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Measurement of TSS and Other Pollutant Removal by a Pervious Concrete System

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SYNOPSIS: Water quality benefits of a pervious concrete system are dependent upon adsorption, permeability, void space and mix constituents. This study illustrates the removal efficiency of fly ash amended pervious concrete, gravel and cellular subbase. Stormwater pollutants commonly addressed in city and county guidelines are total suspended solids (TSS), heavy metals, polycyclic aromatic hydrocarbons (PAHs) and oils. Removal efficiency of a pervious concrete system should exceed 80% for each of these according to Environmental Protection Agency (EPA). Testing of each material separately allows for a greater understanding of its role in the water quality benefit as well as the overall performance of the system. A basic pervious concrete mixture was used with varied fly ash replacements. Fly ash was investigated to determine its adsorption properties both for high carbon and low carbon Class F Ash. The results are anticipated to be useful in verifying a pervious concrete cross section as a valid structural BMP for water quality and water quantity benefits.

KEYWORDS: Total Suspended Solids (TSS), Metals, Hydrocarbons, Pollutants, Pervious Concrete, Soil, Subbase, Fly Ash, Cellular Concrete

Field Performance of Portland Cement Pervious Concrete Pavement in Cold Weather Climates

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SYNOPSIS:

Portland Cement Pervious Concrete (PCPC) is a material of increasing interest for parking lots and other applications. PCPC typically consists of coarse aggregates, portland cement, water, and various admixtures. In this research, in-service PCPC pavements were inspected in the field, and cores were removed in order to investigate properties in the laboratory. Field evaluation methods included visual inspection, two surface drainage measurements, and indirect transmission ultrasonic pulse velocity (UPV). Laboratory testing methods included void ratio, unit weight, compressive strength, splitting tensile strength, hydraulic conductivity, and direct transmission UPV. Because it is compacted on the surface with screeds or rollers, PCPC generally has higher strength, lower void ratio, and lower hydraulic conductivity at the surface than at the bottom. Therefore, the properties of the tops and bottoms of core samples were compared. Generally, the PCPC installations evaluated under this research project have performed well in freeze-thaw environments with little maintenance required. No visual indicators of freeze-thaw damage were observed. With the exception of some installations where the pore structure was sealed during construction with wet mixtures or over compaction, nearly all sites showed fair to good infiltration capability based on drain time measurements.

KEYWORDS:

compressive strength, hydraulic conductivity, nondestructive testing, pervious concrete, ultrasonic pulse velocity, void ratio

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INTRODUCTION

Portland Cement Pervious Concrete (PCPC) is a material of increasing interest for parking lots and other applications^{1, 2, 3, 4}. PCPC typically consists of coarse aggregates, portland cement, water, and various admixtures. Exclusion of fine aggregates and uniform size of coarse aggregates leaves open voids that give the material its porosity and permeability¹. Details of typical mixtures may be found in the literature^{1, 2, 3, 4, 5}. Similar materials are used for cement-stabilized drainage layers in highway and airport pavements.

Unlike conventional concrete, the material properties of PCPC are highly dependent on both concrete materials and placement techniques^{4, 5, 6, 7, 8, 9}. If the mixture is too dry or is under-compacted, then the PCPC will be weak, non-durable, and subject to surface raveling. If, instead, the mixture is too wet or over-compacted, then it will not be pervious and will defeat the purpose of using PCPC. PCPC requires interconnected voids to maintain high hydraulic conductivity and allow water to pass through rapidly.

Vibrating and manual screeds are commonly used for placement of PCPC. Manual screeds can cause surface tearing if the mixture is too stiff, and the frequency of vibration should be kept low, to prevent blocked voids and closing off the surface. Other forms of compaction include manual rollers, with or without additional weight, and hydraulic vibrating Bunyan screeds³.

The American Concrete Institute has published a specification for pervious concrete¹⁰, but there remains a need for widely accepted test methods for ensuring the performance of PCPC. The most reliable method of verifying in-place concrete strength and void ratio is extraction of cores from the finished pavement. Obviously, however, this is damaging to the pavement, so it is important to find alternate techniques.

RESEARCH OBJECTIVES

The main objective of this study was to compare field observations of in-service PCPC pavements with laboratory tests on cores, in order to verify the expected range of field properties. Properties of interest included void ratio, hydraulic conductivity, compressive strength, and tensile strength. The investigators visited pervious concrete installations and performed visual and non-destructive testing to assess infiltration capability, in place consistency, and long-term durability. Field evaluation methods included visual inspection, two surface drainage measurements, and indirect transmission ultrasonic pulse velocity (UPV). Two dozen sites in Ohio, Indiana, Kentucky, and Colorado were investigated. Detailed descriptions of the sites have been published elsewhere^{5, 6, 7}.

For most of the sites visited, it was not possible to extract cores. Cores were extracted from six field sites where permission could be obtained. The pavements at these sites were approximately 6 inches (150 mm) thick. Laboratory testing methods included void ratio, unit weight, compressive strength, splitting tensile strength, hydraulic conductivity, and direct transmission UPV. The testing equipment and methods are described in detail in Delatte et al.⁵ and Mrkajic⁷.

Twelve cores were taken from each of the six sites, except for the site in Gary, Indiana, where 20 cores were removed from a larger project. The cores were taken in accordance with ASTM Standard C 42/C 42M-99. The core barrel was 4 inches (102 mm) in diameter and extracted a core sample with a diameter of 3.75 inches (95 mm). Because it is compacted on the surface with screeds or rollers, PCPC generally has higher strength, lower void ratio, and lower permeability at the surface than at the bottom. Haselbach and Freeman had previously documented this phenomenon¹¹. Therefore, the properties of the tops and bottoms of core samples were compared.

FIELD AND LABORATORY TEST METHODS

For this research, the field evaluations included visual observation, a surface permeability/infiltration rate test, and Ultrasonic Pulse Velocity (UPV). As noted previously, it was possible to remove cores from some of the field installations. Cores were brought back to the laboratory and tested for void ratio, permeability, UPV, and either compressive or splitting tensile strength.

Visual Observation

Visual observations provided information about overall performance of the pervious concrete. For consistency a data sheet was filled out for each site visited, incorporating information about the pervious concrete, as well as a general description of the surrounding topography. Analysis of the surrounding topography led to easier detection of clogged areas, and suggested reasons for any observed clogging. The questionnaire included information about distance between joints and jointing methods used.

The extent of raveling on the surface and along joints was observed and described as minimal, medium (significant) or high (extensive). The surface was also examined for cracks and visual indications of clogging. Owners were questioned about maintenance. Raveling is shown in figure 1.



Figure 1 – example of raveling

The data sheet documented information regarding volumes of heavy-vehicle traffic. Photographs of the pavements and key features were taken. Based on the initial results, areas of pervious concrete were chosen for further nondestructive testing. Visual inspection also provided valuable information about durability and possible construction errors. Specific detailed site observations are provided elsewhere^{5, 6}.

Surface Drainage Test

A simple surface hydraulic conductivity/infiltration apparatus for surface drainage was developed as part of this research. The equipment was made from a 4 by 8 inch (100 by 200 mm) plastic concrete cylinder mold. Foam rubber was attached to the bottom of the plastic mold to try to seal the cylinder against the pavement, and a hole was drilled for water to flow out with a diameter of 7/8 inch (22 mm). The time to drain the cylinder into the pavement

through the hole was measured. Care should be taken not to allow water to freely flow around the perimeter of the mold. Thus, constant pressure should be applied on top of the mold during testing. The test may be used before and after maintenance to quantify the effectiveness of a maintenance technique. The apparatus is shown in figure 2.



Figure 2 – surface hydraulic conductivity/infiltration apparatus

Ultrasonic Pulse Velocity (UPV)

The UPV nondestructive test method measures the velocity of a compression wave through concrete. It has a long history of use with conventional concrete, but has not been used much with PCPC. UPV is based on the modulus of elasticity and density of the material, and the variability of the wave speed indicates the variability of these properties within a concrete pavement or structure¹².

If the mass density of the material and the velocity of the waves are known, the elastic properties of the material can be estimated for traditional concrete. In the UPV test an ultrasonic pulse is typically generated at one end of the test specimen, and the time of its travel from one end to another is measured. Knowing the distance between these two points, the velocity of the pulse can be determined. UPV is most accurate when opposite sides of a specimen may be accessed, and least accurate when only one side may be tested¹².

For this research, only the pavement surface could be accessed in the field, so a direct reflection technique was used with the two transducers 2 in (50 mm) apart. Opposite ends of cores were tested in the laboratory through direct transmission.

Void Ratio

The void ratio was determined by calculating the difference in weight between air dried and saturated samples, using the following equation in consistent force (F) and length (L) units (4, p. 22).

$$V_r = \left[1 - \left(\frac{W_2 - W_1}{\rho_w \times Vol} \right) \right] \times 100\%$$

Where,

V_r = total void ratio, %

W_1 = weight under water, F

W_2 = dry weight, F

Vol = volume of sample, L³

ρ_w = density of water, F/L³

Initial determination of the void ratio was used to divide samples for further testing. Typically four samples were chosen for hydraulic conductivity testing, four for compressive strength testing, and remaining four for splitting tensile testing.

Hydraulic conductivity

Samples tested for hydraulic conductivity were sliced in half, and hydraulic conductivity was repeated on the top and bottom parts. Later, the top and bottom parts were tested in splitting tension. Specimens were prepared by wrapping them in plastic and then in duct tape.

The hydraulic conductivity of the samples was determined using the falling head method. A new apparatus was built specifically for testing the pervious concrete samples. The coefficient of permeability was determined using the following equation found in many soil and pavement texts (4, p. 22).

$$k = \frac{aL}{At} \ln \left(\frac{h_1}{h_2} \right)$$

Where,

k= coefficient of permeability (hydraulic conductivity), L/T

a = cross-sectional area of the standpipe, L²

L = length of sample, L

A = cross-sectional area of specimen, L²

t = time for water to drop from h₁ to h₂, T

h₁ = initial water level, L

h₂ = final water level, L

ln = the natural logarithm

Compressive and splitting tensile strength

Compressive strength and splitting tensile strength tests were performed according to ASTM C39 and ASTM C496, respectively.

SITES VISITED, FIELD OBSERVATIONS, AND RESULTS

The project site visit observations included clogging, raveling, cracking, UPV, and surface drainage.

Clogging

Visual observations were used to estimate clogging. Clogging occurs due to many different types of debris, such as sediment, mulch, stones, and other soil materials. Clogging materials may be carried onto the pavement during storms. Flower beds and bare soil areas may also lead to clogging. In areas where pervious concrete is placed around trees, leaves, twigs, bark, and other tree materials can fall, and clog the pervious concrete. These clogging sources were observed on various site visits.

Some of the sites contained areas where the surface was sealed off by cement paste due to a wet mixture or over compaction during the placement of the pervious concrete. Table 1 shows the fastest and slowest infiltration times, as well as the mean and standard deviation.

Raveling

Most of the sites had areas that were slightly deteriorated and had some missing aggregate. Raveling of aggregate occurs when the aggregate to paste bond is broken, and the aggregate is dislodged from the pervious concrete matrix. Raveling is shown in figure 1. There were few sites that did not show areas of raveling, and the site with the most raveling was at Indian Run Falls in Dublin, Ohio. This site also had the lowest water to cementitious materials ratio, which was 0.21. The w/cm ratio on the sites visited ranged from the 0.21 at Indian Run Falls, to 0.35 at Merry Lea Environmental Learning Center of Goshen College, in Albion, Indiana.

The pavement may also be raveled by aggressive power washing. At the Bettman Natural Resources Center in Cincinnati, Ohio, landscapers dropped mulch onto the pervious concrete and attempted to clean the debris away by power washing, damaging the surface⁵ 6.

Table 1 – UPV and Surface Drainage Results

LOCATION	UPV (ft/s)				Drain time (sec.)			
	Mean	S.D.	Max	Min	Mean	S.D.	Max	Min
Ball Brothers	13,200	1,400	15,800	8,012	70	23	117	23
Bettman Center	12,000	1,300	16,800	8,500	57	30	125	14
Boone Market	13,100	975	15,100	10,250	56	20	85	15
Charter School	13,100	450	14,100	11,600	44	27	149	10
Cleveland State Lot D	12,800	550	13,700	11,100	66	20	112	23
Ernst Pool	13,600	740	14,900	12,400	33	14	80	14
Fred Fuller Park	13,600	925	14,700	11,600	136	24	180	93
Harrison Concrete	13,600	1,850	15,800	9,500	21	10	52	8
Indian Run Falls	12,600	800	14,500	9,600	29	11	65	11
Kentucky Sanitation	11,300	1,600	13,600	8,300	45.5	12	69	19
Kettering Hospital	12,900	475	14,100	12,200	68	15	90	39
Keystone Concrete	13,000	560	13,700	11,800	103	12	125	85
Kuert Concrete	12,970	465	13,700	11,100	31	18	90	9
Lakewood Park	13,100	465	14,100	11,700	36	13	73	19
Merry Lea	11,900	380	13,100	11,300	77	21	141	44
Patterson Dental	12,500	850	14,100	11,300	42	13	67	21
Phillips	NA	NA	NA	NA	64	14	120	31

Cracking

Six of the sites that were visited showed signs of cracking. The cracking in two cases came from heavy vehicular traffic. One case was in Gary, Indiana, at a Charter School where the local fire department fills the water tank on the truck at the hydrant, and food and other materials are brought in by delivery trucks and semi trucks. The second site

was located in Monroe, Ohio, at Ball Brothers Contracting. The pervious concrete was used as a storage area for large, heavy concrete forms. Heavy vehicles drive daily onto this pervious concrete to load and unload forms from the trucks. Skid steers and fork lifts are also used. At Boone County Farmer's Market in Burlington, Kentucky, a crack occurred due to small landscaping dump trucks and other vehicles parking for long periods of time. One other site had cracks due to a lack of construction joints along an 80 foot (24.4 meter) length (Kuert Concrete, South Bend, IN). Another crack occurred due to difficulty in placement and possibly an overly wet mixture (Merry Lea, Albion, Indiana).

Ultrasonic Pulse Velocity

Table 1 shows UPV and surface permeability results. The first column shows the average of the UPV measurements. Columns two, three, and four show standard deviation, maximum, and minimum values, respectively. Higher UPV numbers suggest a tighter structure and possible clogging.

Surface Drainage

Table 1 shows the surface drainage results. Typically, if the surface is slightly clogged water flow around the cylinder will be evenly distributed, and water will infiltrate without creating a large diameter water spot. However, clogged surfaces produce larger size diameter spots, and in some instances sheet flow was observed on the surface. This usually happens only if the time to drain exceeds two minutes, indicating a nearly impermeable surface. As an example, conventional impermeable concrete and asphalt pavements generally have approximately 2 minute drain times.

A smaller size diameter spot is observed if it takes less than a minute to drain the cylinder, and in some instances no water is observed around the cylinder. This phenomenon usually occurs with test times between 13 and 20 seconds. A small diameter spot is shown on the left side of figure 2.

Test times for areas around the edges of pavements are usually high, inflating overall permeability values. Generally, the outer edges clog first as debris is carried onto the pavement from adjacent soil or landscaping. Average values around one minute and less with a small standard deviation suggest acceptable infiltration capability. Restoration through vacuuming and pressure washing could prevent further clogging, and improve infiltration capacity.

LABORATORY TEST RESULTS

Individual laboratory test results for each sample are provided elsewhere^{5, 7}. Figures 3 and 4 summarize the overall trends. Several samples were cut in two, and the results between the top and the bottom of the core were compared. Figure 3 compares void ratios for top and bottom samples, and Figure 4 compares hydraulic conductivity for those samples.

Haselbach and Freeman¹¹ found that the void ratio at the top of a pervious concrete pavement was much lower than that at the bottom. The tests results reported in this section confirmed that finding. In general, the bottom samples have higher void ratio and hydraulic conductivity.

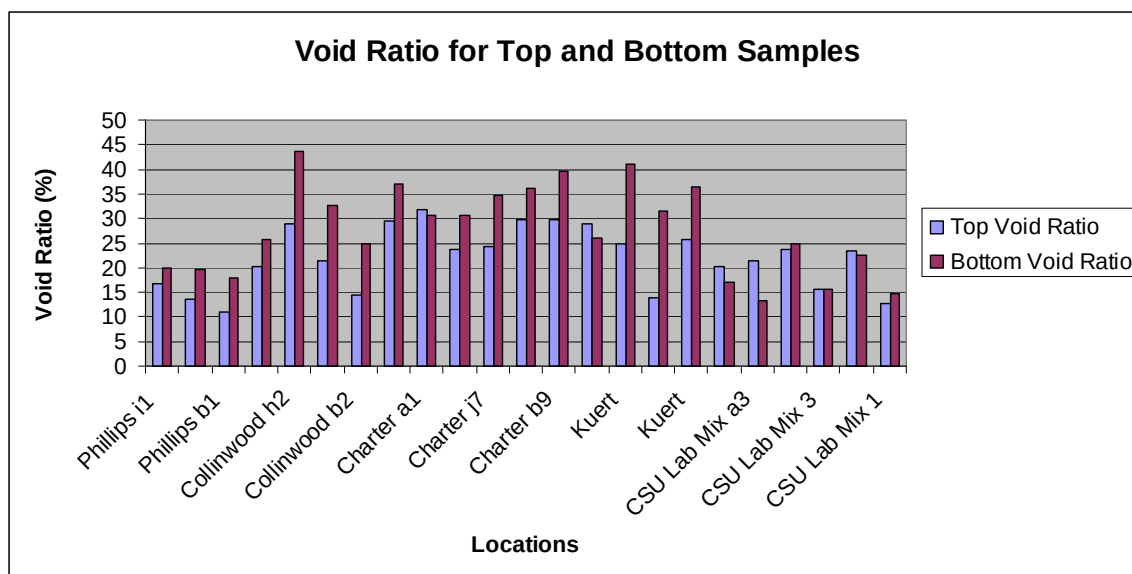


Figure 3 – Void Ratio for Top and Bottom Samples

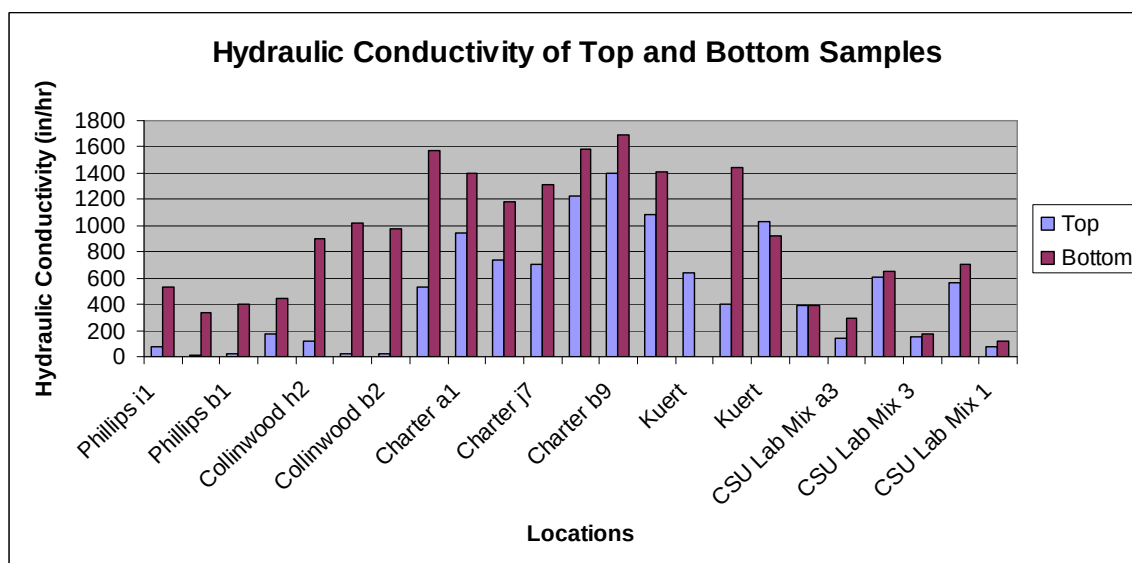


Figure 4 – Hydraulic conductivity for the Top and Bottom Samples (1 in. = 25.4 mm)

Comparison between Field Drainage Time and Laboratory Hydraulic Conductivity

The field infiltration/ drain time test developed as part of this research will be more useful if it can be correlated to hydraulic conductivity. At six locations, the drain time was measured prior to coring. The hydraulic conductivity and drain time values are plotted in figure 5. With drainage times over 60 seconds, hydraulic conductivity is nearly zero. The arrow in figure 5 shows the approximate break point in drainage time between draining and non-draining pervious concrete.

Figure 5 – Comparison between Hydraulic Conductivity and Drain Time Values (1 in. = 25.4 mm)

The subsequent set of figures investigates the correlations between the following relationships:

Hydraulic conductivity versus void ratio (figure 6)

Hydraulic conductivity versus pulse velocity (figure 7)

Compressive strength versus void ratio (figure 8Figure)

Compressive strength versus pulse velocity (figure 9Figure)

Tensile strength versus void ratio (figure 10)

Tensile strength versus pulse velocity (figure 11)

Overall, exponential relationships were found to fit the data best. Correlation coefficients (R^2) ranged from 0.63 to 0.86.

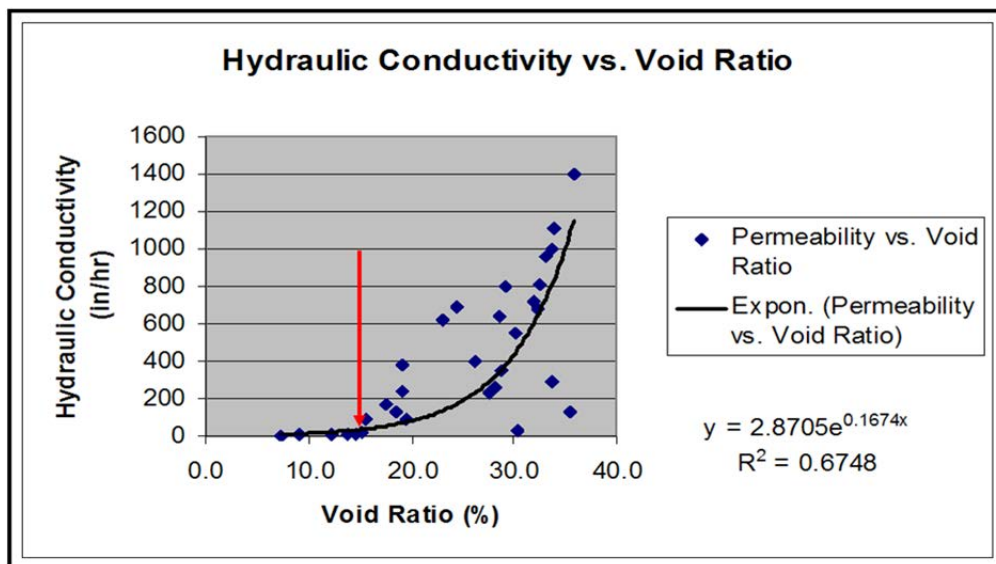


Figure 6 – Relationship between Hydraulic Conductivity and Void Ratio (1 in. = 25.4 mm). The arrow shows the approximate break point in drainage time between draining and non-draining pervious concrete.

As expected, hydraulic conductivity and void ratio are closely related, but there are some discrepancies. This is because the hydraulic conductivity depends on the interconnectivity of the voids, as well on as the void ratio. At void ratios less than 15 %, the hydraulic conductivity is nearly zero. This 15 % void ratio point is shown by the arrow in figures 6, 8, and 10.

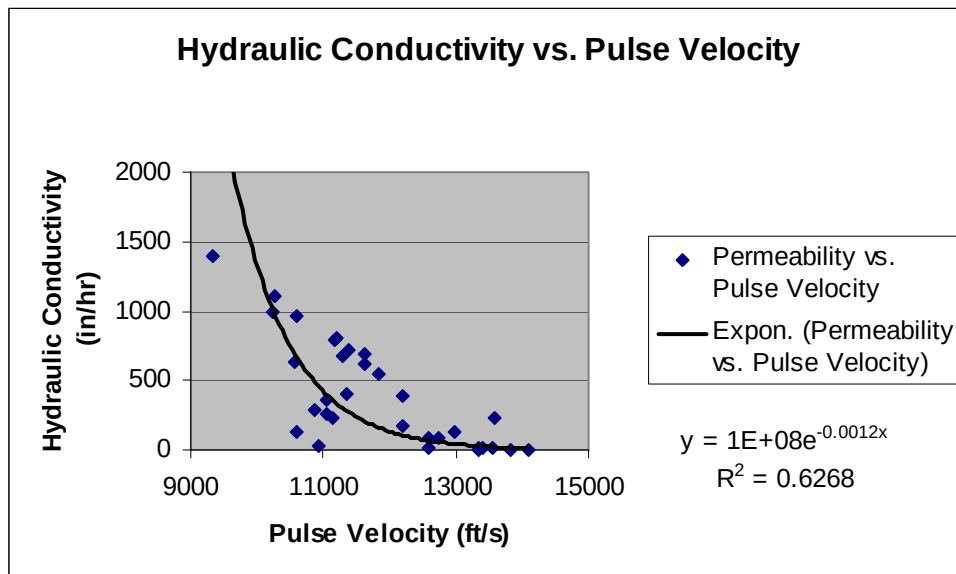


Figure 7 – Relationship between Hydraulic conductivity and Pulse Velocity (1 ft. = 0.305 m)

The relationship between hydraulic conductivity and pulse velocity is the weakest of the six relationships developed. Pulse velocity is apparently a more reliable indicator of strength and modulus of elasticity than of hydraulic conductivity. It can, however, provide a rough prediction. In most cases where the pulse velocity exceed 12,500 feet per second, (3,800 m/s), the hydraulic conductivity was very low.

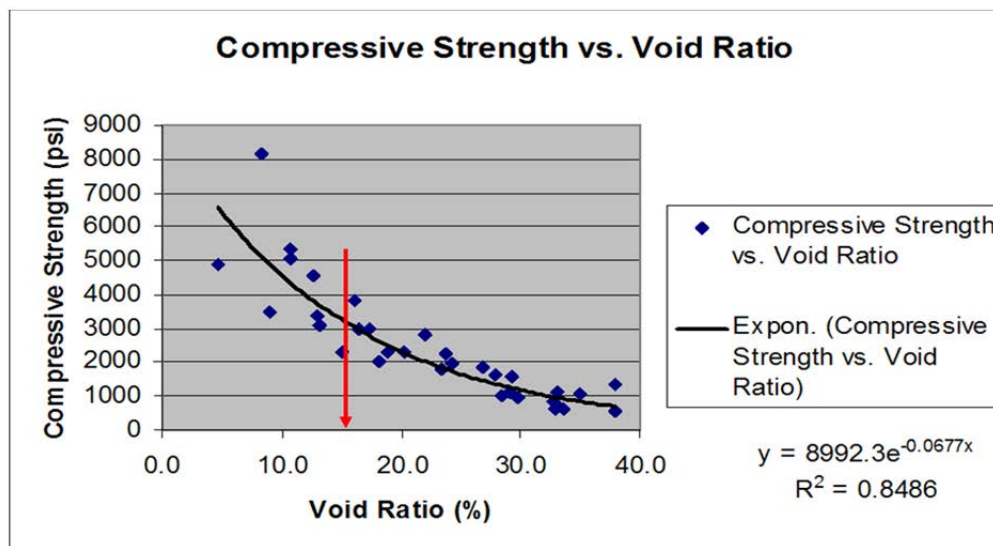


Figure 8 – Relationship between Compressive Strength and Void Ratio (1 psi = 6.89 kPa). The arrow shows the approximate break point in drainage time between draining and non-draining pervious concrete.

The relationship between compressive strength and void ratio has been documented by others, such as Schaefer et al.4, and is obviously strong. The relationship between pulse velocity and strength is also strong. The relationship would probably be improved without including one 8,000 psi (55 MPa) outlier in the data. Therefore, UPV has the

potential for reliably predicting pervious concrete strength in the field. The relationship between void ratio and tensile strength is strong, as it is with compressive strength. Results indicated that UPV can be a reliable predictor of tensile strength as well as compressive strength.

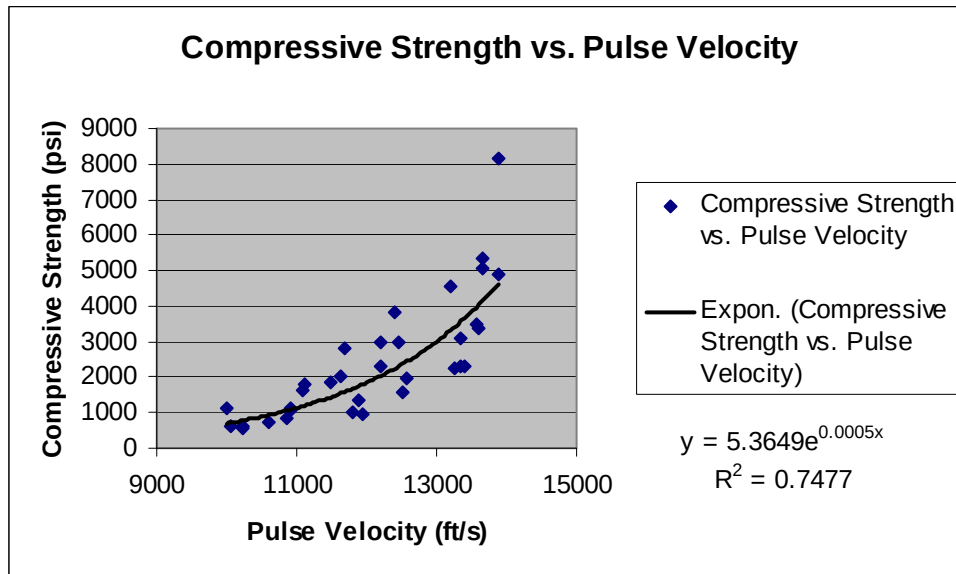


Figure 9 – Relationship between Compressive Strength and Pulse Velocity (1 psi = 6.89 kPa, 1 ft. = 0.305 m)

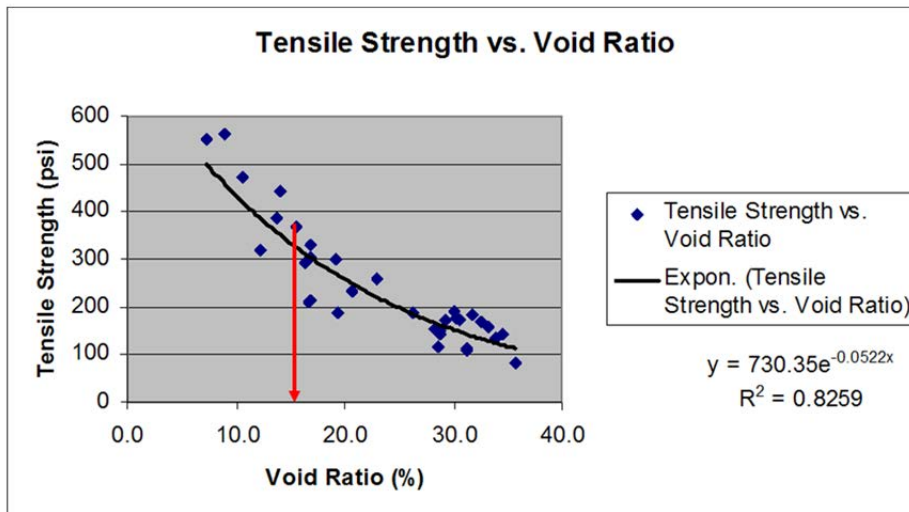


Figure 10 – Relationship between Tensile Strength and Void Ratio (1 psi = 6.89 kPa). The arrow shows the approximate break point in drainage time between draining and non-draining pervious concrete.

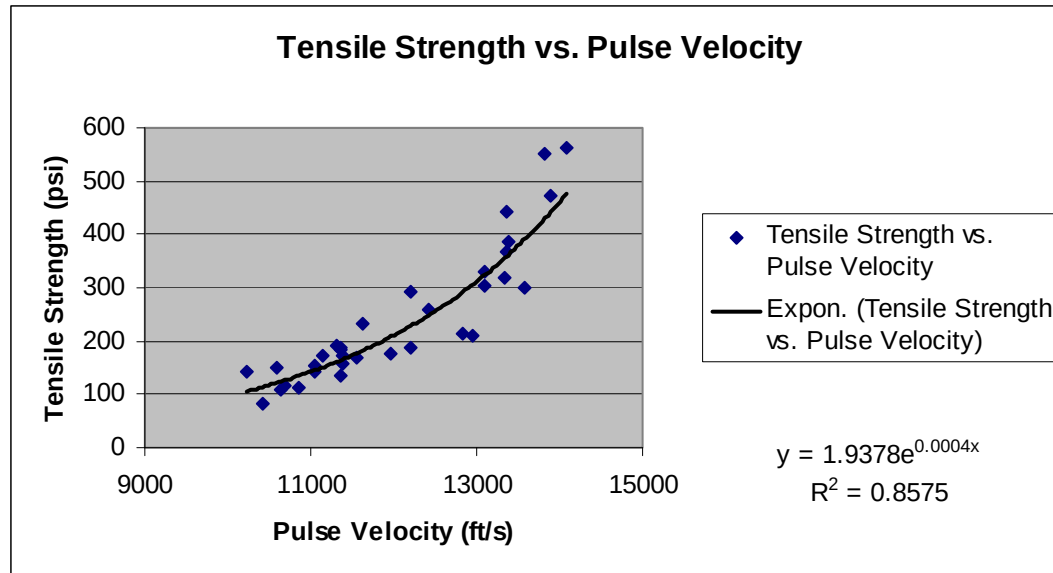


Figure 11 – Relationship between Tensile Strength and Pulse Velocity (1 psi = 6.89 kPa, 1 ft. = 0.305 m)

Separating mixtures made with the gravel coarse aggregate, and those made with limestone aggregate revealed much stronger relationships developing for the mixtures with gravels. These results are provided by Mrkajic7.

Figure 6 shows that a minimum void ratio of approximately 15 % is necessary for permeability. Figures 8 and 10, in turn, show that at this void ratio a compressive strength of 2,000 – 3,000 psi (14 – 21 MPa) and a splitting tensile strength of 200 – 300 psi (1,400 – 2,100 kPa) can be expected, although strength is also affected by other constituent and mixture variables.

SUMMARY OF OBSERVATIONS

Observations from test sites address raveling, cracking, clogging, results of maintenance, and test results. Raveling often appeared early after construction, but decreased as the pervious concrete aged and the top loose rocks were removed. Most raveling was a product of low water to cement ratio, poor compaction, or dry weather conditions during placement. Tooled contraction joints raveled more than saw cut joints.

Major causes of cracking were heavy vehicle traffic, lack of contraction joints, or a large distance between joints. Joint spacing should probably follow recommendations for conventional concrete until rules for PCPC joint spacing can be developed. Figure 12 shows an example of heavy vehicle damage.

Clogging was mainly caused by sediment and debris that had been carried onto the pervious concrete. In some areas, clogging was caused during the installation process by paste smudging across the surface, over compaction, wet mixes, or high water to cement ratio.

Vacuuming and pressure washing successfully restored appearance and permeability of the pervious concrete at the Kentucky Sewer District. A similar technique was unsuccessful at the Kuert Concrete Plant due to shingle debris that had washed onto the pervious concrete from building down spouts. Drain times before and after maintenance activity at CSU Lot D are shown in figures 13 and 14, respectively. Prior to maintenance, several of the locations had drain times close to or more than 60 seconds. After maintenance, drain times were considerably reduced.

Surface drainage results indicate that the concrete with an average value less than one minute and a small standard deviation suggest acceptable infiltration capability.

Field UPV testing was inconclusive. Laboratory tests on cored samples suggest a relationship between compressive and tensile strengths and the ultrasonic pulse velocity.



Figure 12 – Heavy Vehicle Damage

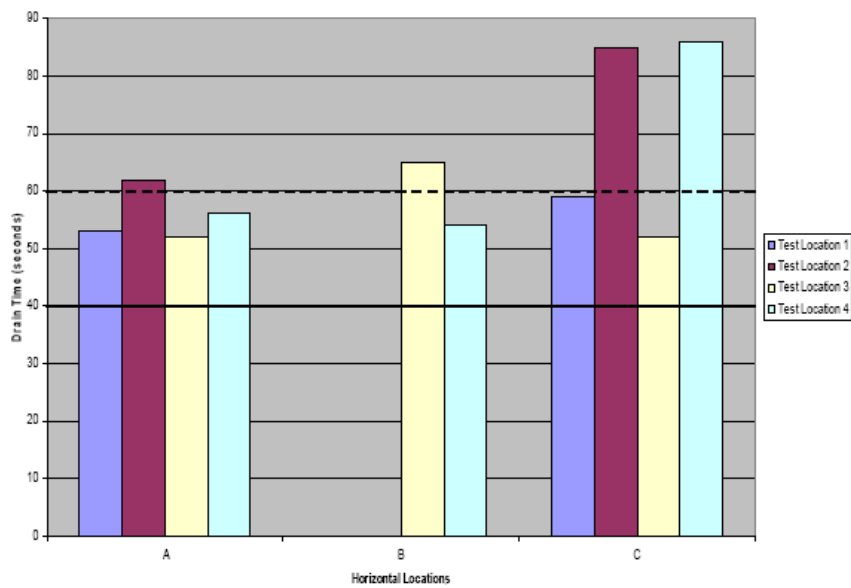


Figure 13 – Drain Times before Maintenance, CSU Lot D

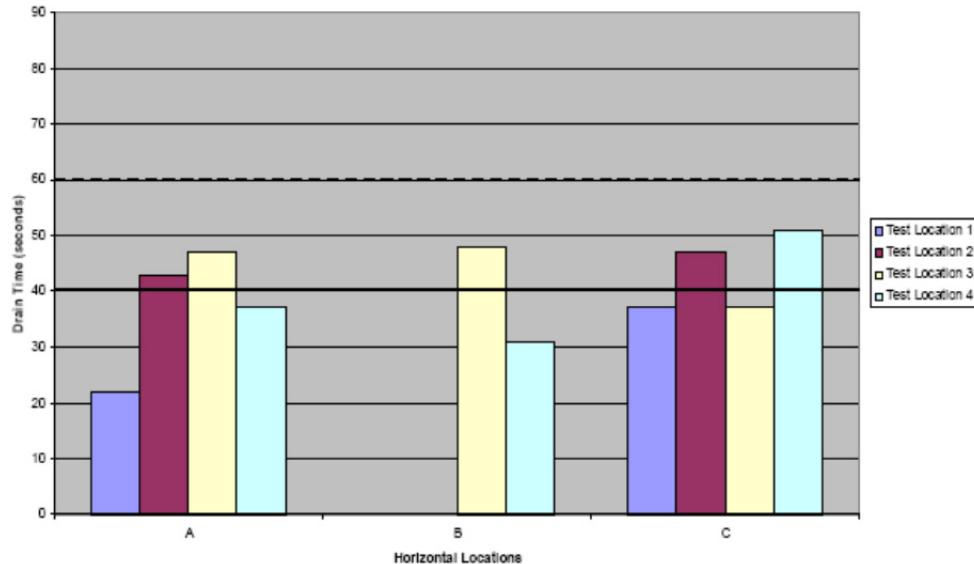


Figure 14 – Drain Times after Maintenance, CSU Lot D

CONCLUSIONS

Generally, the PCPC installations evaluated under this research project have performed well in freeze-thaw environments with little maintenance required. No visual indicators of freeze-thaw damage were observed. With the exception of some installations where the pore structure was sealed during construction with wet mixtures or over-compaction, nearly all sites showed fair to good infiltration capability based on drain time measurements. Most of the sites visited do not yet require maintenance.

Because use of PCPC in this region began fairly recently, the sites visited were less than four years old at the conclusion of the research project in 2007. Although most are performing well now, it would be useful to revisit them periodically in the future. If future visits are made, the results reported in this research will provide a useful baseline for comparing performance.

Designing and Building Freeze-Thaw Durable PCPC Pavements

None of the sites investigated showed any sign of freeze-thaw damage. The damage observed was either due to early age raveling or to structural overload. This was probably because the sites were adequately drained, and therefore the pervious concrete was not saturated when the temperature was below freezing.

In conventional concrete, however, freeze-thaw damage may take many years to become apparent. It eventually results in disintegration. Therefore, in pervious concrete, freeze-thaw damage would be expected to take the form of widespread raveling progressing through the thickness of the pavement. This was not observed at any of the sites visited.

In the laboratory, the relative dynamic modulus determined using a sonometer is used to calculate the durability factor of a concrete specimen. Because UPV works on very similar principles to a sonometer, UPV should be able to detect freeze-thaw damage in the field as a reduction in wave velocity. However, this requires further work.

In addition, this research validated the result found in other studies^{4, 11} that there is a considerable difference between the void ratio at the top and at the bottom of a PCPC pavement. Generally, the top is much better compacted.

Field Investigation Techniques

This research employed a number of field investigation techniques that may be of value to future researchers engaged in similar studies.

Visual observations – It has been suggested that visual observations are some of the most powerful and useful investigative tools. Visual observations can identify structural and nonstructural problems in PCPC pavements, and can often identify locations most likely to be clogged and sources of clogging material.

Drain Time Testing – The 4 x 8 inch (100 x 200 mm) plastic cylinder mold drain time test has been found to correlate reasonably well to hydraulic conductivity. This test may be used to assess infiltration capability of newly built pavements, or to determine whether maintenance is needed. It would be useful to track results over time, in order to assess the need for and the effectiveness of different maintenance treatments.

Ultrasonic Pulse Velocity – Laboratory UPV results, found by direct transmission, correlate very well with hydraulic conductivity and strength of PCPC. Field indirect transmission UPV results have so far been less reliable, but results may be improved with future research.

Testing of Cores – Unfortunately, at this time cores remain the best way to measure thickness, strength, and void ratio of PCPC pavements. In order to avoid the damage and expense of core removal, it would be desirable to develop other test methods. Of course, the new test methods would have to first be calibrated to cores. Nondestructive testing (NDT) methods such as UPV show promise, but require further development. Although this research did not make use of surface wave methods, those would also seem to have promise.

Future Research

The main drawback of the present study has been the relatively recent construction of PCPC pavements in this area. As these pavements are subjected to weather and traffic, the performance trends will become clearer.

For the sites investigated in this project, the test results provided will provide a benchmark for comparison with future test results. More complete data for the individual sites are provided by Miller⁶ and Mrkajic⁷. It is recommended that this study be repeated at 5 and 10 years, to determine the long term performance trends.

As new materials, mixtures, and construction methods are used for PCPC, the methods outlined in this report should be used to document the initial condition after construction. Thus, the long term effect of new technologies on PCPC performance may be assessed.

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The Declining pH of Waters Exfiltrated through Pervious Concrete

Jonathan Thomle and Liv Haselbach

Synopsis:

The focus of this study is on the pH changes over time of water in contact with pervious concrete 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 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 samples were representative of typical in-place conditions in an arid environment with little buffering and yet the pH declined sufficiently in well under a year.

Keywords: carbon dioxide, carbonation, pervious concrete, pH, runoff

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INTRODUCTION

Pervious concrete is a remarkable pavement material that allows stormwater to infiltrate by replacing impervious material with this 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).

Pervious concrete is mainly used to reduce or eliminate runoff from parking lots, driveways, sidewalks, pathways and streets with light traffic. As suburban areas expand, the need increases for stormwater best management practices (BMPs) such as pervious concrete which reduce runoff. 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). As people become more aware of the positive environmental impacts and benefits of pervious concrete it is expected to become more widely used in future pavement design.

Counter measures are usually recommended for freshly placed concrete surfaces contiguous to natural waters sensitive to high alkalinity. Water running off of newly placed concrete could have a high pH that may be potentially damaging to adjacent sensitive water bodies if directly discharged into these waters (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. If these waters pass over or through soils and landscaping prior to discharge, the mineral reactions with these other materials tend to sufficiently buffer the pH. Typically this is not a concern with pervious concrete, as the water is usually infiltrated and does not runoff, or it also passes through the pervious concrete system, which may include subbase or subgrade layers of aggregate and soils which may also buffer the pH. However, this may become a concern if a pervious concrete system has a direct discharge or the system overflows to adjacent sensitive water bodies, without buffering from other materials in the system. Elevated or low pH values in streams may negatively affect aquatic life.

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). As concrete ages the pH drops within the concrete's crystalline structure, particularly at the surface (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). This process is commonly referred to as carbonation. In order to design appropriately for the aforementioned sensitive flow conditions, it is important to know how long it will take for the pH in concrete to drop to more ecologically favorable levels.

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 an anthropogenic change from the pH range of 6.5-8.5, 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 or buffering before the pH drops sufficiently from carbonation to no longer be of concern.

There are various water quality studies on pervious concrete that report pollutant removals in the stormwater with its use. Several of these studies reviewed reported pH measurements. An additional study by Horst et al. (2008) included the change in pH from water flowing horizontally through pervious concrete, but did not include any pH data.

The reported pH values from the Collins (2007, 2010) studies and the Kwiatkowski et al. (2007) study were 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. 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).

In general, the data reported from the studies include the pH and age of pervious concrete, and show a decline in pH from the typically elevated levels of freshly placed concrete to much lower levels within a year. Data from one of the Collins (2007) field studies shows some of the initial pH measurements as high as 11.4, but these eventually converge to an average pH around 9.1 ± 1.1 within a year of placement. The other Collins field study (2010) measured pH from 12 to 18 months after placement with an average pH of 9.2 and a range from 8.5 to 10.

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.) The Kwiatkowski et al. (2007) study 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 the Kwiatkowski et al. (2007) study were much lower than in other studies presumably because of buffering from exposure to lime stone aggregate. 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. These water quality studies on pervious concrete show a trend that the pH declines as pervious concrete ages.

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 Guimareas 2007). Pade and Guimareas (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 percent, and increases with higher porosity, higher temperature, increased surface area, higher partial pressure of carbon dioxide, and with added pozzolan. It is theorized that pervious concrete will carbonate faster than traditional concrete due to its exposed surface areas.

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 rainwaters, versus deionized water, which is more representative of concrete pore waters.

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 were made with a similar mix using #8 aggregate (fines removed), water and straight portland cement, 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 1). 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. All the samples were cured for a minimum of seven days fully covered prior to aging.

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-situ 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 embedded 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 2 for the WA, WB, WC, and WD batches. The laboratory setting was a large laboratory with only partial conditioning and ample air exchange. Over the course of the research the relative humidity was low (averaging around 30%) and the temperature fluctuated over the seasons (8 to 22°C).

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 a 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. Some additional limited testing was performed using tap water in the pH infiltration (and immersion tests) 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. (These tests using tap water were not performed often to limit the introduction of other minerals to the pervious concrete specimens.) 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. (The Montes et al. (2005) study 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 a pH meter. The pH immersion test gave a more averaged result over the entire specimen, even partially connected, smaller, interior pores.

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

RESULTS

The pH values from both the infiltration and immersion tests using deionized water indicate a decline in pH as pervious concrete ages, but the pH of specimens with ambient air restrictions showed less of a decline. The results from these infiltration tests are summarized in Figures 1 and 2, respectively. As can be seen in Figures 1 and 2, 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, had a pH that declined slowest. 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 absorbed 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 samples. The added air exchange in the BC specimens only showed a slight acceleration from the TBC specimens. Also the TBC and BC specimens tended to retain water, which may have also restricted airflow.

The vertical intercepts in the linear regression equations portrayed in Figures 1 and 2 were normalized to a pH of 12 for three reasons. The first is for comparative purposes of the slopes between the TBC, BC and NC sets. 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 vertical 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 3 and 4, respectively.

Specimens with carbon dioxide restrictions (TBC and BC) also showed less of a decline in pH than those with no restrictions (NC). There is an approximately linear section of pH decline in the curves and a non-linear section with a rate that may decline less rapidly as it approaches an asymptote. Only the section that is thought to be linear is plotted in Figures 3 and 4.

Comparing Figures 1 to 2 and Figures 3 to 4, it is apparent that the tap water tests have a lower pH at the same age than the deionized water tests, and this 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 is any significant differences in the slope from the TBC, BC, and NC specimens. As shown in Figure 5 there is a significant difference between the rate of decline of the different levels of carbon dioxide restriction using the immersion test with deionized water. 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.

Note that the time given in Figures 1, 2, 3, 4, and 5 are time from exposure in the Albrook Laboratory. Two of the sets were first located in a small room with restricted carbon dioxide availability. Therefore significant carbon dioxide exposure began when relocated to the large Albrook 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 specimens age. Table 3 shows the average pH of cored specimens from 5 different pervious concrete placements versus approximate age. 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 and with different compositions, all have a pH less than 10. The pH also continues to drop as the specimens continue to age.

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 1-5 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 6.

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.

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.

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 the Kwiatkowski et al. (2007) study which reported much lower pH values than in the Collins (2007) study, as the pervious concrete in the Kwiatkowski et al. (2007) study mainly exfiltrated runoff from other areas with higher levels of dissolved minerals, but the pervious concrete in the Collins (2007) study 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 restriction of ambient air, and the rate of pH decline is greatly slowed by ambient air restrictions. Engelson 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.

If the pH of stormwaters entering sensitive water bodies is too high, this might negatively impact aquatic life. Typically concrete placements are not of concern when interfacing with stormwater runoff as either the surface of the concrete has carbonated sufficiently over time so that the pH has dropped, or the waters are further buffered by soils and other minerals on the ground or in the subbase so that the pH is lowered. However, when first placed, there is the potential for higher pH values running off from traditional concrete surfaces or through pervious concrete. It is therefore important to know if any precautionary measures such as buffering in the landscape may be needed when pervious concrete is first placed and for how long. This study found that the pH of stormwater exposed to typical pervious concrete placements (NC) drops sufficiently in well under a year, usually in under 6 months, even in conditions representative of arid regions of the country. This drop is from the pervious concrete layer alone, without further reductions in pH from base material.

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Table 1 - Dimensions and characteristics of samples made from different concrete batches.

Batch	Number of samples	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*

*Some fines additionally removed

** Replaced 25 percent of Portland cement with fly ash

Table 2 - The specimen numbers of WA, WB, WC, and WD specimens and associated ambient air restrictions.

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

Table 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

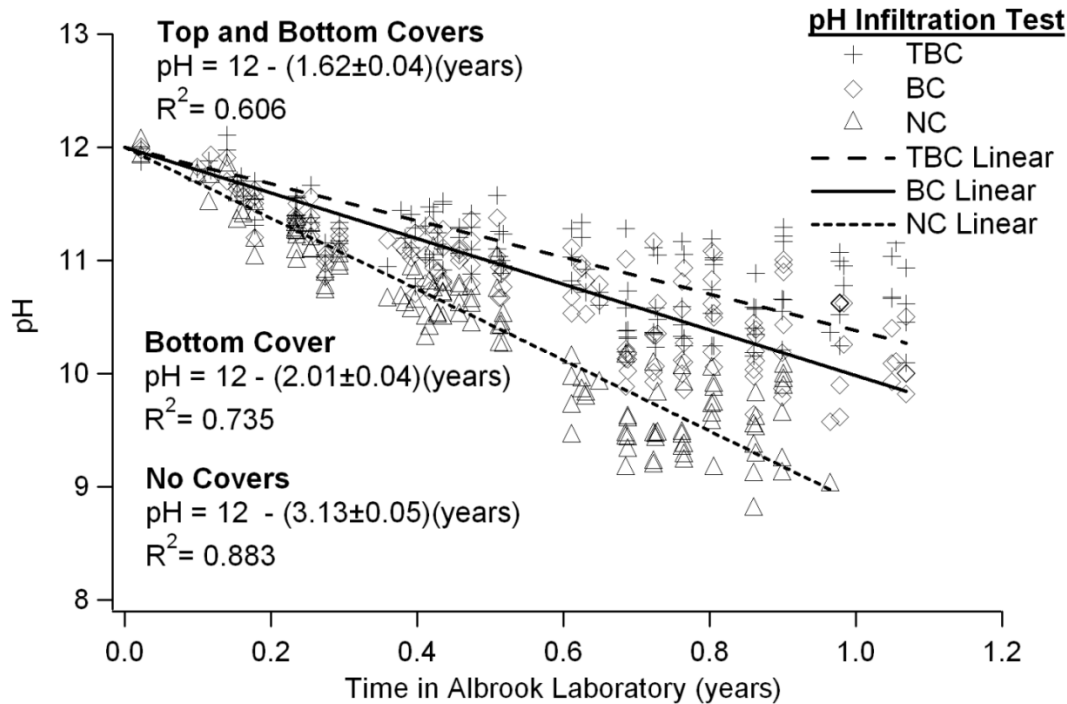


Figure 1 - The pH infiltration test results from all laboratory prepared pervious concrete specimens using deionized water (averaged for each batch of cores).

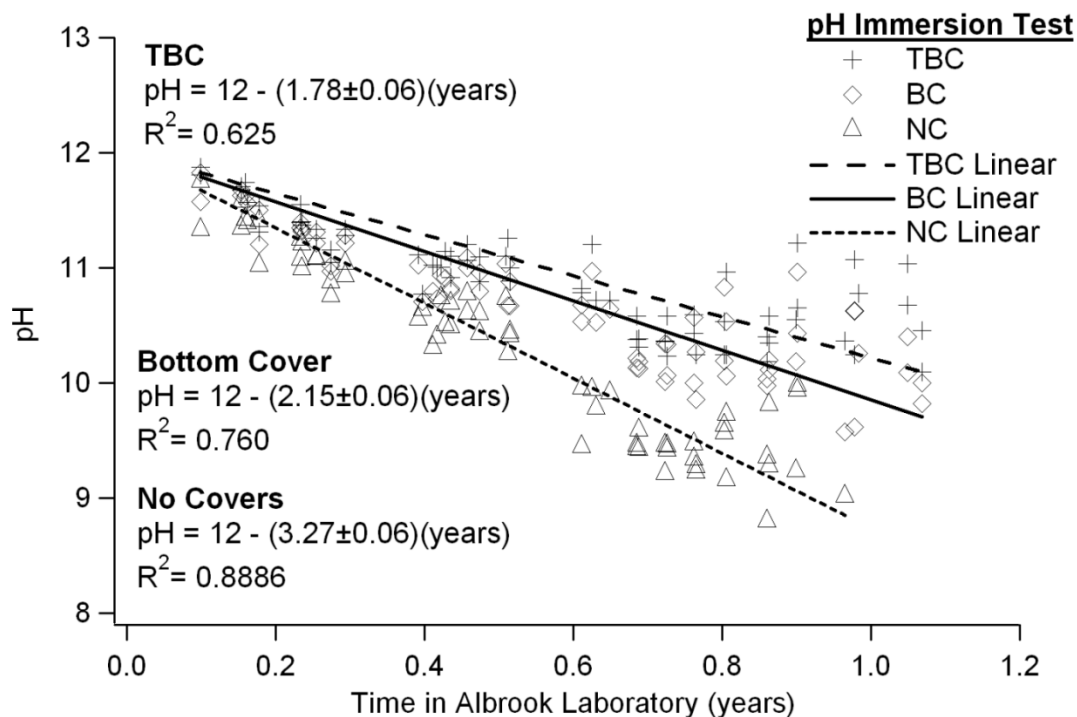


Figure 2 - The pH immersion test results from all laboratory prepared pervious concrete specimens using deionized water (averaged for each batch of cores).

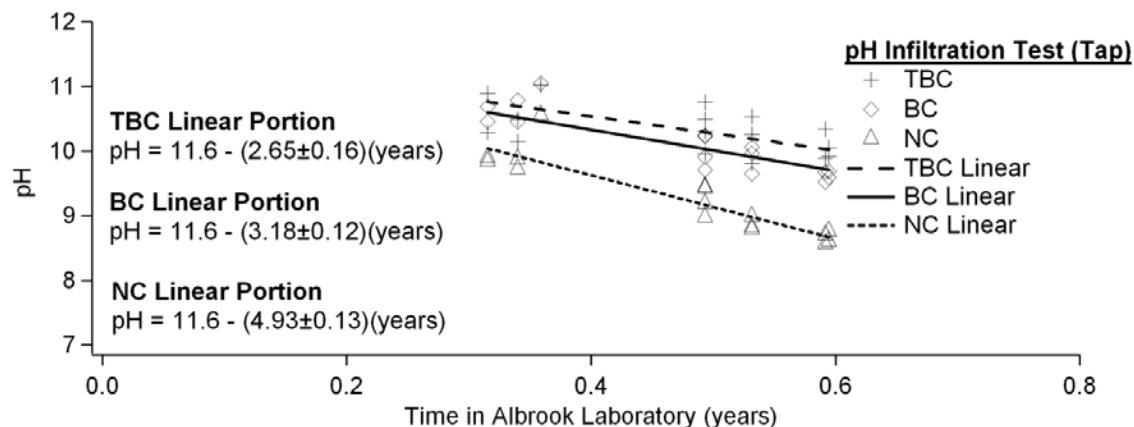


Figure 3 - The pH infiltration test results from all laboratory prepared pervious concrete specimens using tap water (averaged for each batch of cores).

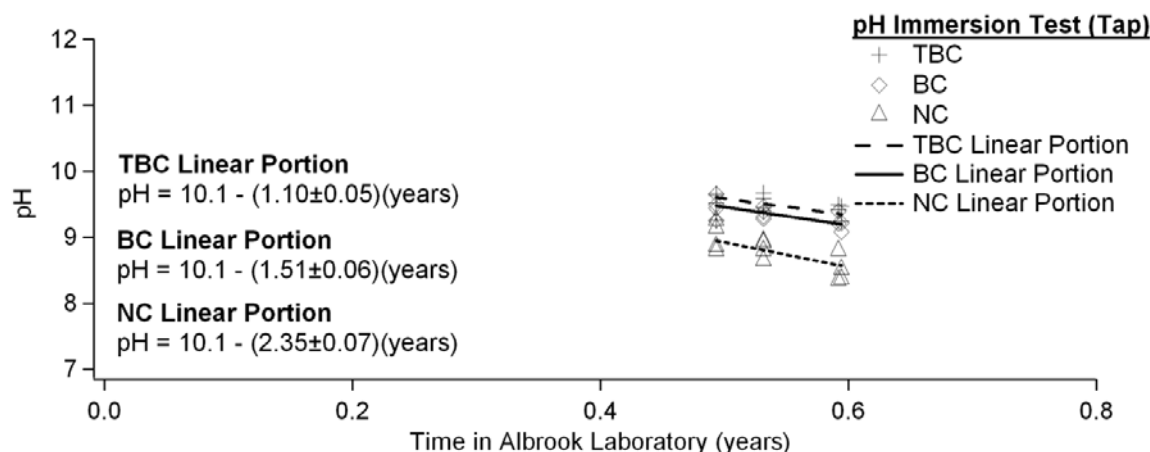


Figure 4 - The pH immersion test results from all of the pervious concrete specimens using tap water (averaged for each batch of cores).

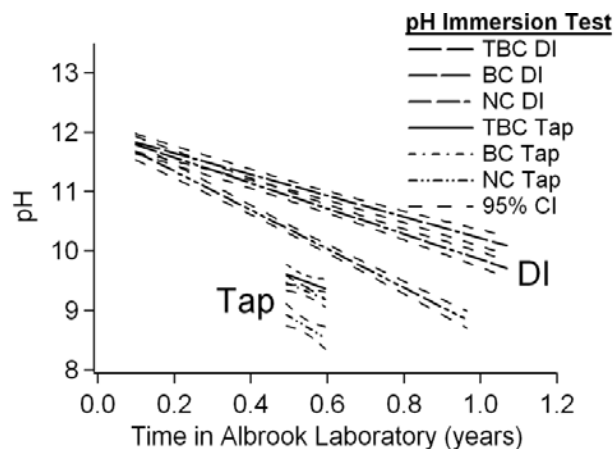


Figure 5 - The pH immersion test results from both deionized and tap water with a 95 percent confidence level

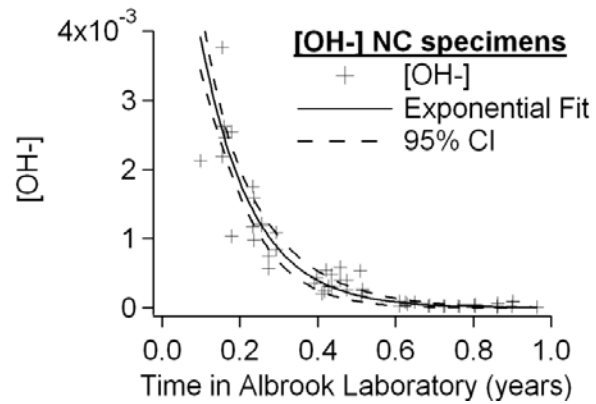


Figure 6 - Concentration of hydroxide ions from pH immersion test using deionized water for the NC specimens.

