.3	11.4	11.6
4/19/2009	11.2	11.4	11.5	11.5	11.5	11.2	11.3	11.4	11.1	11.5	11.4	11.4	11.2	11.3	11.2	11.1	11.1	11.3
5/3/2009	10.8	11	11.3	11.2	11.2	11.1	11	11.2	10.7	11.2	11	11.1	11	11.1	11	10.5	11	11
5/18/2009	9.09	9.02	9.55	9.41	8.19	8.1	9.7	8.18	8.85	8.31	9.05	9.35	9.52	8.77	8.87	9.04	8.53	8.58
6/3/2009	10.1	10.5	10.6	9.66	9.42	10.3	10.7	9.38	9.76	11	10.1	10.7	10.2	10.1	9.5	10.2	9.91	9.55
6/15/2009	11.3	11.2	11.3	11.1	11.5	10.7	11.1	11.9	11.1	10.9	10.9	10.9	11	11	10.9	10.5	10.7	10.1
6/26/2009	11.2	11.2	10.9	10.6	11.4	11.3	11	11.2	10.6	10.9	11.1	11.1	10.9	10.9	10.6	10.6	10.9	10.7

Table B.2. pH immersion test data from the WA specimens (dates underlined used tap water for testing and highlighted data was omitted due to human error) (Continuation).

WA Specimens	1	2	6	8	9	15	5	7	10	14	16	17	3	4	11	12	13	18
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC	NC
7/9/2009	11.1	11.2	11	11.2	11.2	10.8	11.1	11	11.2	11.1	11	11.3	10.8	10.8	10.6	10.8	10.9	10.8
<u>7/22/2009</u>	9.48	9.54	9.71	9.74	9.76	9.21	9.65	9.55	9.69	9.67	9.6	9.8	9.12	9.22	9.21	9.71	9.25	9.19
7/28/2009	11.1	11	11.3	11.1	11.1	11	11.1	10.9	11	11	11	11.2	10.8	10.8	10.7	10.6	10.7	10.8
<u>8/5/2009</u>	9.35	9.31	9.58	9.58	9.55	9.42	9.38	9.34	9.51	9.32	9.25	9.63	9	8.9	8.99	8.89	8.97	8.9
8/18/2009	10.1	10.2	10.6	10.6	10.7	10.7	9.96	10.2	10.4	9.98	10.5	9.98	9.32	9.73	9.38	9.41	9.35	9.22
<u>8/27/2009</u>	9.36	9.2	9.68	9.45	9.46	9.55	9.3	9.32	9.33	9.63	9.43	9.46	8.83	8.94	8.86	8.71	8.86	8.64
9/3/2009	10.8	10.7	11	10.8	10.8	10.7	10.7	10.6	10.7	10.7	10.8	10.6	10.1	9.92	10.3	10	9.98	9.66
9/17/2009	10.6	10.6	10.8	10.8	11.2	10.7	10.5	10.6	10.7	10.7	10.7	10.7	10.1	10.1	10.1	9.91	10.1	9.53
9/30/2009	10.3	10.4	10.5	11.1	10.9	11	9.86	10.9	9.93	10.8	10.5	10.4	9.83	10.4	9.46	9.53	9.51	9.02
10/14/2009	10.2	10.2	10.6	10.6	10.3	10.5	10.4	10.4	10.3	10.4	10.2	10.6	9.8	9.47	9.79	9.7	9.51	9.03
10/28/2009	10.2	10.7	10.5	11	10.6	11	10.3	10.9	10.8	10.9	10.3	10.9	9.37	9.55	10.1	9.64	9.51	9.14
11/12/2009	11	10.1	11.1	10.7	10.6	10.5	11	11	10.9	10.9	11.1	10.5	9.48	10	9.68	9.86	10.1	9.26
12/3/2009	10.2	10.2	10.2	10.2	10.1	10.2	10.1	10.2	9.63	10.2	9.98	10.2	8.61	8.65	8.7	9.1	8.98	8.95
12/17/2009	10.6	10.4	10.7	10.7	10.3	10.8	10.1	10.7	9.67	11	10.6	10.4	9.17	9.53	9.14	9.35	9.25	9.11
1/15/2010	10.9	10.4	11.1	10.8	10.8	11.1	11.1	9.58	10.9	10.6	10.9	11.1	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	8.77	8.73	9.13	8.9	9.02	8.91	8.64	8.56	7.62	8.75	8.88	8.98	7.59	7.55	7.64	7.65	7.65	7.5
2/10/2010	10.5	10.6	10.8	11.2	10.6	10.7	10.4	10.7	9.45	10.6	10.6	10.7	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.

Shown in Figure B.9 are the average pH values of the WB pervious concrete specimens tested with the pH infiltration test. The specimens are aged under the three levels of ambient air restrictions as described in Section 2.1. No data points were omitted from Figure B.9 because there are no obvious discrepancies in Figures B.10-B.12. The deionized water on August 18, 2009 may not have been contaminated during testing of the WB set. Table B.3 is the raw data from the pH infiltration test on the WB set and just gives supporting information.

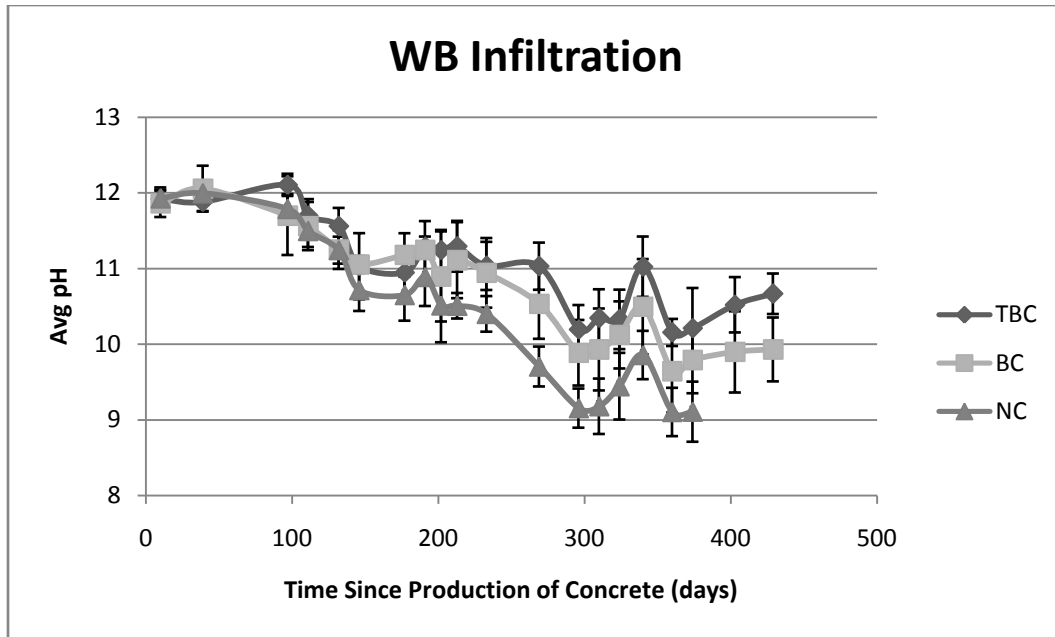


Figure B.9. Averaged pH infiltration test data from the WB batch of pervious concrete (error bars are at a 90 percent confidence interval).

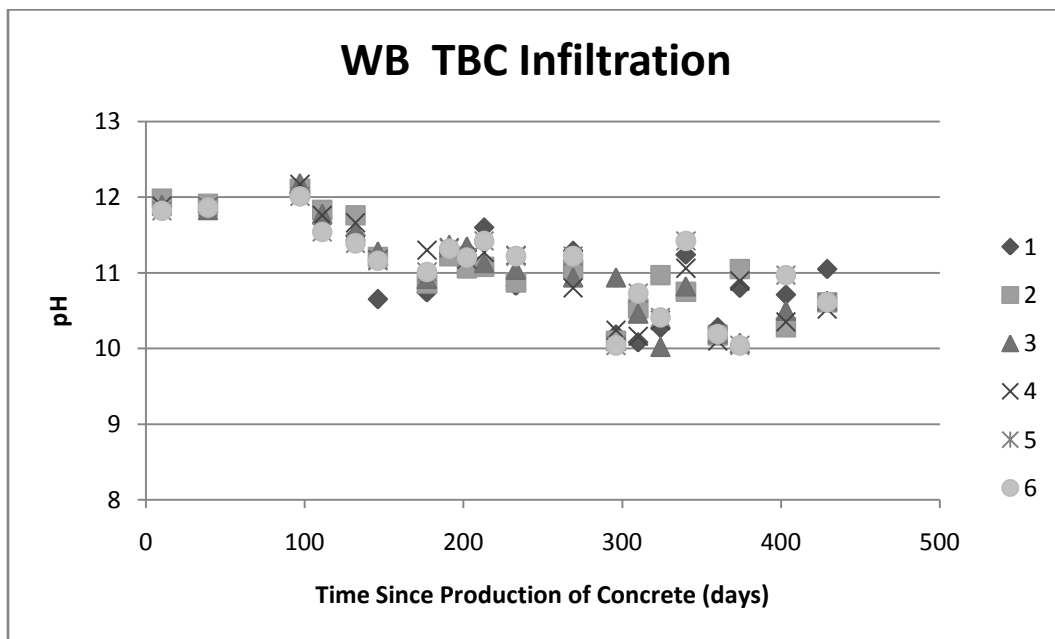


Figure B.10. pH infiltration data from individual WB specimens aged with ambient air restriction on both the top and the bottom (TBC).

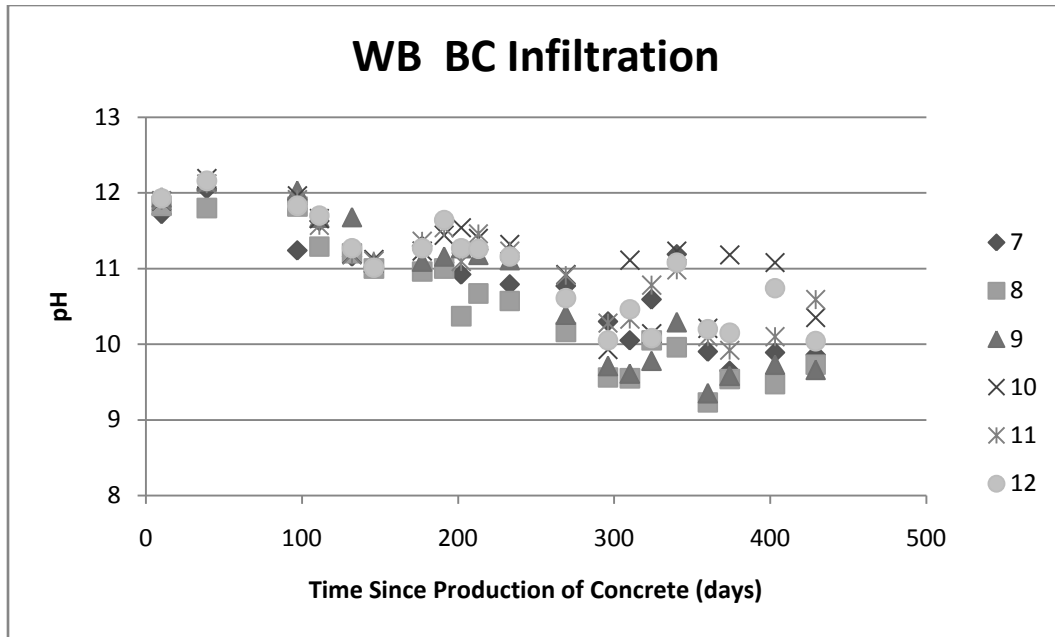


Figure B.11. pH infiltration data from individual WB specimens aged with ambient air restriction on the bottom (BC).

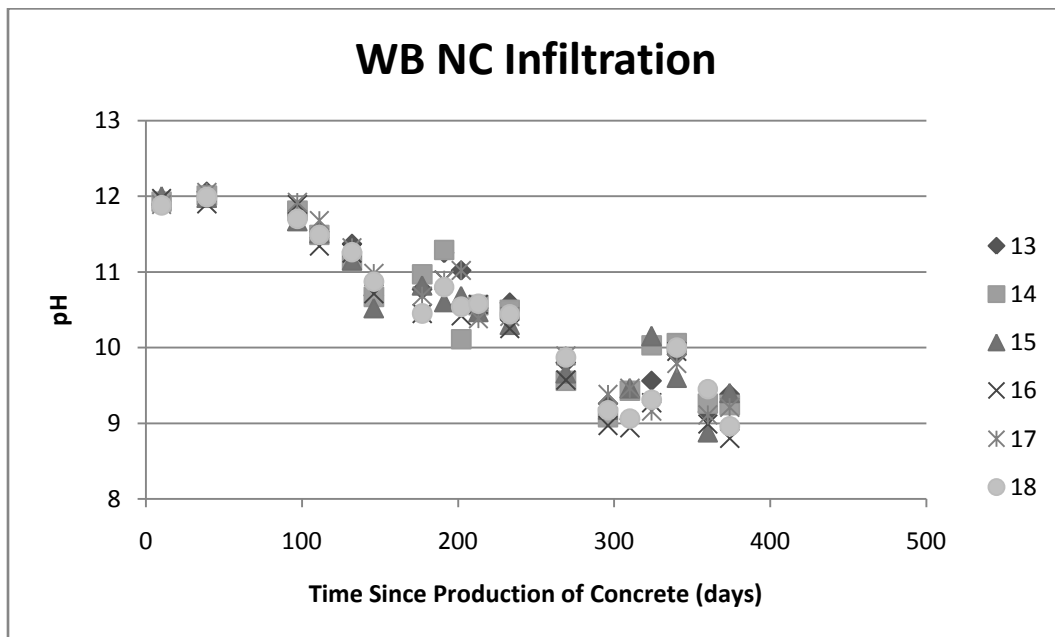


Figure B.12. pH infiltration data from individual WB specimens aged without ambient air restriction on the top or bottom (NC).

Table B.3. pH infiltration test data from the WB specimens (dates underlined used tap water for testing).

WB Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC	NC
12/18/2008	11.93	11.98	11.90	11.88	12.03	11.82	11.72	11.83	11.94	11.89	11.90	11.93	11.90	11.93	12.00	11.97	11.89	11.88
1/16/2009	11.84	11.91	11.83	11.87	11.99	11.86	12.05	11.80	12.15	12.19	12.12	12.16	12.06	12.01	11.98	11.90	12.05	11.99
3/15/2009	12.05	12.11	12.18	12.17	12.14	12.01	11.24	11.82	12.03	11.96	11.91	11.83	11.79	11.81	11.67	11.89	11.92	11.70
3/29/2009	11.72	11.83	11.78	11.76	11.64	11.54	11.63	11.29	11.67	11.66	11.57	11.70	11.53	11.49	11.51	11.34	11.68	11.49
4/19/2009	11.49	11.76	11.55	11.66	11.60	11.39	11.16	11.20	11.68	11.19	11.18	11.27	11.37	11.15	11.15	11.25	11.32	11.26
5/3/2009	10.65	11.21	11.28	11.17	11.07	11.16	11.02	11.00	11.08	11.12	11.10	11.01	10.69	10.67	10.52	10.71	10.98	10.87
<u>5/18/2009</u>	11.54	10.62	11.34	10.56	11.08	11.08	10.16	10.91	10.56	11.11	10.11	10.81	10.32	9.74	9.66	9.66	10.03	9.92
6/3/2009	10.74	10.86	10.92	11.30	11.05	11.01	11.30	10.96	11.09	11.23	11.36	11.27	10.77	10.97	10.82	10.45	10.68	10.45
6/17/2009	11.30	11.22	11.37	11.33	11.22	11.32	11.08	11.00	11.16	11.44	11.54	11.64	11.25	11.29	10.60	10.89	10.89	10.80
6/28/2009	11.29	11.06	11.35	11.18	11.51	11.20	10.92	10.37	11.27	11.54	11.09	11.27	11.02	10.11	10.68	10.42	11.02	10.54
7/9/2009	11.60	11.08	11.13	11.27	11.51	11.42	11.25	10.67	11.18	11.40	11.46	11.26	10.52	10.56	10.47	10.57	10.38	10.58
<u>7/22/2009</u>	10.16	10.02	9.72	10.36	10.02	9.78	9.64	9.38	9.47	10.59	9.91	10.46	9.37	8.82	8.98	10.36	8.54	9.30
7/29/2009	10.83	10.87	11.04	11.23	11.21	11.22	10.79	10.57	11.11	11.32	11.23	11.16	10.59	10.50	10.30	10.25	10.41	10.44
<u>8/5/2009</u>	9.97	9.75	10.01	9.45	9.95	10.09	9.56	9.66	9.69	9.74	9.79	9.52	8.65	8.55	8.83	9.28	8.92	9.12
8/18/2009	10.86	10.12	10.40	10.31	10.87	10.56	10.04	9.46	9.62	11.26	10.67	10.13	8.93	8.96	8.60	8.73	8.91	8.80
<u>8/27/2009</u>	9.86	9.76	10.50	9.59	10.10	10.05	9.62	9.76	9.32	10.20	9.37	9.38	9.00	8.43	8.53	8.53	8.45	8.64
9/3/2009	11.29	11.05	10.94	10.80	11.07	11.22	10.77	10.16	10.39	10.92	10.91	10.61	9.80	9.56	9.66	9.57	9.89	9.87
9/30/2009	10.18	10.10	10.94	10.24	10.11	10.04	10.30	9.56	9.71	9.93	10.28	10.05	9.26	9.08	9.18	8.97	9.38	9.17
10/14/2009	10.08	10.53	10.46	10.16	10.45	10.73	10.05	9.55	9.61	11.11	10.33	10.46	9.05	9.43	9.46	8.94	9.46	9.06
10/28/2009	10.27	10.97	10.02	10.37	10.39	10.41	10.59	10.05	9.78	10.14	10.78	10.08	9.56	10.03	10.15	9.27	9.16	9.31
11/13/2009	11.24	10.75	10.82	11.06	11.25	11.42	11.19	9.96	10.29	11.23	10.98	11.08	9.91	10.06	9.60	9.95	9.79	10.00
12/3/2009	10.28	10.17	10.20	10.10	10.03	10.19	9.90	9.23	9.35	10.21	10.10	10.20	9.15	9.26	8.88	8.99	9.11	9.45
12/17/2009	10.80	11.05	10.07	10.89	9.81	10.04	9.65	9.54	9.58	11.18	9.92	10.15	9.38	9.24	9.40	8.80	9.21	8.96
1/15/2010	10.7	10.3	10.5	10.4	10.7	11	9.89	9.47	9.73	11.1	10.1	10.7	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	9.7	9.5	9.3	9.3	9.5	9.5	8.9	8.1	8.8	9.2	8.9	8.7	8.2	8.4	8.2	8.1	8.1	8.2
2/10/2010	11.1	10.6	10.6	10.5	10.8	10.6	9.86	9.73	9.66	10.4	10.6	10	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.

Shown in Figure B.13 are the average pH values of the WB pervious concrete specimens tested with the pH immersion test. The specimens are aged under the three levels of ambient air restrictions as described in Section 2.1. No data points were omitted from Figure B.13 because there are no obvious discrepancies in Figures B.14-B.16. Two data sets were omitted from Figures B.13-B.16 because of poor mixing of sample water from the pH immersion test. The dates of the omitted data sets are highlighted in Table B.4. Table B.4 is the raw data from the pH infiltration test on the WB set and just gives supporting information.

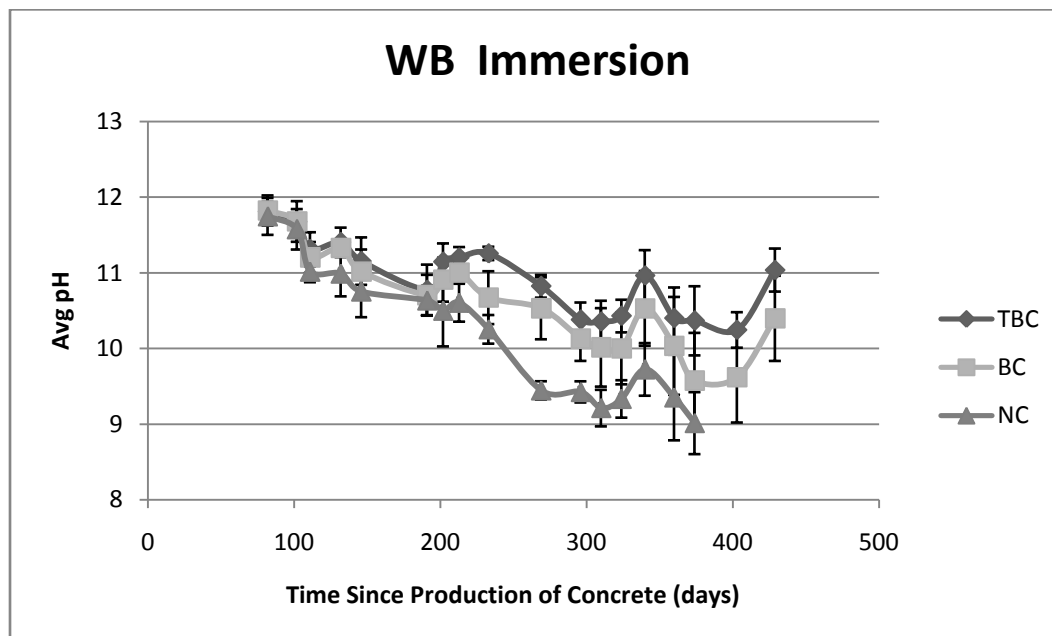


Figure B.13. Averaged pH immersion test data from the WB batch of pervious concrete (error bars are at a 90 percent confidence interval).

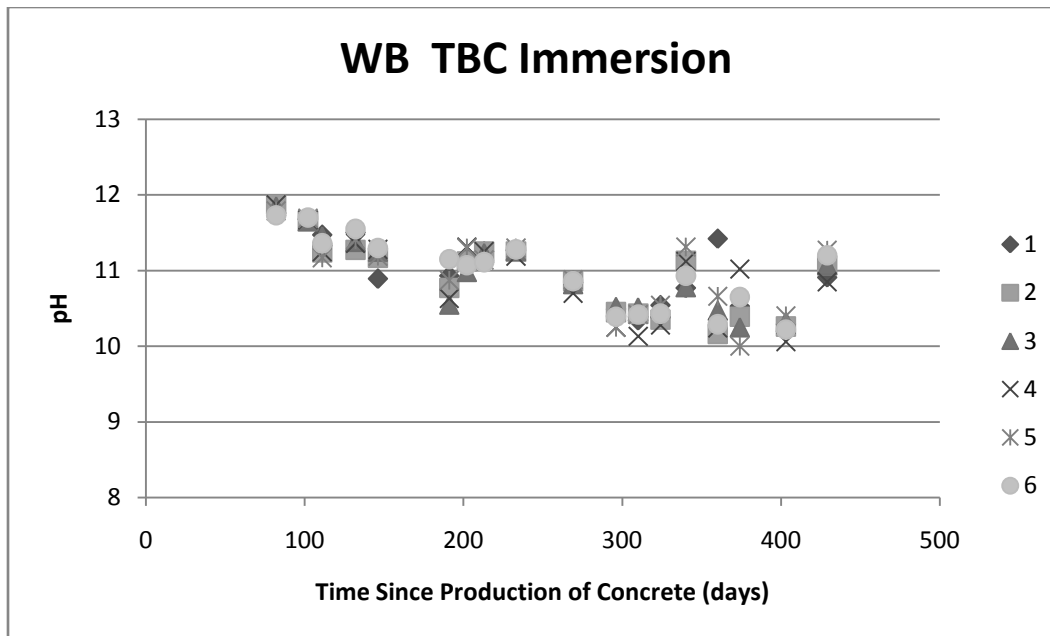


Figure B.14. pH immersion data from individual WB specimens aged with ambient air restriction on both the top and the bottom (TBC).

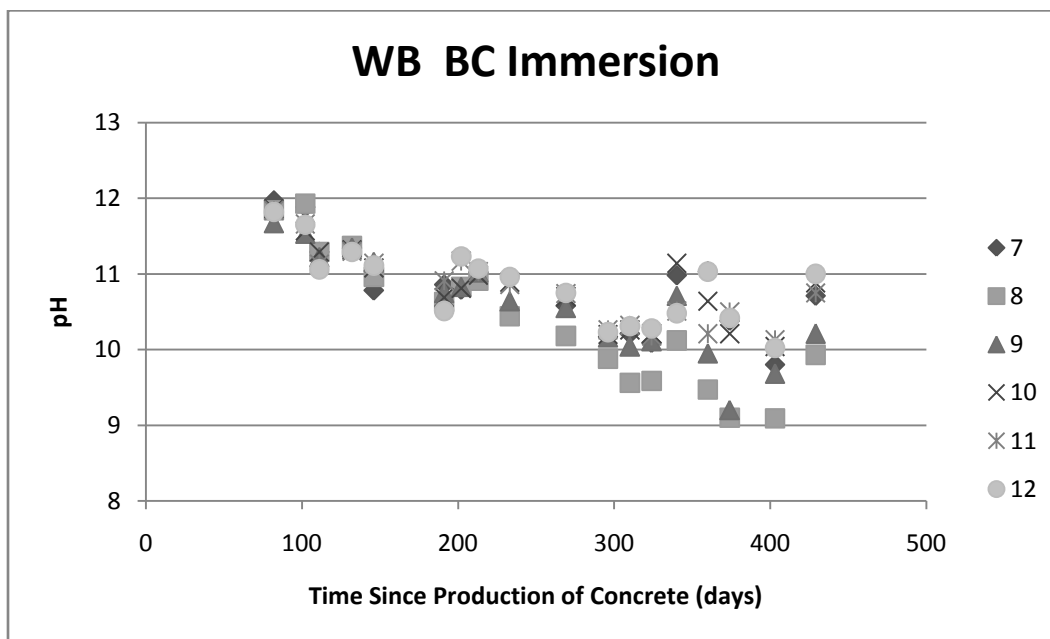


Figure B.15. pH immersion data from individual WB specimens aged with ambient air restriction on the bottom (BC).

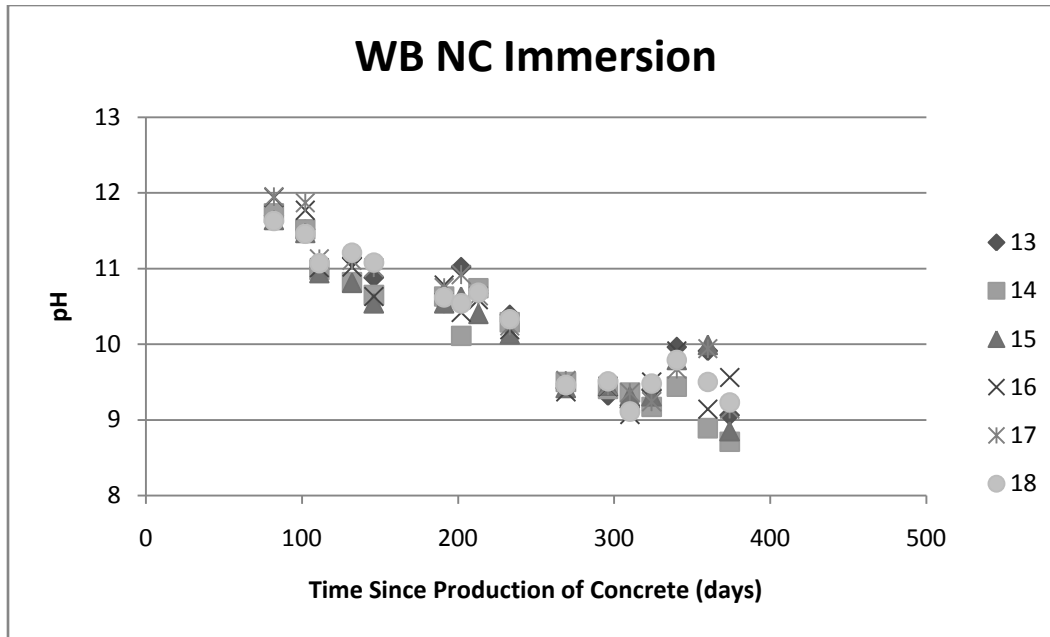


Figure B.16. pH immersion data from individual WB specimens aged without ambient air restriction on the top or bottom (NC).

Table B.4. pH immersion test data from the WB specimens (dates underlined used tap water for testing and highlighted data was omitted due to human error) (Continued).

WB Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC	NC
2/28/2009	11.8	11.9	11.9	11.9	11.8	11.7	12	11.8	11.7	11.9	11.8	11.8	11.7	11.7	11.6	11.9	12	11.6
3/20/2009	11.7	11.7	11.7	11.7	11.7	11.7	11.9	11.9	11.5	11.6	11.7	11.7	11.5	11.5	11.5	11.8	11.9	11.5
3/29/2009	11.5	11.2	11.5	11.3	11.2	11.4	11.3	11.3	11.2	11.3	11.1	11.1	11	11	10.9	11	11.1	11.1
4/19/2009	11.5	11.3	11.4	11.4	11.4	11.6	11.3	11.4	11.4	11.3	11.3	11.3	11.1	10.8	10.8	11	11.1	11.2
5/3/2009	10.9	11.2	11.3	11.3	11.2	11.3	10.8	11	11.2	11.1	11.1	11.1	10.9	10.7	10.5	10.6	11	11.1
5/18/2009	9.76	8.76	8.84	9.76	9.28	9.47	9.26	8.98	9.23	9.33	9.21	9.18	9.18	9.14	9.45	9	9.21	9.37
6/3/2009	10.1	10.4	10.5	11	10.4	10.9	10.3	10.9	11	10.5	10.6	10.4	10.4	10.2	10.6	10.5	10.2	10.1
6/17/2009	10.9	10.8	10.6	10.6	10.9	11.2	10.9	10.6	10.8	10.7	10.9	10.5	10.5	10.6	10.5	10.8	10.8	10.6
6/28/2009	11.2	11.1	11	11.3	11.3	11.1	10.8	10.8	10.8	10.8	11.2	11.2	11	10.1	10.6	10.4	10.9	10.5
7/9/2009	11.3	11.3	11.2	11.3	11.1	11.1	11	10.9	11	11	11	11.1	10.7	10.7	10.4	10.6	10.6	10.7
<u>7/22/2009</u>	9.81	9.59	9.63	9.53	9.72	9.78	9.61	9.25	9.47	9.74	9.45	9.66	8.79	8.87	8.6	8.75	9.2	8.75

Table B.4. pH immersion test data from the WB specimens (dates underlined used tap water for testing and highlighted data was omitted due to human error) (Continuation).

WB Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC	NC
7/29/2009	11.3	11.3	11.3	11.2	11.3	11.3	10.5	10.4	10.6	10.9	10.9	11	10.4	10.3	10.1	10.2	10.2	10.3
<u>8/5/2009</u>	9.61	9.58	9.56	9.39	9.95	9.57	9.28	9.05	9.55	9.34	9.34	9.52	8.69	8.73	8.58	8.56	8.59	8.72
8/18/2009	10.7	10.7	10.7	10.5	10.7	10.9	10.5	9.86	10.4	10.4	10.4	10.5	9.12	9.3	8.83	8.91	8.83	9.03
<u>8/27/2009</u>	9.5	9.61	9.54	9.38	9.47	9.48	9.2	8.91	9.22	9.41	9.3	9.41	8.42	8.36	8.32	8.3	8.31	8.4
9/3/2009	10.8	10.9	10.8	10.7	10.9	10.9	10.6	10.2	10.6	10.7	10.7	10.8	9.42	9.5	9.42	9.37	9.52	9.46
9/30/2009	10.5	10.5	10.5	10.3	10.3	10.4	10.2	9.88	10.2	10.2	10.3	10.2	9.32	9.41	9.45	9.44	9.45	9.51
10/14/2009	10.3	10.4	10.5	10.1	10.4	10.4	10.2	9.56	10	10.3	10.3	10.3	9.16	9.36	9.31	9.07	9.36	9.11
10/28/2009	10.54	10.35	10.5	10.28	10.54	10.43	10.09	9.585	10.11	10.21	10.18	10.28	9.4	9.17	9.31	9.5	9.24	9.48
11/13/2009	10.8	11.1	10.8	11.1	11.3	10.9	11	10.1	10.7	11.1	10.5	10.5	9.96	9.44	9.79	9.91	9.67	9.79
12/3/2009	11.4	10.2	10.5	10.2	10.7	10.3	11	9.47	9.95	10.6	10.2	11	9.91	8.89	9.99	9.14	9.94	9.5
12/17/2009	10.5	10.4	10.3	11	10	10.7	10.4	9.1	9.2	10.2	10.5	10.4	9.06	8.71	8.85	9.56	9.14	9.23
1/15/2010	10.3	10.3	10.3	10.1	10.4	10.2	9.8	9.09	9.68	10	10.1	10	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	9.28	9.29	9.27	8.92	9.23	9.3	8.69	7.95	8.25	9.02	9.03	9	8.02	7.92	7.86	7.92	7.99	7.98
2/10/2010	10.9	11.1	11.1	10.9	11.3	11.2	10.7	9.93	10.2	10.9	10.8	11	N.T.	N.T.	N.T.	N.T.	N.T.	N.T.

Shown in Figure B.17 are the average pH values of the WC pervious concrete specimens tested with the pH infiltration test. The specimens are aged under the three levels of ambient air restrictions as described in Section 2.1. One data point was omitted from Figure B.17, Chapter 4 results, and all slope of pH decline equations because of the obvious discrepancy, which is depicted in Figures B.18-B.20 as well as Table B.5. The discrepancy may have been caused by contaminated deionized water on August 19, 2010 as can be seen in Table B.5. In Figures B.18-B.20, the data from approximately the 225th day after production was omitted because possible deionized water contamination.

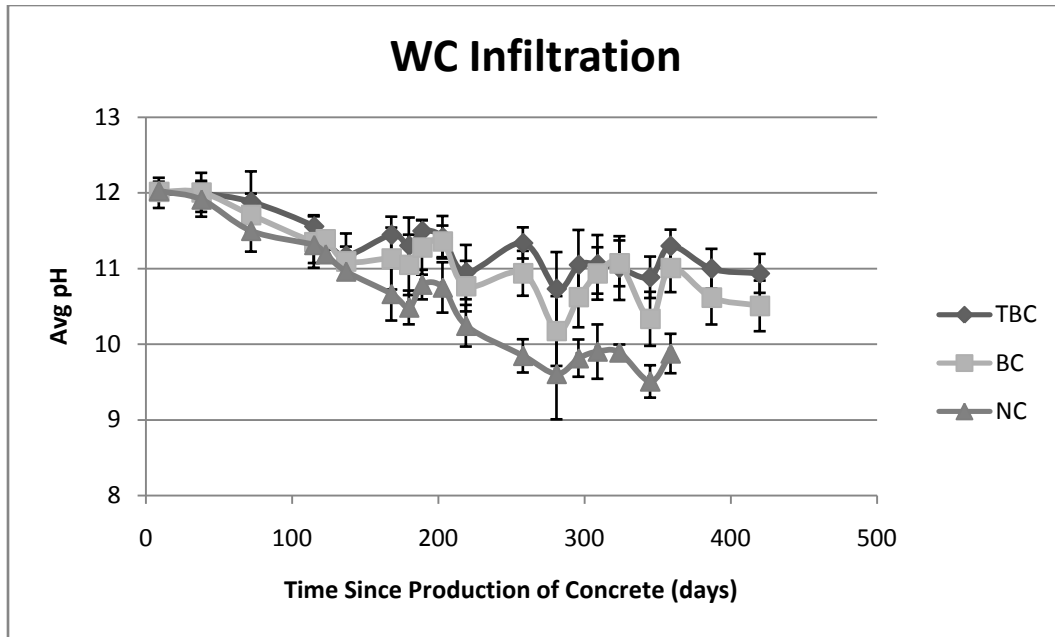


Figure B.17. Averaged pH infiltration test data from the WC batch of pervious concrete (error bars are at a 90 percent confidence interval).

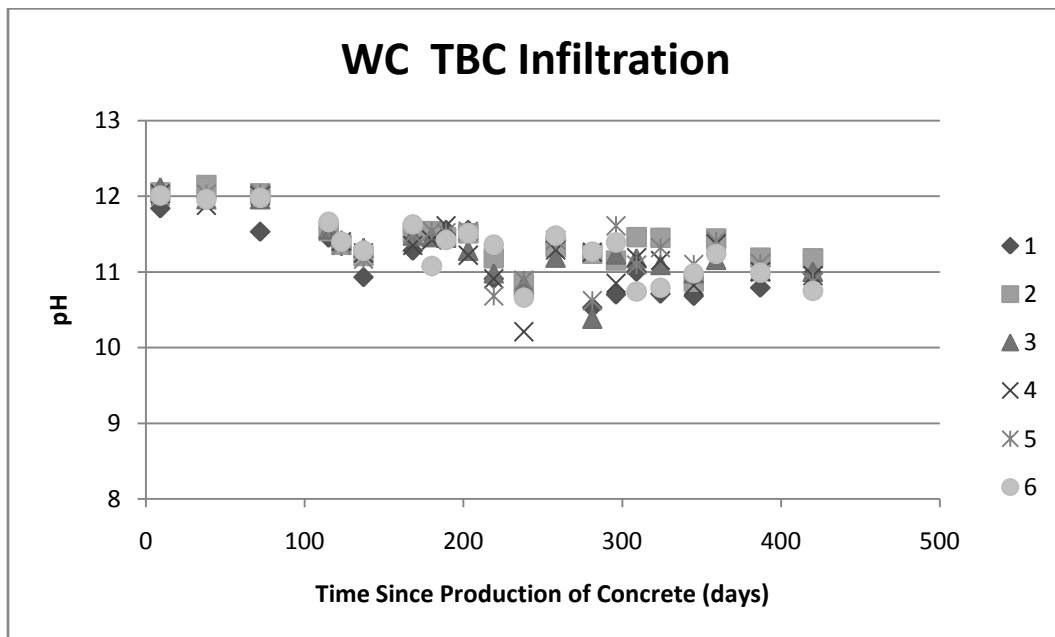


Figure B.18. pH infiltration data from individual WC specimens aged with ambient air restriction on both the top and the bottom (TBC).

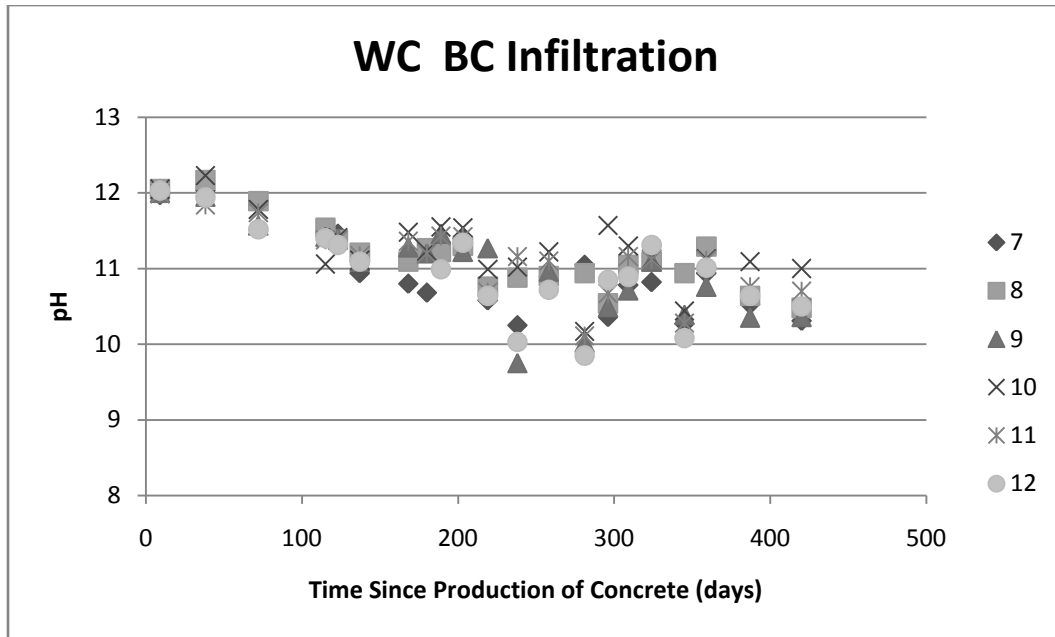


Figure B.19. pH infiltration data from individual WC specimens aged with ambient air restriction on the bottom (BC).

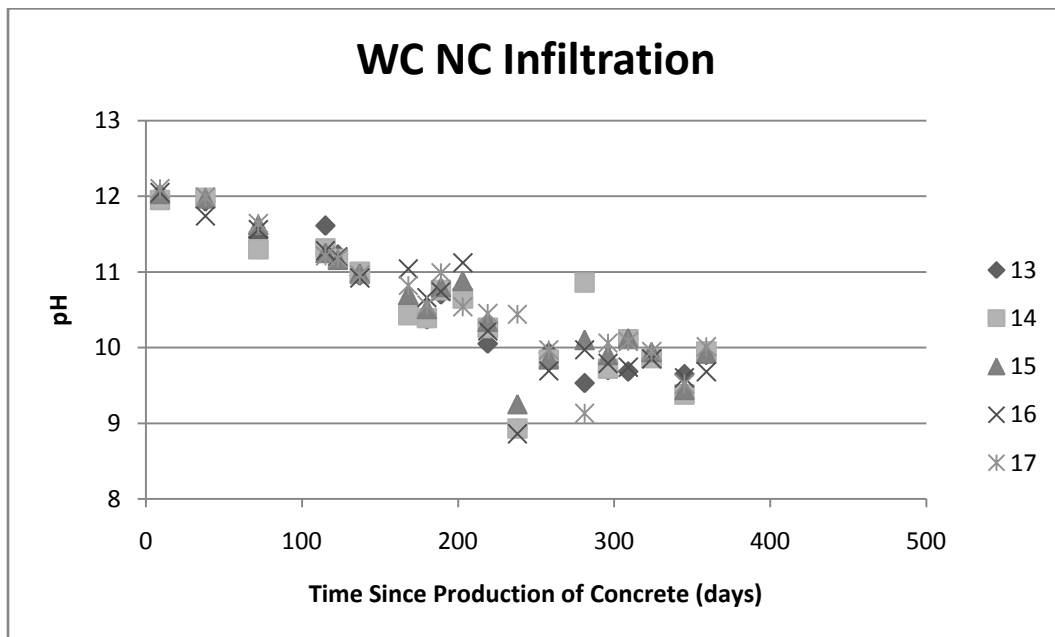


Figure B.20. pH infiltration data from individual WC specimens aged without ambient air restriction on the top or bottom (NC).

Table B.5. pH infiltration test data from the WC specimens (dates underlined used tap water for testing) (Continued).

WC Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC
1/2/2009	11.8	12.1	12.1	12	12	12	12	12.1	12	12.1	12	12	12	12	12	12.1	12.1
1/31/2009	12	12.2	12	11.9	12	12	12	12.2	12	12.2	11.8	11.9	11.9	12	12	11.7	12
3/22/2009	11.5	12	12	12	12	12	11.9	11.9	11.6	11.8	11.7	11.5	11.5	11.3	11.6	11.6	11.6
4/18/2009	11.5	11.5	11.6	11.6	11.6	11.7	11.5	11.5	11.4	11.1	11.4	11.4	11.6	11.3	11.3	11.3	11.2
4/26/2009	11.3	11.4	11.4	11.4	11.4	11.4	11.5	11.4	11.4	11.4	11.4	11.3	11.2	11.2	11.2	11.2	11.2
5/10/2009	10.9	11.2	11.3	11.3	11.2	11.3	10.9	11.2	11.1	11.1	11.2	11.1	11	11	11	10.9	11
<u>5/27/2009</u>	10.8	10.4	10.6	10.4	10.5	10.4	10.4	11	10.8	11.3	11	9.67	10.2	9.59	9.62	10.6	10
6/10/2009	11.3	11.5	11.5	11.4	11.5	11.6	10.8	11.1	11.3	11.5	11.4	N.T.	10.6	10.4	10.7	11	10.8
6/22/2009	11.1	11.5	11.5	11.4	11.5	11.1	10.7	11.3	11.2	11.2	11.2	N.T.	10.4	10.4	10.5	10.7	10.6
7/1/2009	11.6	11.5	11.5	11.6	11.5	11.4	11.3	11.2	11.5	11.6	11.4	11	10.7	10.8	10.8	10.7	11
7/15/2009	11.6	11.5	11.3	11.2	11.5	11.5	11.4	11.3	11.2	11.5	11.4	11.3	10.8	10.7	10.9	11.1	10.5
<u>7/22/2009</u>	10.2	10.9	10.3	10.3	11.2	10.8	10.6	10.3	10.3	10.4	10.6	9.82	9.27	9.35	9.48	9.91	9.36
7/31/2009	10.9	11.2	11	10.9	10.7	11.4	10.6	10.8	11.3	11	10.7	10.6	10.1	10.3	10.3	10.2	10.5
<u>8/5/2009</u>	10.1	10.7	11.2	10.2	10	10.2	9.82	10.1	9.95	11	9.96	9.73	8.88	8.8	8.77	8.61	8.92
8/19/2009	10.7	10.9	10.8	10.2	10.9	10.7	10.3	10.9	9.75	11	11.2	10	8.93	8.93	9.25	8.86	10.4
9/8/2009	11.4	11.3	11.2	11.3	11.4	11.5	10.9	10.9	11	11.2	11.1	10.7	9.93	9.84	9.85	9.69	9.97
10/1/2009	10.5	11.2	10.4	11.3	10.6	11.3	11.1	10.9	10	10.2	10.1	9.85	9.53	10.9	10.1	9.97	9.13
10/15/2009	10.7	11.2	11.2	10.9	11.6	11.4	10.4	10.5	10.5	11.6	10.7	10.9	9.7	9.72	9.9	9.79	10.1
10/29/2009	11	11.5	11.2	11.2	11.1	10.7	10.8	11.1	10.7	11.3	11.2	10.9	9.68	10.1	10.1	9.74	10.1

Table B.5. pH infiltration test data from the WC specimens (dates underlined used tap water for testing) (Continuation).

WC Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC
11/13/2009	10.7	11.5	11.1	11.2	11.3	10.8	10.8	11.1	11.1	11.1	11.1	11.3	9.86	9.86	9.94	9.85	9.95
12/4/2009	10.7	10.9	11	10.8	11.1	11	10.3	10.9	10.4	10.4	10.3	10.1	9.65	9.38	9.44	9.6	9.52
12/18/2009	11.2	11.4	11.2	11.4	11.4	11.2	10.9	11.3	10.8	11.1	11.1	11	9.9	9.95	9.92	9.68	10
1/15/2010	10.8	11.2	11	11	11.1	11	10.5	10.6	10.4	11.1	10.8	10.6	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	8.86	9.8	9.51	9.2	9.62	9.4	8.66	9.05	8.86	9.25	9.27	8.88	8.04	8.23	8.07	8.11	8.07
2/17/2010	11	11.2	11	11	10.9	10.8	10.3	10.5	10.4	11	10.7	10.5	N.T.	N.T.	N.T.	N.T.	N.T.

Shown in Figure B.21 are the average pH values of the WC pervious concrete specimens tested with the pH immersion test. One data point was also omitted from Figure B.21, Chapter 4 results, and all slope of pH decline equations because of the obvious discrepancy, which is depicted in Figures B.22-B.24 as well as Table B.6. The discrepancy may have been caused by contaminated deionized water. As can be seen in Figures B.22-B.24, the data from approximately the 225th day, August 19, 2009, after production was omitted because of possible deionized water contamination. Two other data sets were omitted entirely from Figures B.5-B.8 because of pore mixing of the sample water in the pH immersion test. The testing dates of the omitted data points are highlighted in Table B.6.

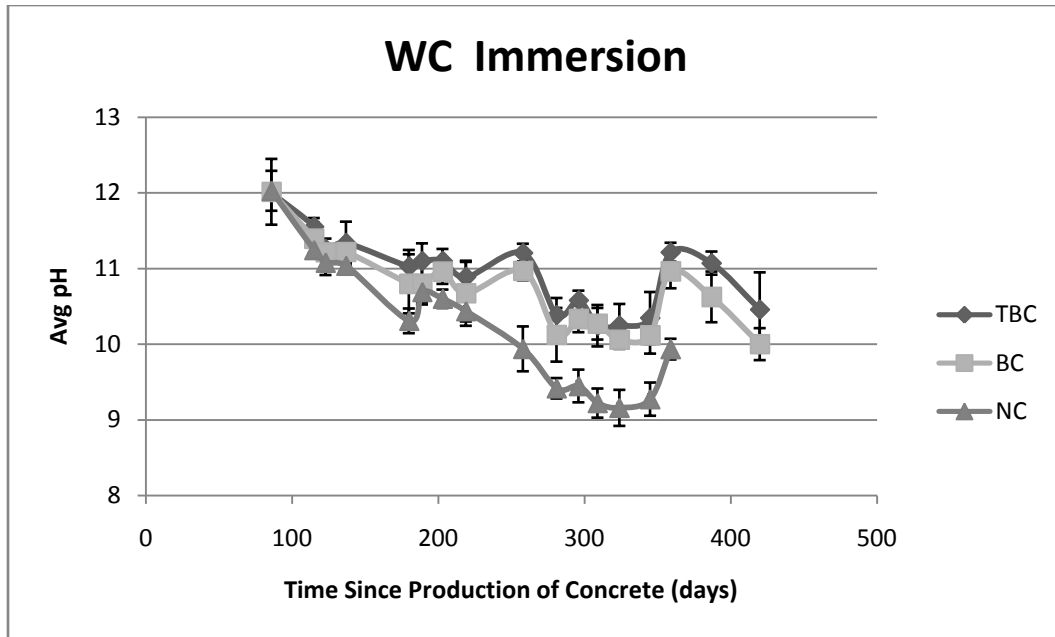


Figure B.21. Averaged pH immersion test data from the WC batch of pervious concrete (error bars are at a 90 percent confidence interval).

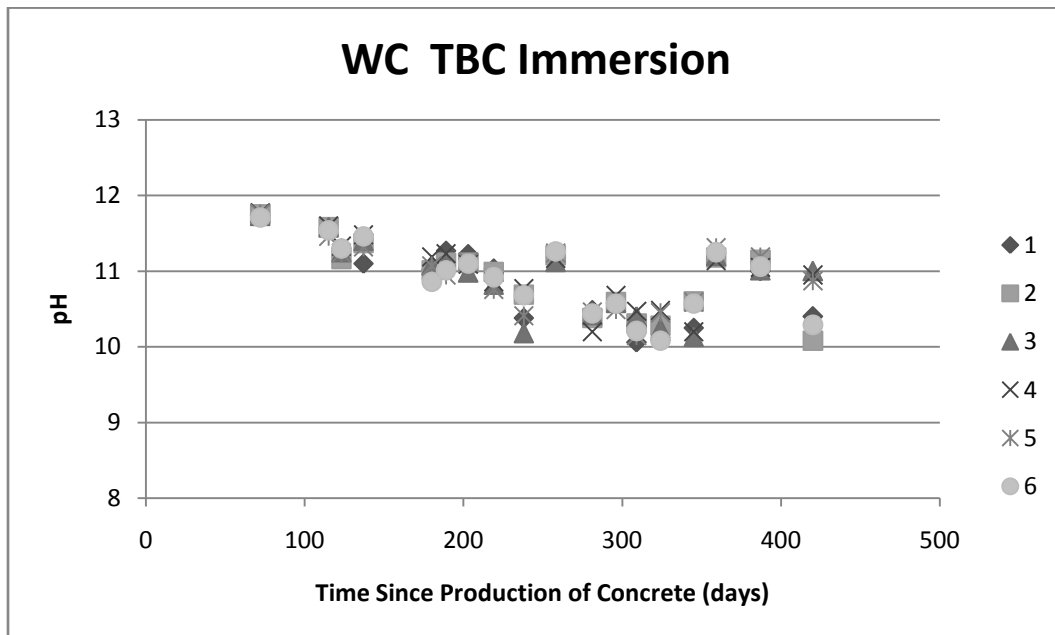


Figure B.22. pH immersion data from individual WC specimens aged with ambient air restriction on both the top and the bottom (TBC).

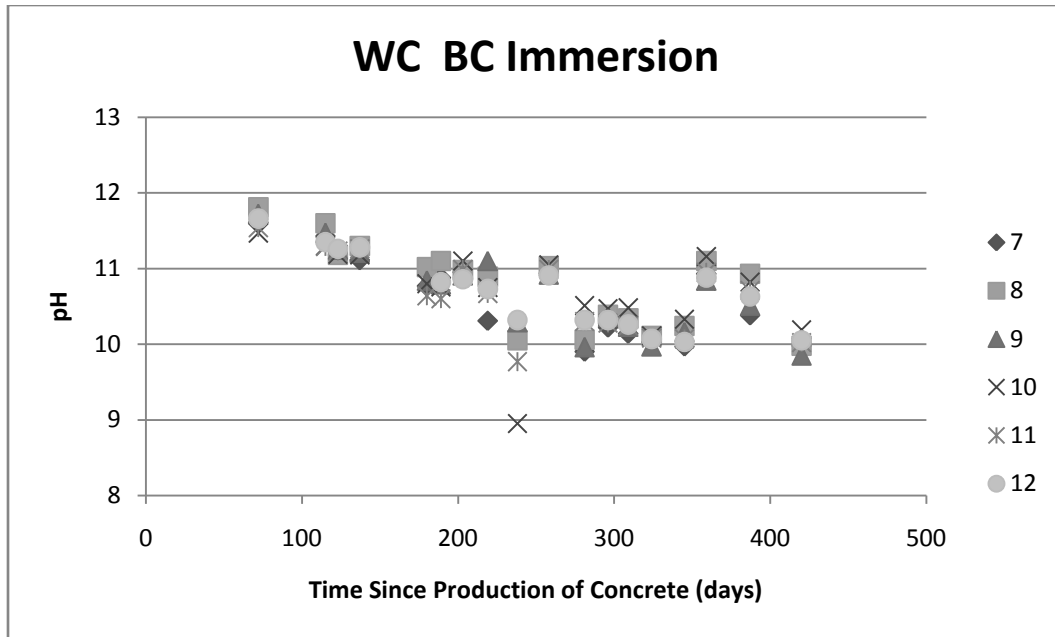


Figure B.23. pH immersion data from individual WC specimens aged with ambient air restriction on the bottom (BC).

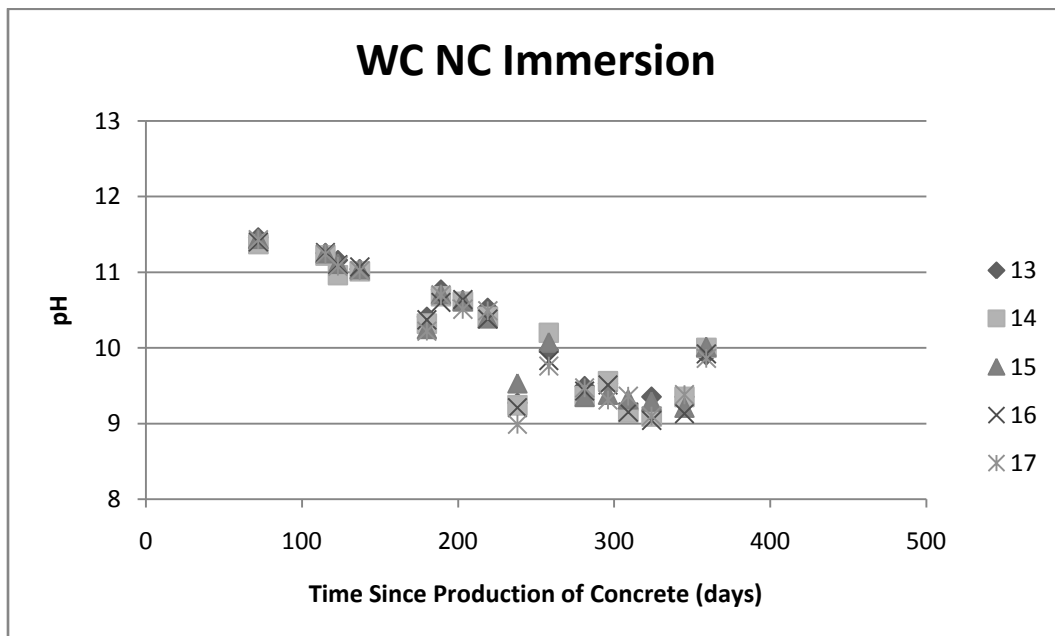


Figure B.24. pH immersion data from individual WC specimens aged without ambient air restriction on the top or bottom (NC).

Table B.6. pH immersion test data from the WC specimens (dates underlined used tap water for testing and highlighted data was omitted due human error).

WC Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC
3/22/2009	11.74	11.75	11.73	11.77	11.76	11.71	11.61	11.81	11.72	11.47	11.54	11.66	11.46	11.37	11.44	11.4	11.43
4/18/2009	11.56	11.58	11.58	11.6	11.46	11.54	11.43	11.6	11.47	11.3	11.29	11.35	11.25	11.22	11.25	11.26	11.24
4/26/2009	11.3	11.16	11.25	11.33	11.24	11.3	11.18	11.18	11.25	11.19	11.23	11.26	11.16	10.96	11.11	11.1	11.08
5/10/2009	11.1	11.37	11.4	11.48	11.32	11.46	11.11	11.3	11.21	11.18	11.26	11.28	11.04	11.01	11.04	11.07	11.02
5/27/2009	9.05	8.97	9.43	9.25	10.05	9.46	8.78	9.25	8.69	9.1	9.15	9	8.41	8.51	8.69	8.98	9.12
6/10/2009	10.67	11.05	11.16	10.88	10.7	10.98	9.46	9.98	10.48	10.08	10.13	N.T.	9.49	9.46	10.16	10.23	10.33
6/22/2009	11.02	11.01	11.08	11.19	11.07	10.86	10.77	11.02	10.84	10.8	10.64	N.T.	10.41	10.32	10.25	10.37	10.22
7/1/2009	11.27	11.11	11.12	11.23	10.95	11.01	10.88	11.1	10.79	10.76	10.6	10.82	10.77	10.68	10.71	10.6	10.7
7/15/2009	11.22	11.11	10.98	11.09	11.12	11.1	10.95	10.98	10.91	11.1	10.99	10.86	10.63	10.61	10.62	10.64	10.51
<u>7/22/2009</u>	9.67	9.67	9.59	9.62	9.82	9.51	9.26	9.71	9.26	9.71	9.3	9.74	9.03	8.98	9.98	9.65	8.88
7/31/2009	11.03	10.99	10.82	10.86	10.76	10.92	10.31	10.89	11.1	10.75	10.67	10.73	10.53	10.41	10.39	10.38	10.49
<u>8/5/2009</u>	9.81	9.71	9.6	9.6	9.76	9.63	9.32	9.58	9.42	9.65	9.48	9.42	8.94	8.91	8.98	8.85	8.9
8/19/2009	10.38	10.69	10.18	10.77	10.41	10.68	10.17	10.05	10.29	8.95	9.77	10.32	9.27	9.24	9.53	9.21	8.99
<u>8/28/2009</u>	9.43	9.46	9.48	9.45	9.54	9.44	9.11	9.27	9.17	9.38	9.2	9.23	8.49	8.28	8.58	8.26	8.31
9/8/2009	11.25	11.21	11.12	11.17	11.24	11.26	10.94	11.03	10.92	11.05	10.99	10.91	9.97	10.2	10.07	9.83	9.76
10/1/2009	10.48	10.38	10.42	10.2	10.46	10.44	9.9	10.06	9.96	10.51	10.3	10.32	9.49	9.36	9.35	9.43	9.47
10/15/2009	10.58	10.59	10.58	10.68	10.49	10.57	10.22	10.39	10.36	10.47	10.28	10.32	9.53	9.56	9.38	9.51	9.31
10/29/2009	10.06	10.31	10.4	10.47	10.15	10.21	10.14	10.34	10.23	10.48	10.24	10.26	9.18	9.14	9.32	9.15	9.36
11/13/2009	10.09	10.28	10.24	10.48	10.45	10.08	10.03	10.11	9.97	10.11	10.08	10.07	9.35	9.09	9.29	9.04	9.1
12/4/2009	10.25	10.6	10.13	10.2	10.59	10.57	9.97	10.24	10.16	10.33	10.07	10.03	9.35	9.35	9.21	9.13	9.38
12/18/2009	11.23	11.18	11.2	11.14	11.31	11.25	10.93	11.1	10.84	11.16	10.95	10.88	9.9	10	10.01	9.92	9.86
1/15/2010	11	11.15	11.01	11.05	11.19	11.06	10.38	10.93	10.51	10.82	10.71	10.63	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	9.14	9.09	9.06	9.13	9.33	9.18	8.76	8.83	8.39	9.17	8.73	8.74	7.91	7.91	7.85	7.99	7.88
2/17/2010	10.4	10.08	11	10.95	10.87	10.29	9.98	9.98	9.85	10.19	10.02	10.05	N.T.	N.T.	N.T.	N.T.	N.T.

Shown in Figure B.25 are the average pH values of the WD pervious concrete specimens tested with the pH infiltration test. The specimens are aged under the three levels of ambient air restrictions as described in Section 2.1. No data points were omitted from Figure B.25 because there are no obvious discrepancies in Figures B.26-B.28. The deionized water on August 20, 2009 may not have been contaminated during testing of the WD set. Table B.7 is the raw data from the pH infiltration test on the WD set and just gives supporting information.

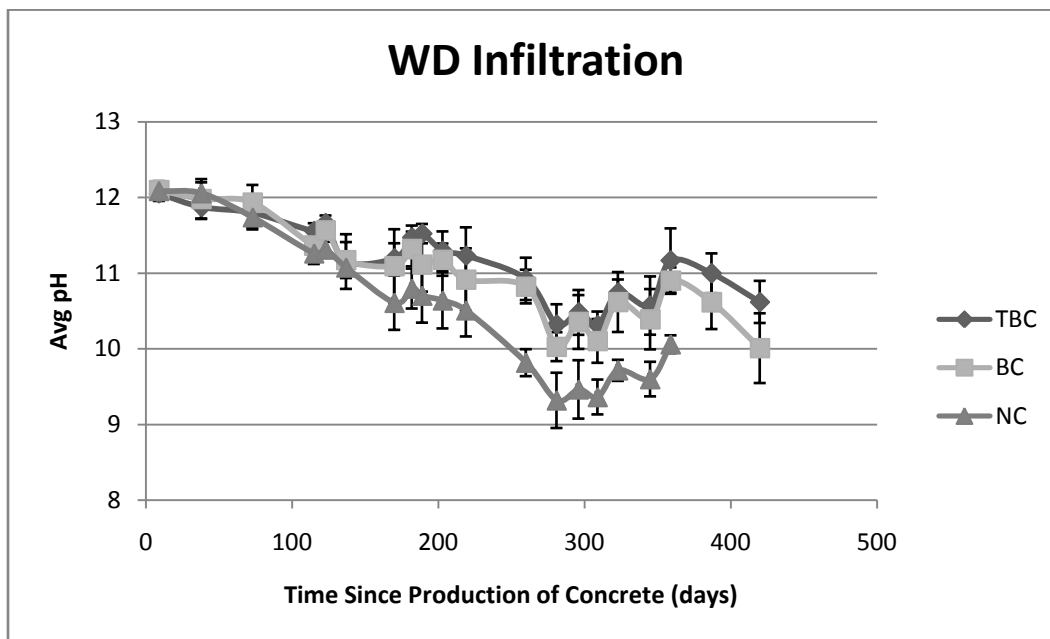


Figure B.25. Averaged pH infiltration test data from the WD batch of pervious concrete (error bars are at a 90 percent confidence interval).

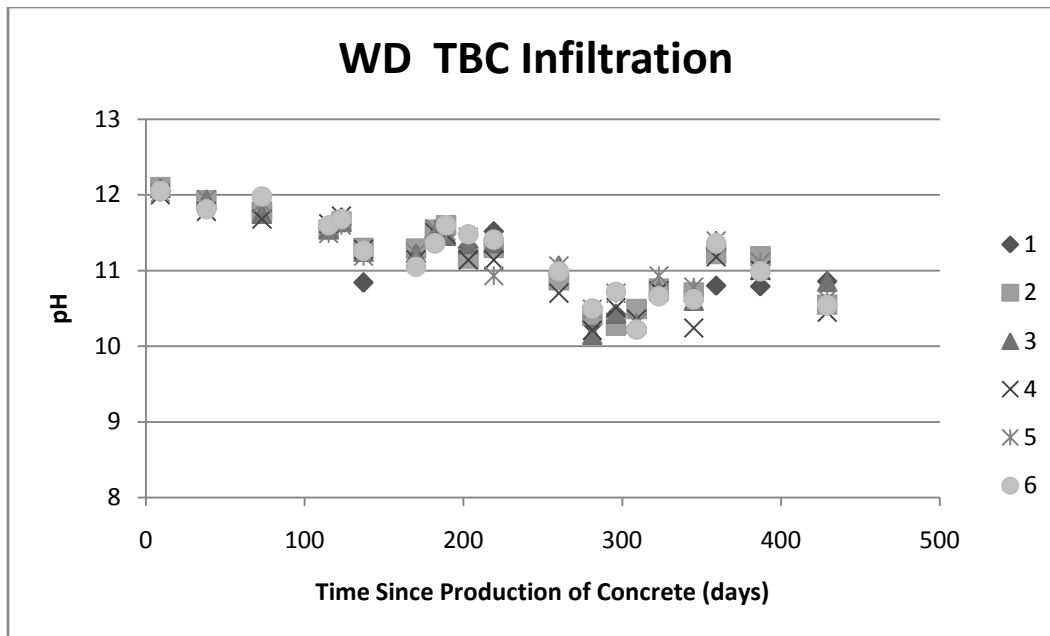


Figure B.26. pH infiltration data from individual WD specimens aged with ambient air restriction on both the top and the bottom (TBC).

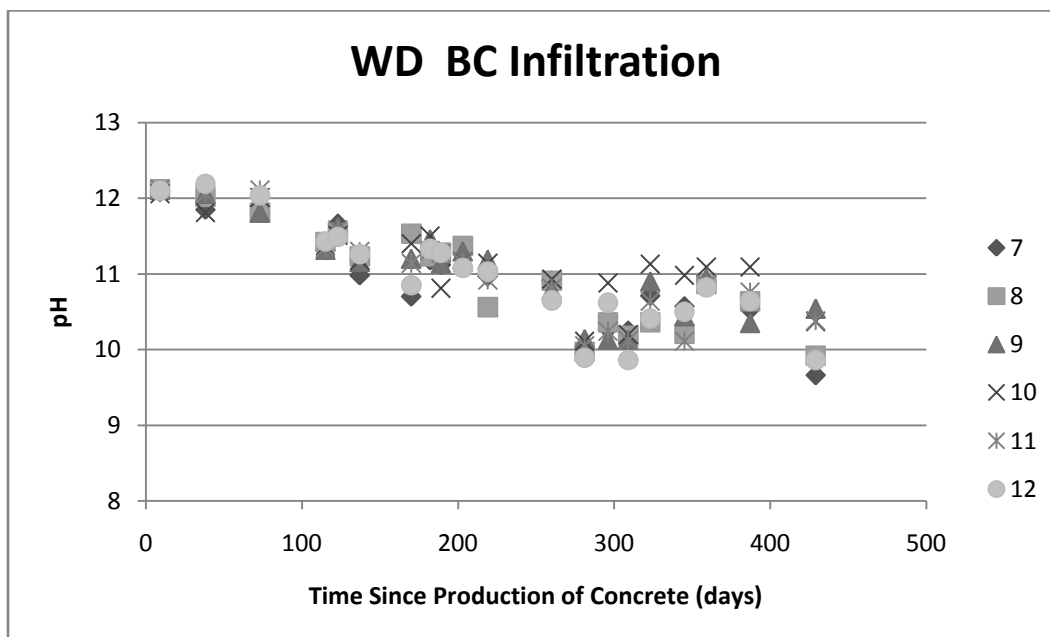


Figure B.27. pH infiltration data from individual WD specimens aged with ambient air restriction on the bottom (BC).

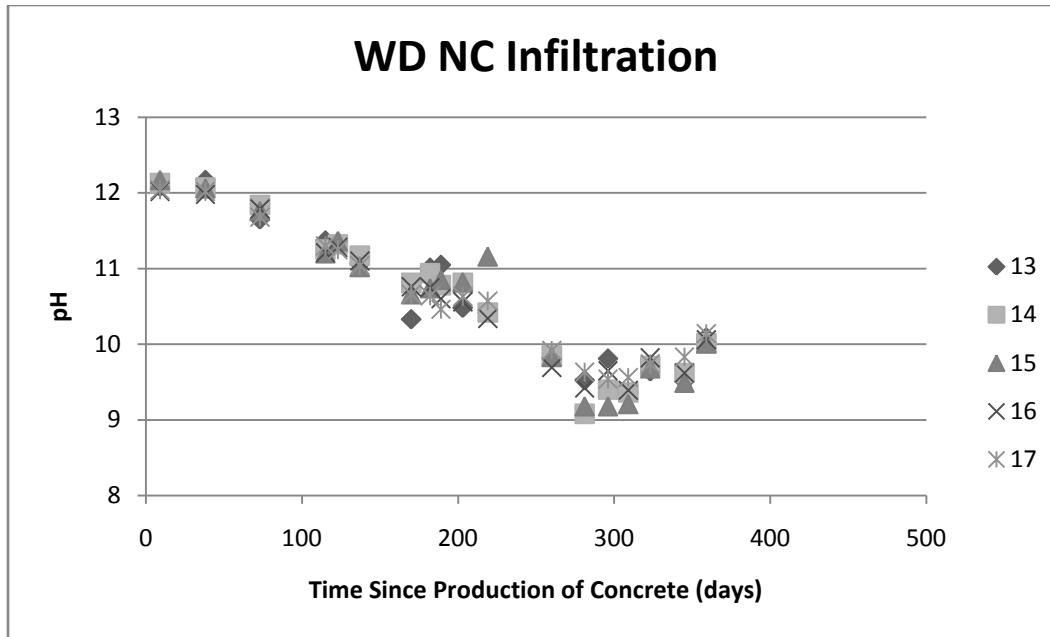


Figure B.28. pH infiltration data from individual WD specimens aged without ambient air restriction on the top or bottom (NC).

Table B.7. pH infiltration test data from the WD specimens (dates underlined used tap water for testing) (continued).

WD Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC
1/2/2009	12.1	12.1	12.1	12	12	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.2	12	12
1/31/2009	11.9	11.9	11.9	11.8	11.9	11.8	11.9	12	12.1	11.8	12.1	12.2	12.2	12.1	12.1	12	12
3/23/2009	11.8	11.8	11.8	11.7	11.9	12	11.9	11.8	11.8	12	12.1	12	11.7	11.8	11.8	11.8	11.7
4/18/2009	11.6	11.5	11.6	11.6	11.5	11.6	11.3	11.4	11.3	11.4	11.4	11.4	11.4	11.3	11.2	11.2	11.3
4/26/2009	11.7	11.7	11.6	11.7	11.6	11.7	11.7	11.5	11.6	11.5	11.6	11.5	11.4	11.3	11.4	11.3	11.3
5/10/2009	10.8	11.3	11.3	11.3	11.2	11.3	11	11.2	11.2	11.2	11.3	11.3	11.1	11.2	11	11.1	11
<u>5/27/2009</u>	10.3	10.1	9.88	10.4	10.1	10.3	10.7	10.4	10.4	10.3	10.6	9.84	9.68	10.6	10.1	9.72	9.35
6/12/2009	11.3	11.3	11.2	11.1	11.2	11.1	10.7	11.5	11.2	11.4	11.1	10.9	10.3	10.8	10.7	10.8	10.7
6/24/2009	11.4	11.5	11.5	11.5	11.6	11.4	11.2	11.2	11.5	11.5	11.3	11.3	11	10.9	10.7	10.8	10.6
7/1/2009	11.5	11.6	11.5	11.5	11.5	11.6	11.1	11.3	11.1	10.8	11.3	11.3	11.1	10.8	10.9	10.6	10.5

Table B.7. pH infiltration test data from the WD specimens (dates underlined used tap water for testing) (continuation).

WD Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC
7/15/2009	11.3	11.2	11.4	11.1	11.4	11.5	11.1	11.4	11.3	11.2	11.2	11.1	10.5	10.8	10.8	10.6	10.6
<u>7/22/2009</u>	11	11.2	11	10.4	11	10.7	10	10.4	10.6	10.2	10	10.4	9.29	9.76	9.15	9.6	9.77
7/31/2009	11.5	11.3	11.4	11.1	10.9	11.4	11	10.6	11.2	11.1	10.9	11	10.4	10.4	11.2	10.3	10.6
<u>8/5/2009</u>	10.7	10.4	10.4	10.3	10.9	10.8	9.94	10.1	9.9	10.7	10.1	10	8.92	8.91	9.23	8.82	9.21
8/20/2009	11	10.9	10.9	10.7	10.9	10.8	11	10.9	10.5	10.7	10.5	10.4	9.62	9.73	9.31	9.75	9.47
<u>8/28/2009</u>	9.83	10.2	10.4	9.71	10.3	10.4	9.23	9.92	10.1	9.81	9.88	9.8	9.32	8.81	8.7	8.58	8.7
9/10/2009	11	10.9	11.1	10.7	11.1	11	10.9	10.9	10.8	10.9	10.8	10.7	9.82	9.85	9.83	9.69	9.92
10/1/2009	10.3	10.4	10.2	10.2	10.5	10.5	10.1	9.97	10.1	10.1	10.1	9.89	9.52	9.08	9.18	9.42	9.63
10/15/2009	10.4	10.3	10.4	10.5	10.7	10.7	10.3	10.4	10.1	10.9	10.2	10.6	9.81	9.4	9.18	9.65	9.54
10/29/2009	10.3	10.5	10.3	10.4	10.3	10.2	10.3	10.2	10.1	10.2	10.1	9.86	9.36	9.36	9.21	9.39	9.56
11/12/2009	10.7	10.8	10.7	10.7	10.9	10.7	10.7	10.4	10.9	11.1	10.6	10.4	9.64	9.71	9.68	9.82	9.74
12/4/2009	10.7	10.7	10.6	10.2	10.8	10.6	10.6	10.2	10.4	11	10.1	10.5	9.51	9.62	9.49	9.62	9.83
12/18/2009	10.8	11.2	11.4	11.2	11.4	11.4	10.9	10.9	10.9	11.1	10.9	10.8	10.1	10	10	10.1	10.1
1/15/2010	10.8	11.2	11	11	11.1	11	10.5	10.6	10.4	11.1	10.8	10.6	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	9.44	9.19	9.81	9.65	9.67	9.36	9.16	9.12	9.13	9.17	9.17	8.57	8.17	7.95	7.99	7.91	8.31
2/17/2010	10.9	10.6	10.9	10.5	10.6	10.5	9.66	9.92	10.5	10.4	10.4	9.86	N.T.	N.T.	N.T.	N.T.	N.T.

Shown in Figure B.29 are the average pH values of the WD pervious concrete specimens tested with the pH immersion test. The specimens are aged under the three levels of ambient air restrictions as described in Section 2.1. No data points were omitted from Figure B.29 because there are no obvious discrepancies in Figures B.30-B.32. Two data sets were omitted from Figures B.29-B.32 because of poor mixing of sample water from the pH immersion test. The dates of the omitted data sets are highlighted in Table B.8. Table B.8 is the raw data from the pH infiltration test on the WD set and just gives supporting information.

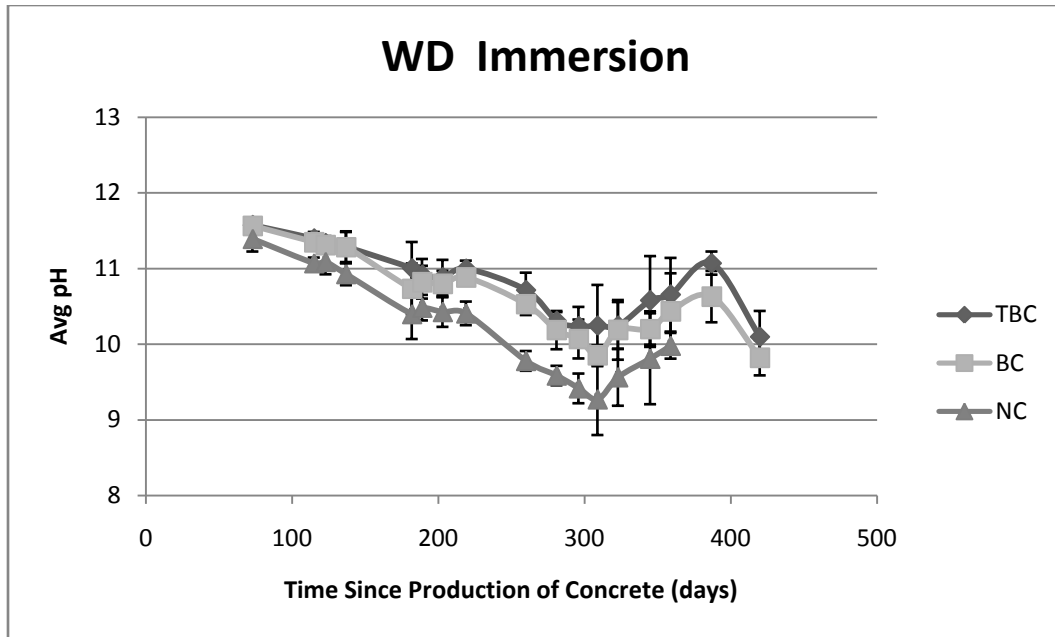


Figure B.29. Averaged pH immersion test data from the WD batch of pervious concrete (error bars are at a 90 percent confidence interval).

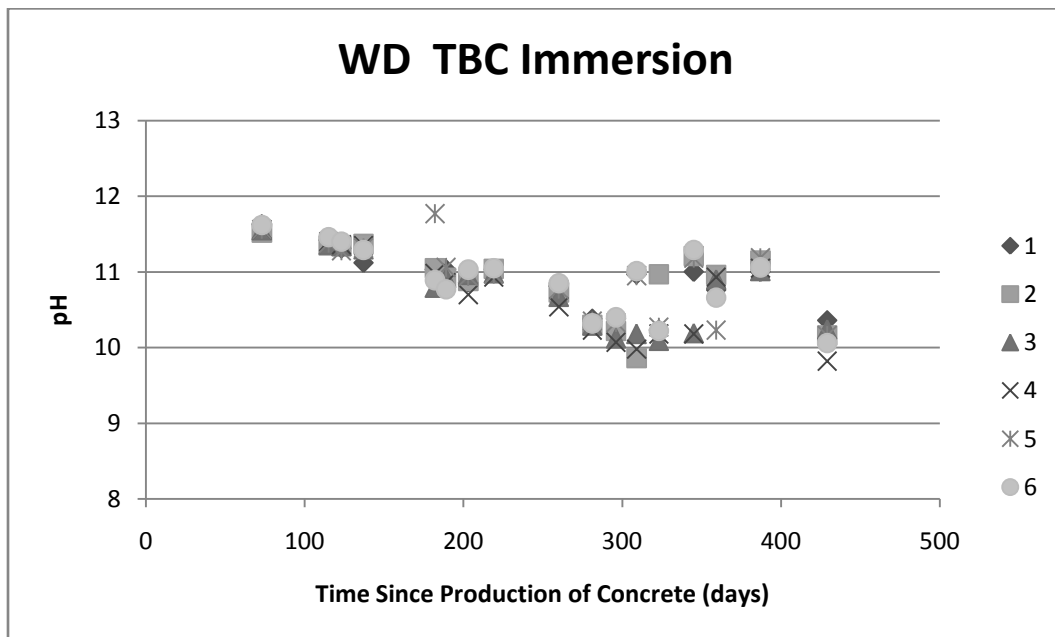


Figure B.30. pH immersion data from individual WD specimens aged with ambient air restriction on both the top and the bottom (TBC).

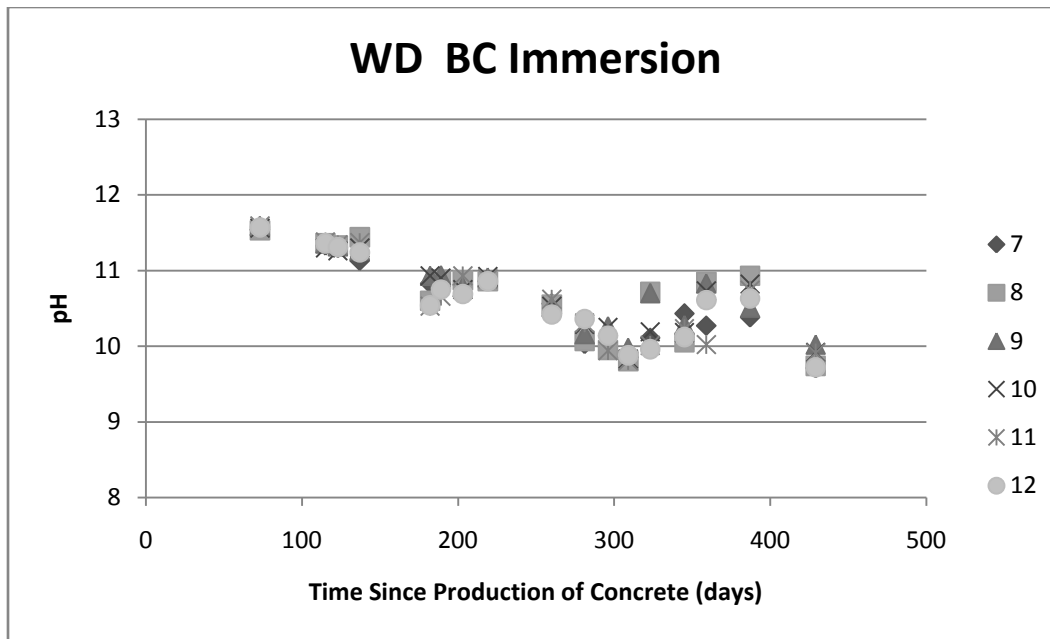


Figure B.31. pH immersion data from individual WD specimens aged with ambient air restriction on the bottom (BC).

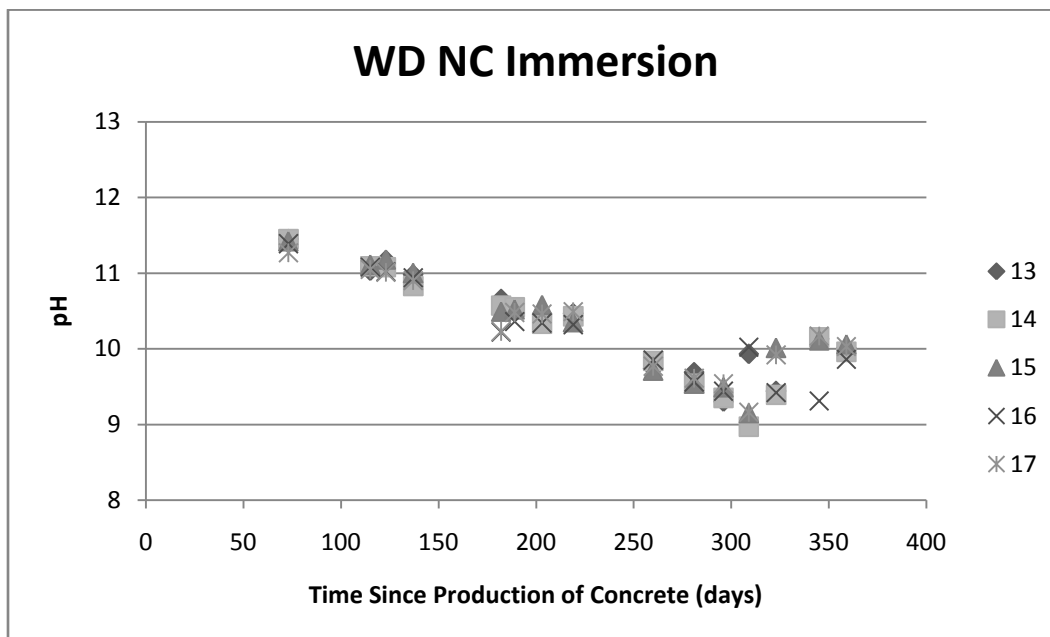


Figure B.32. pH immersion data from individual WD specimens aged without ambient air restriction on the top or bottom (NC).

Table B.8. pH immersion test data from the WD specimens (dates underlined used tap water for testing and highlighted data was omitted due human error).

WD Specimens	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Covering	TBC	TBC	TBC	TBC	TBC	TBC	BC	BC	BC	BC	BC	BC	NC	NC	NC	NC	NC
3/23/2009	11.63	11.52	11.55	11.56	11.56	11.62	11.54	11.53	11.59	11.56	11.59	11.57	11.45	11.45	11.42	11.39	11.27
4/18/2009	11.42	11.35	11.36	11.4	11.38	11.46	11.33	11.36	11.36	11.3	11.38	11.36	11.03	11.09	11.11	11.08	11.05
4/26/2009	11.31	11.34	11.34	11.36	11.28	11.4	11.3	11.33	11.32	11.26	11.34	11.31	11.17	11.08	11.18	11.02	11.01
5/10/2009	11.12	11.37	11.3	11.35	11.32	11.29	11.13	11.44	11.27	11.3	11.37	11.24	10.98	10.83	11	10.94	10.9
5/27/2009	10.88	9.41	9	9.57	9.04	9.7	9.19	9.33	9.49	8.63	9.03	8.64	8.62	8.81	8.79	8.9	8.96
6/12/2009	11.57	11.51	11.5	11.57	11.38	11.16	10.99	10.26	10.26	10.27	10.13	10.2	10.22	10.22	10.39	10.06	9.7
6/24/2009	11.03	11.05	10.79	10.98	11.77	10.89	10.83	10.6	10.93	10.93	10.53	10.54	10.66	10.57	10.49	10.22	10.23
7/1/2009	11.03	10.92	10.92	10.86	11.06	10.77	10.85	10.88	10.94	10.9	10.66	10.75	10.53	10.55	10.52	10.36	10.48
7/15/2009	10.86	10.88	10.96	10.7	10.94	11.03	10.81	10.87	10.78	10.75	10.93	10.69	10.46	10.33	10.58	10.34	10.46
<u>7/22/2009</u>	9.2	9.23	9.18	9.12	9.5	9.53	9.32	9.16	9.14	9.35	9.27	9.35	8.84	8.93	8.84	8.73	8.99
7/31/2009	11.03	11.04	10.98	10.93	10.97	11.05	10.86	10.86	10.91	10.92	10.89	10.86	10.47	10.43	10.35	10.32	10.49
<u>8/5/2009</u>	9.48	9.44	9.4	9.32	9.34	9.46	9.24	9.27	9.28	9.32	9.27	9.31	8.78	8.81	8.84	8.75	8.82
8/20/2009	10.21	9.94	10.02	10.13	10.07	10.52	10	9.84	9.95	9.89	9.83	9.96	9.3	9.13	9.25	9.1	9.31
<u>8/28/2009</u>	9.35	9.13	9.23	9.32	9.31	9.19	9.14	9.13	9.15	9.12	8.9	9.1	8.58	8.49	8.55	8.35	8.62
9/10/2009	10.81	10.73	10.67	10.54	10.77	10.85	10.56	10.55	10.52	10.53	10.62	10.42	9.74	9.84	9.71	9.85	9.77
10/1/2009	10.38	10.3	10.29	10.23	10.35	10.32	10.03	10.07	10.16	10.29	10.31	10.36	9.69	9.54	9.54	9.56	9.61
10/15/2009	10.38	10.22	10.12	10.07	10.33	10.4	9.99	9.95	10.26	10.25	9.94	10.14	9.3	9.35	9.49	9.44	9.54
10/29/2009	10.97	9.86	10.18	9.98	10.95	11.01	9.85	9.8	9.98	9.83	9.81	9.88	9.93	9.97	9.15	10.02	9.16
11/12/2009	10.23	10.97	10.09	10.18	10.27	10.22	10.11	10.72	10.7	10.19	10.01	9.96	9.44	9.39	10.01	9.42	9.92
12/4/2009	11	11.21	10.19	10.18	11.18	11.29	10.43	10.05	10.28	10.18	10.23	10.12	10.13	10.15	10.11	9.31	10.17
12/18/2009	10.76	10.96	10.9	10.93	10.23	10.66	10.27	10.85	10.83	10.73	10.02	10.61	10.01	9.96	10.06	9.86	10.03
1/15/2010	11	11.15	11.01	11.05	11.19	11.06	10.38	10.93	10.51	10.82	10.74	10.63	N.T.	N.T.	N.T.	N.T.	N.T.
<u>1/29/2010</u>	8.75	8.71	8.9	8.76	8.99	8.79	8.79	8.79	8.3	8.48	8.4	8.15	7.8	7.73	7.71	7.71	7.86
2/17/2010	10.36	10.16	10.24	9.82	10.16	10.06	9.71	9.74	10.02	9.92	9.91	9.72	N.T.	N.T.	N.T.	N.T.	N.T.

Appendix C: pH data from specimens exposed to ambient air

This appendix is supporting information for Section 4.3 and Section 6.5. The word count limitations of Chapter 4 did not permit the following information, which supports that the slopes of pH decline of the three levels of ambient air carbon dioxide are significantly different. This appendix includes Figures C.1-C.4 that were made using IGOR Pro, which show that the significant difference in slope of pH decline within a 95 percent confidence interval bands.

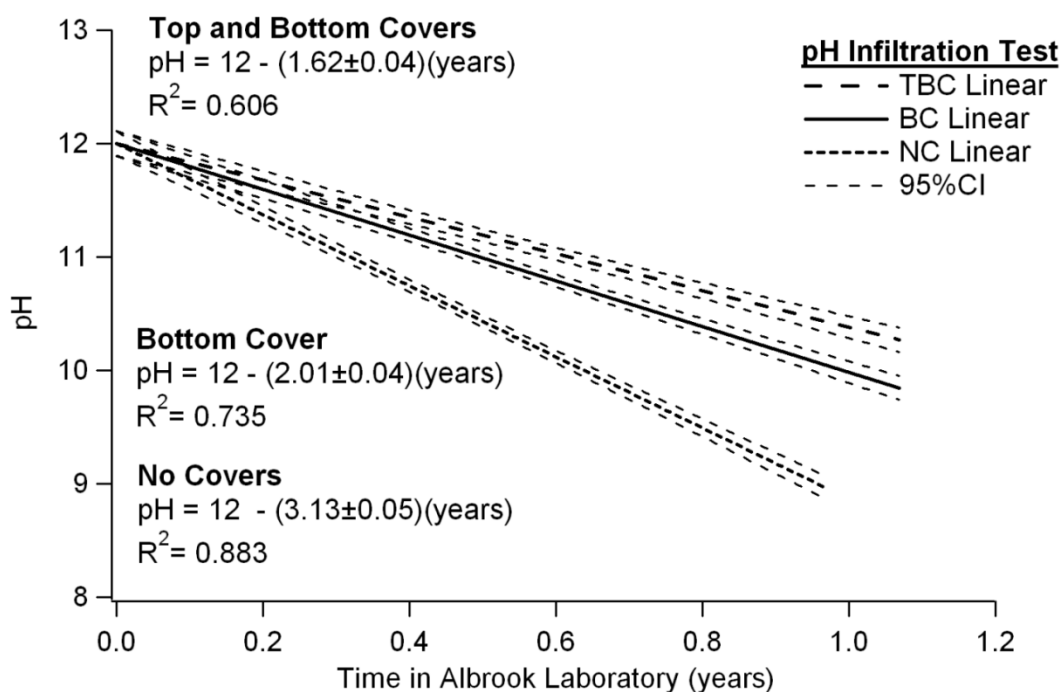


Figure C.1. pH infiltration test variation in slope of three levels of ambient air restrictions at a 95 percent Confidence interval (tested with deionized water).

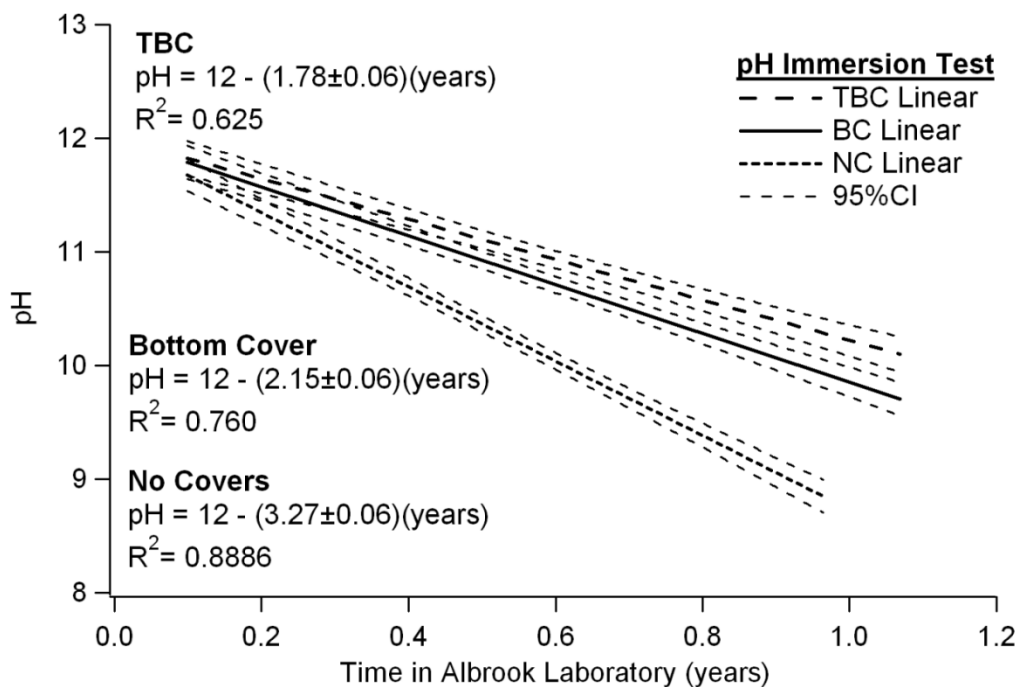


Figure C.2. pH immersion test variation in slope of three levels of ambient air restrictions at a 95 percent Confidence interval (tested with deionized water).

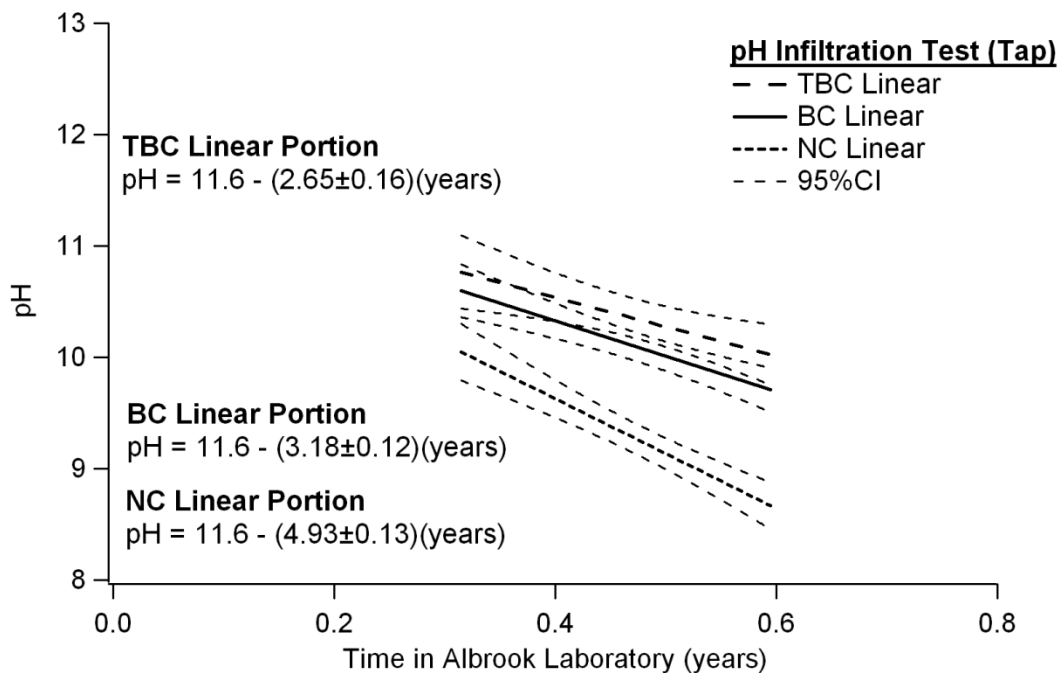


Figure C.2. pH infiltration test variation in slope of three levels of ambient air restrictions at a 95 percent Confidence interval (tested with tap water).

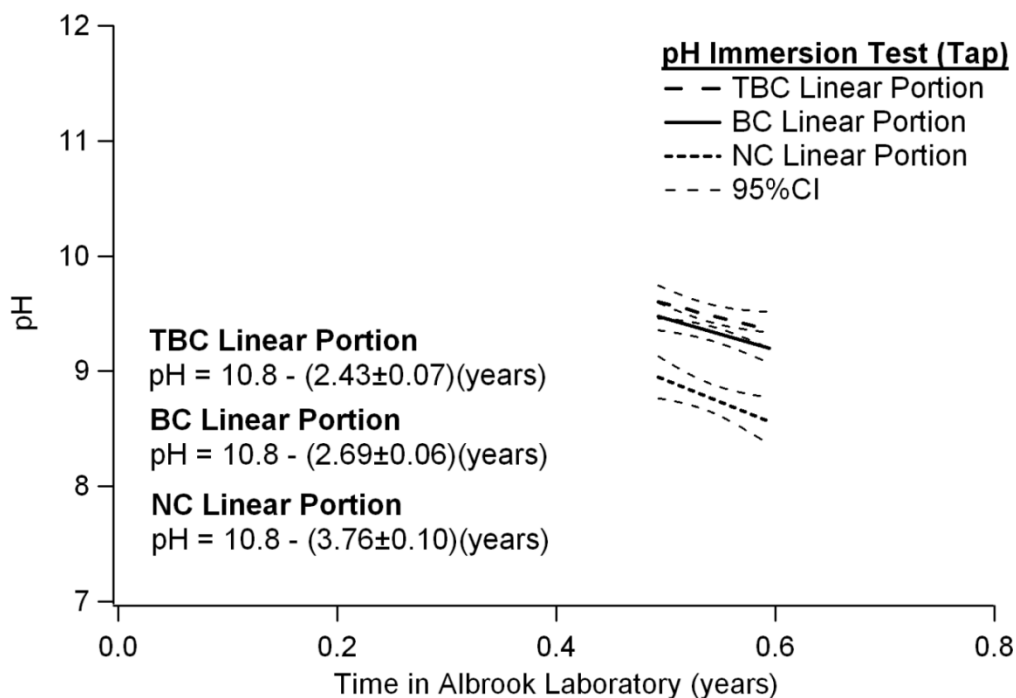


Figure C.4. pH Immersion test variation in slope of three levels of ambient air restrictions at a 95 percent Confidence interval (tested with tap water).

As can be seen in Figures C.3-C.4, not all of the slopes are significantly different. Refer to Equation 6.1 for calculations used to determine the 95 percent confidence interval bands. As shown in Section 6.5, the significant difference in slopes of pH decline as determined by the 95 percent confidence interval bands from IGOR Pro were verified for some of the slopes of pH decline using Fcalc tests. The calculations for the Fcalc tests are also included in this appendix and are summarized in Table C.1. Refer to Section 6.5 for notation and equations for Table C.1 and C.2. As depicted in Tables C.1 and C.2, the slopes of pH decline of the specimens aged without covers on the ends, with a cover on the bottom, and with covers on both the top and bottom are significantly different. Thus, it can be concluded that the calculations used by IGOR Pro to create Figure C.1 are correct in indicating the significant difference between slopes of pH

decline. Therefore, all other 95 percent confidence interval bands used in Figures C.2-C.4 are considered to identify a significant difference between slopes of pH decline.

Table C.1. F-test used to determine the significant difference between the slopes of pH decline from the specimens without covers (NC) and with a cover on just the bottom (BC) as indicated by the pH infiltration test using deionized water.

Null Hypothesis	NC = BC
n	391
ESS = $\Sigma(y_1 - y_{obs1})^2$	56.24
EMS = ESS/(df_{EMS})	0.14
df_{EMS} = (n-1)	390
HSS = $\Sigma(y_2 - y_{obs1})^2$	240.70
df_{HMS} = n-(n-1)	1
CMS = (HSS-ESS)/(df_{CMS})	184.46
F_{calc} = CMS/EMS	1279.15
F_{0.05,1,(n-1)}	3.89
Hypothesis	FALSE

Table C.2. F-test used to determine the significant difference between the slopes of pH decline from the specimens with covers on both the top and bottom (TBC) and with a cover on just the bottom (BC) as indicated by the pH infiltration test using deionized water.

Null Hypothesis	TBC = BC
n	474
ESS = $\Sigma(y_1 - y_{obs1})^2$	64.11
EMS = ESS/(df_{EMS})	0.14
df_{EMS} = (n-1)	473
HSS = $\Sigma(y_2 - y_{obs1})^2$	89.0877
df_{HMS} = n-(n-1)	1
CMS = (HSS-ESS)/(df_{CMS})	24.98
F_{calc} = CMS/EMS	184.26
F_{0.05,1,(n-1)}	3.89
Hypothesis	FALSE

Appendix D: pH data from specimens submerged in a sodium bicarbonate solution

This appendix includes supporting information for Chapter 5. Most of the information in this appendix was presented within figures in Chapter 5, but other details such as dates and omitted data were added to the tables in this section.

Tables D.1-D.5 are of pH data from specimens submerged in sodium bicarbonate solutions. The highlighted values on Tables D.1-D.5 were omitted from Figure 5.7 because of obvious problems with contaminated deionized water. On November 4, 2009, the pH of some of the deionized water was below 5, which is very unusual for deionized water. Also, pH immersion test values with the same deionized water were approximately 7.5. The testing was immediately stopped. Only the testing of specimens that used uncontaminated water were recorded. The reason for low pH on December 2, 2009 is unknown, but these pH values were also removed from Figure 5.7.

Table D.1. Supporting pH data from the specimens submerged in the basin with 0 mg/L of sodium bicarbonate.

Sodium Bicarbonate @ 0 mg/L					80% CI		
Date	Time (yr)	Avg. pH	Stdev [H ⁺]	pH Stdev	t(σ)	Min	Max
9/22/2009	0.000	11.47	6.26E-13	0.074	0.116	11.36	11.55
10/8/2009	0.041	10.62	8.38E-12	0.131	0.198	10.43	10.77
10/21/2009	0.079	10.55	1.62E-11	0.198	0.320	10.23	10.89
11/4/2009	0.118	9.71	1.03E-10	0.184	0.419	9.29	10.13
11/17/2009	0.159	10.57	7.90E-12	0.112	0.171	10.40	10.69
12/2/2009	0.195	9.48	1.57E-10	0.168	0.249	9.23	9.69
12/23/2009	0.233	10.67	1.23E-11	0.197	0.288	10.38	10.95
1/6/2010	0.271	10.73	4.38E-12	0.092	0.142	10.59	10.82
2/10/2010	0.367	10.58	4.32E-12	0.065	0.103	10.47	10.64
2/23/2010	<i>0.403</i>	<i>9.26</i>	<i>1.63E-10</i>	<i>0.114</i>	<i>0.173</i>	<i>9.09</i>	<i>9.39</i>

Table D.2. Supporting pH data from the specimens submerged in the basin with 20 mg/L of sodium bicarbonate.

Sodium Bicarbonate @ 20 mg/L					80% CI		
Date	Time (yr)	Avg. pH	Stdev [H+]	pH Stdev	t(σ)	Min	Max
9/22/2009	0.000	11.48	5.80E-13	0.070	0.110	11.37	11.62
10/8/2009	0.041	10.62	8.17E-12	0.128	0.194	10.43	10.77
10/21/2009	0.079	10.70	5.76E-12	0.110	0.188	10.51	10.84
11/4/2009	0.118	9.75	2.01E-11	0.047	0.130	9.62	9.84
11/17/2009	0.159	10.47	1.19E-11	0.132	0.199	10.27	10.62
12/2/2009	0.195	9.43	2.13E-10	0.197	0.287	9.14	9.71
12/23/2009	0.233	10.64	1.07E-11	0.168	0.249	10.40	10.86
1/6/2010	0.271	10.69	4.97E-12	0.095	0.147	10.55	10.79
2/10/2010	0.367	10.47	7.98E-12	0.092	0.142	10.33	10.56
2/23/2010	<i>0.403</i>	<i>9.38</i>	<i>1.04E-10</i>	<i>0.096</i>	<i>0.148</i>	<i>9.23</i>	<i>9.47</i>

Table D.3. Supporting pH data from the specimens submerged in the basin with 100 mg/L of sodium bicarbonate.

Sodium Bicarbonate @ 100 mg/L					80% CI		
Date	Time (yr)	Avg. pH	Stdev [H+]	pH Stdev	t(σ)	Min	Max
9/22/2009	0.000	11.47	6.77E-13	0.080	0.124	11.35	11.47
10/8/2009	0.041	10.33	2.02E-11	0.157	0.234	10.10	10.33
10/21/2009	0.079	10.30	1.51E-11	0.115	0.197	10.11	10.30
11/4/2009	0.118	9.73	1.29E-10	0.230	0.498	9.24	9.73
11/17/2009	0.159	10.19	2.16E-11	0.126	0.190	10.00	10.19
12/2/2009	0.195	9.03	1.79E-10	0.076	0.119	8.91	9.03
12/23/2009	0.233	10.16	5.33E-11	0.246	0.352	9.80	10.16
1/6/2010	0.271	10.33	9.02E-12	0.076	0.118	10.21	10.33
2/10/2010	0.367	10.23	2.69E-11	0.162	0.240	9.98	10.23
2/23/2010	<i>0.403</i>	<i>9.49</i>	<i>6.77E-11</i>	<i>0.082</i>	<i>0.127</i>	<i>9.36</i>	<i>9.57</i>

Table D.4. Supporting pH data from the specimens submerged in the basin with 250 mg/L of sodium bicarbonate.

Sodium Bicarbonate @ 250 mg/L					80% CI		
Date	Time (yr)	Avg. pH	Stdev [H+]	pH Stdev	t(σ)	Min	Max
9/22/2009	0.000	11.55	4.98E-13	0.071	0.111	11.44	11.69
10/8/2009	0.041	10.33	2.02E-11	0.157	0.234	10.10	10.52
10/21/2009	0.079	10.30	1.51E-11	0.115	0.197	10.11	10.45
11/4/2009	0.118	9.08	N.A.	N.A.	N.A.	N.A.	N.A.
11/17/2009	0.159	9.91	1.68E-11	0.056	0.088	9.83	10.00
12/2/2009	0.195	8.80	1.10E-09	0.230	0.331	8.47	9.13
12/23/2009	0.233	9.49	3.49E-10	0.316	0.440	9.05	9.93
1/6/2010	0.271	9.91	1.24E-11	0.042	0.066	9.84	9.95
2/10/2010	0.367	9.65	5.60E-11	0.096	0.148	9.50	9.75
2/23/2010	<i>0.403</i>	<i>9.61</i>	<i>3.22E-11</i>	<i>0.054</i>	<i>0.085</i>	<i>9.53</i>	<i>9.66</i>

Table D.5. Supporting pH data from the specimens submerged in the basin with 100 mg/L of non-replenished sodium bicarbonate.

Sodium Bicarbonate @ 100NR mg/L					80% CI		
Date	Time (yr)	Avg. pH	Stdev [H+]	pH Stdev	t(σ)	Min	Max
9/22/2009	0.000	11.54	6.64E-13	0.089	0.138	11.40	11.72
10/8/2009	0.041	10.37	1.55E-11	0.135	0.204	10.17	10.53
10/21/2009	0.079	10.54	4.71E-12	0.065	0.116	10.42	10.61
11/4/2009	0.118	9.49	N.A.	N.A.	N.A.	N.A.	N.A.
11/17/2009	0.159	10.19	1.90E-11	0.111	0.169	10.02	10.35
12/2/2009	0.195	9.10	3.96E-10	0.175	0.259	8.84	9.36
12/23/2009	0.233	10.12	4.09E-11	0.188	0.276	9.85	10.40
1/6/2010	0.271	10.27	5.22E-12	0.040	0.064	10.20	10.33
2/10/2010	0.367	10.02	2.10E-11	0.087	0.135	9.89	10.11
2/23/2010	<i>0.403</i>	<i>9.60</i>	<i>1.06E-10</i>	<i>0.153</i>	<i>0.229</i>	<i>9.37</i>	<i>9.78</i>

The basin pH values with corresponding sodium bicarbonate concentrations, date, and time submerged are listed in Table D.6. Generally, the basin pH values were recorded before the pH immersion tests of the specimens submerged in varying levels of carbonate laden waters, but were not recorded during the first three replenishment cycles.

Table D.6. pH data from basins with varying concentrations of sodium bicarbonate

Basins	Time Submerged (yr)	Sodium Bicarbonate Concentrations				
		0	20	100	250	100NR
11/4/2009	0.118	11.29	11.26	11.02	10.19	10.82
11/17/2009	0.159	11.11	10.29	10.04	9.22	9.85
12/2/2009	0.195	10.9	10.82	9.92	8.93	9.73
12/23/2009	0.233	10.88	10.8	10.32	9.36	9.95
1/6/2010	0.271	11	10.54	9.93	9.03	9.5
2/5/2010	0.353	10.46	10.17	9.95	9.14	9.71

Appendix E. Exfiltration Test Results from WF specimens.

As described in the Section 2.3 the exfiltration test was used to find the exfiltration rate of the WF pervious concrete specimens. The difference between the exfiltration rate and the infiltration rate should be negligible because of the volume used during the test. The exfiltration rate for each specimen is listed in Table E.1. Specimen WF04 was not tested (N.T.) because it was damaged during removal from its cylindrical mold.

Table E.1. The exfiltration rate of the WF specimens.

Specimen	Exfiltration Rate	
	(cm/hr)	(in/hr)
WF01	4148	1633
WF02	4936	1943
WF03	3642	1434
WF04	N.T	N.T
WF05	3284	1293
WF06	3977	1566
WF07	3995	1573
WF08	2457	967
WF09	3338	1314
WF10	3566	1404
WF11	2721	1071
WF12	2630	1036
WF13	2908	1145
WF14	3840	1512
WF15	2621	1032
WF16	3571	1406
WF17	2659	1047
WF18	3642	1434
WF19	3169	1248
WF20	2409	949
Avg	3343	1316
Stdev	679	267

Appendix F. Specimen Porosity

As described in the Section 2.4 the specific gravity test was used to find the porosity of each specimen. The porosities for each specimen tested for pH are listed in Tables F.1-F.10, and are considered supporting information.

Table F.1. The porosity of all WA specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
WA01	1470	2805	1664	22.38
WA02	1460	2735	1637	24.79
WA03	1470	2854	1699	21.43
WA04	1470	2820	1682	22.59
WA05	1470	2814	1680	22.86
WA06	1440	2502	1496	30.14
WA07	1470	2917	1723	18.78
WA08	1470	2694	1603	25.78
WA09	1470	2856	1682	20.14
WA10	1460	2673	1593	26.03
WA11	1460	2722	1628	25.07
WA12	1470	2955	1755	18.37
WA13	1460	2785	1653	22.47
WA14	1470	2954	1755	18.44
WA15	1470	2986	1775	17.62
WA16	1460	2794	1665	22.67
WA17	1450	2529	1517	30.21
WA18	1440	2476	1487	31.32
Avg	1463	2771	1650	23.39
Stdev	10	152	85	4.16

Table F.2. The porosity of all WB specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
WB01	1493	2827	1686	23.55
WB02	1493	2862	1701	22.26
WB03	1493	2822	1691	24.21
WB04	1493	2717	1669	29.80
WB05	1493	2832	1686	23.23
WB06	1493	2813	1686	24.53
WB07	1493	2839	1699	23.66
WB08	1493	2975	1775	19.57
WB09	1493	2832	1689	23.46
WB10	1493	2813	1670	23.41
WB11	1493	2830	1680	22.99
WB12	1493	2828	1685	23.46
WB13	1493	2818	1680	23.80
WB14	1493	2802	1668	24.05
WB15	1493	2851	1686	21.96
WB16	1493	2830	1672	22.40
WB17	1493	2847	1676	21.55
WB18	1493	2818	1676	23.49
Avg	1493	2831	1687	23.41
Stdev	0	47	24	1.97

Table F.3. The porosity of all WC specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
WC01	1490	2794	1672	24.74
WC02	1490	2799	1672	24.32
WC03	1490	2842	1696	23.13
WC04	1490	2833	1694	23.50
WC05	1490	2859	1706	22.61
WC06	1490	2842	1692	22.81
WC07	1490	2859	1694	21.83
WC08	1490	2845	1695	22.78
WC09	1490	2801	1674	24.34
WC10	1490	2823	1674	22.91
WC11	1490	2831	1689	23.40
WC12	1490	2842	1689	22.63
WC13	1490	2832	1692	23.49
WC14	1490	2844	1692	22.69
WC15	1490	2849	1691	22.33
WC16	1490	2820	1676	23.19
WC17	1490	2845	1695	22.77
Avg	1490	2833	1688	23.14
Stdev	0	20	10	0.76

Table F.4. The porosity of all WD specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
WD01	1490	2814	1690	24.53
WD02	1490	2829	1696	23.94
WD03	1490	2827	1695	24.03
WD04	1490	2836	1702	23.85
WD05	1490	2840	1698	23.35
WD06	1490	2838	1700	23.62
WD07	1490	2838	1685	22.58
WD08	1490	2857	1700	22.34
WD09	1490	2813	1682	24.08
WD10	1490	2814	1678	23.74
WD11	1490	2803	1672	24.07
WD12	1490	2785	1665	24.81
WD13	1490	2841	1695	23.05
WD14	1490	2825	1691	23.91
WD15	1490	2835	1697	23.61
WD16	1490	2777	1658	24.87
WD17	1490	2866	1711	22.43
Avg	1490	2826	1689	23.69
Stdev	0	23	14	0.75

Table F.5. The porosity of all WF specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
WF01	1513	2836	1731	26.94
WF02	1509	2773	1691	28.30
WF03	1509	2760	1688	28.96
WF04	1239	2259	1379	29.03
WF05	1474	2738	1671	27.63
WF06	1502	2763	1681	27.95
WF07	1505	2761	1687	28.64
WF08	1496	2781	1698	27.63
WF09	1490	2761	1687	27.99
WF10	1488	2717	1661	29.06
WF11	1500	2822	1723	26.79
WF12	1498	2819	1721	26.70
WF13	1500	2808	1713	27.01
WF14	1498	2750	1676	28.34
WF15	1492	2775	1693	27.50
WF16	1490	2764	1683	27.48
WF17	1502	2754	1678	28.39
WF18	1498	2765	1690	28.27
WF19	1496	2769	1688	27.78
WF20	1492	2791	1695	26.56
Avg	1485	2748	1677	27.85
Stdev	58	119	72	0.78

Table F.6. The porosity of EA specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
EA1a	622.18	1182.1	663.8	16.70
EA1d	649.79	1129.4	636	24.07
EA1g	633.76	1153.3	655.9	21.52
EA2ab	304.59	566.1	316.3	17.99
EA2cb	307.86	542.1	304	22.66
EA2eb	307.74	590.1	328	14.83
EA2gb	302.51	560.4	285.8	9.23
EA2hb	307.26	538.1	280.1	16.03
EA3ab	283.59	523.1	294.3	19.32
EA3bb	294.36	539.8	287.6	14.32
EA3cb	299.94	552.5	310.2	19.22
EA4a	600.73	1074	606.8	22.23
EA4d	598.17	1071.2	586.4	18.95
EA4g	584.61	1068.1	596	19.24
Avg	436	792	439	18.31
Stdev	162	290	168	3.91

Table F.7. The porosity of B specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
B41d	590.52	1133.4	653.8	18.78
B52a	635.76	1343.2	761.1	8.44
B52d	632.00	1349.6	764.1	7.36
B52h	649.19	1361.7	778.3	10.13
B53c	590.24	1223.9	696	10.56
Avg	620	1282	731	11.06
Stdev	24	90	48	4.03

Table F.8. The porosity of C specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
C8d	596	1006	566	26.19
C11a	679	1237	698	20.64
C12a	630	1065	607	27.24
C15e	597	993	575	29.88
Avg	626	1075	611	25.99
Stdev	39	112	60	3.89

Table F.9. The porosity of TP specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
TP2	673	1396	759	5.37
TP4	778	1417	792	19.60
TP5	560	975	557	25.30
Avg	670	1263	702	16.76
Stdev	109	250	127	10.26

Table F.10. The porosity of J specimens.

Specimen	Total Volume (CC)	Dry Mass (g)	Submerged Mass (g)	Porosity (%)
J1	624	964	573	37.45
J5	652	1102	639	28.86
J10	742	1316	768	26.23
Avg	673	1127	660	30.85
Stdev	62	177	99	5.87