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The Use of Porous Concrete for Sidewalks

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16. Abstract

Pervious concrete have been increasing in popularity as a potential solution to reduce the amount of impermeable surface area associated with sidewalks, reduce puddling, and potentially slow storm water surface high flow rates. As important as these benefits are to surface runoff mitigation, there are concerns with the ability of pervious concrete mixes to provide sufficient structural support and longevity for the expected service life of the sidewalks as well as life cycle costs. The composition of pervious concrete creates limitations to its mechanical strength and challenges in its maintenance to achieve the expected service life. The performance of pervious concrete pavements is relevant to its geographical location and application as well. Eleven different pervious concrete mix designs that include commercially available mixes as well as laboratory designed mixes were evaluated in this study. Mechanical properties such as compressive strength, flexural strength, splitting tensile strength, and elastic modulus were measured. Shrinkage and freeze and thaw properties were also evaluated. The study also evaluated hydraulic conductivities using the falling head and constant head test methods. A life cycle cost analysis was performed to evaluate the cost-benefit of using pervious concrete in sidewalks. Conventional and previous concrete field slabs were cast and tested for thermal and radiation performance. Compressive strength values varied from 1100 to 3400 psi at 28 days while those for the modulus of rupture were between 150 to 370 psi. Hydraulic conductivities were between 0.04 to 0.06 cm/sec and elastic modulus values were between 1000 to 2800 ksi. Freeze and thaw tests up to 100 cycles showed about 6% loss of mass. The vibration and placement methods have an impact of the mechanical and hydrological properties. The life cycle cost analysis showed that that the initial construction cost of porous concrete is slightly greater than that of conventional concrete for sidewalks without subsurface drainage systems. The initial construction cost of porous asphalt sidewalks is lower than those of conventional concrete sidewalks. When the service life ratio of porous asphalt compared to conventional concrete is greater than 0.60, the porous asphalt would be the most economically competitive option compared to porous concrete and conventional concrete.

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EXECUTIVE SUMMARY

Pervious concrete have been increasing in popularity as a potential solution to reduce the amount of impermeable surface area associated with sidewalks, reduce puddling, and potentially slow storm water surface high flow rates. As important as these benefits are to surface runoff mitigation, there are concerns with the ability of pervious concrete mixes to provide sufficient structural support and longevity for the expected service life of the sidewalks as well as life cycle costs. The composition of pervious concrete creates limitations to its mechanical strength and challenges in its maintenance to achieve the expected service life. The performance of pervious concrete pavements is relevant to its geographical location and application as well. Eleven different pervious concrete mix designs that include commercially available mixes as well as laboratory designed mixes were evaluated in this study. Mechanical properties such as compressive strength, flexural strength, splitting tensile strength, and elastic modulus were measured. Shrinkage and freeze and thaw properties were also evaluated. The study also evaluated hydraulic conductivities using the falling head and constant head test methods. A life cycle cost analysis was performed to evaluate the cost-benefit of using pervious concrete in sidewalks. Conventional and previous concrete field slabs were cast and tested for thermal and radiation performance. Compressive strength values varied from 1100 to 3400 psi at 28 days while those for the modulus of rupture were between 150 to 370 psi. Hydraulic conductivities were between 0.04 to 0.06 cm/sec and elastic modulus values were between 1000 to 2800 ksi. Freeze and thaw tests up to 100 cycles showed about 6% loss of mass. The vibration and placement methods have an impact of the mechanical and hydrological properties. The life cycle cost analysis showed that that the initial construction cost of porous concrete is slightly greater than that of conventional concrete for sidewalks without subsurface drainage systems. The initial construction cost of porous asphalt sidewalks is lower than those of conventional concrete sidewalks. When the service life ratio of porous asphalt compared to conventional concrete is greater than 0.60, the porous asphalt would be the most economically competitive option compared to porous concrete and conventional concrete. There is a need to collect performance data on porous sidewalks. This requires constructing test sidewalks made from porous concrete and porous asphalt in the field in urban areas. These sidewalks will be monitored and evaluated overtime to assess their performance.

BACKGROUND

Porous concrete, also known as pervious, gap-graded, or enhanced porosity concrete is concrete with reduced or no sand or fines that allow water to drain through it. Porous concrete placed over an aggregate storage bed will reduce storm water runoff volume, reduce the runoff rate, and help mitigate the urban heat island effect, reduce noise and filter potential pollutants. The reduced fines leave stable air pockets in the concrete and a total void space of between 15 and 35 percent, with an average of 20 percent. The compressive strength for pervious concrete can range anywhere from 700 psi to 3000 psi.The void space allows storm water to flow through the concrete and enter a crushed stone aggregate bedding layer and base that supports the concrete while providing storage and runoff treatment. Pervious concrete is typically made from coarse aggregates and cement. Pervious concrete has little to no fine aggregates and has just enough cementitious paste to coat and bond the coarse aggregate particles while preserving the interconnectivity of the voids. The porous surface is typically placed over a highly permeable layer of open-graded gravel and crushed stone. The void spaces in the aggregate layers act as a storage reservoir for runoff. A filter fabric is placed beneath the gravel and stone layers to screen out fine soil particles and sediments. Subsurface soils should have field-verified permeability rates of greater than 0.5 inches per hour, and there should be a 1.2 meter (4-foot) minimum clearance from the bottom of the system to bedrock or the water table [35]. When properly constructed and maintained, pervious concrete is durable and can be cost effective [35]. Like conventional sidewalks, it can be made of asphalt or concrete that's either poured in place or sold as precast slabs or pavers, and it can be used in a variety of settings including playgrounds and driveways. The main issues associated with the application of porous concrete are maintenance, durability, constructability, and cost, especially in areas susceptible to frost heave and rapid freeze/thaw cycles, clogging, and raveling. The initial cost of constructing porous sidewalks is generally higher than conventional sidewalks. For proper use and application of this material for sidewalks, there is a need to understand the performance of this product in New Jersey, which includes specific climatological conditions, aggregate types and maintenance. Several maintenance issues have been reported with porous pavement use such as clogging, sloped areas, freezing if saturated, snow removal and deicing chemicals, inadvertent overload, and raveling. However, certain requirements and maintenance protocols and procedures would alleviate such issues and make porous pavements more durable and with minimum periodic maintenance. Porous concrete and porous asphalt has shown to clog with time without the proper periodic vacuuming, cleaning and maintenance. It can also ravel and fail if used in unstabilized areas and not properly designed, constructed, and maintained. Pervious concrete construction also requires skilled labor and has higher initial costs. This study will address the factors that influence the performance of pervious concrete along with cost comparisons with other types commonly used for sidewalks and recommendations for use and maintenance. There are several benefits for using pervious concrete in sidewalks. While pervious concrete and asphalt have become popular in the area of storm water management, the true applicability in specific applications still needs further evaluation. A site investigation is critical to evaluate whether pervious sidewalks are an appropriate BMP for a site.

OBJECTIVES

The primary objective of this study is the use of porous concrete for sidewalk. Porous concrete would create a pervious surface and eliminate sidewalk construction from being considered in the NJDEP permitting process. Maintenance, as a potential downside, is always mentioned regarding porous concrete. This study shall address maintenance issues regarding porous sidewalk used for State Highway projects, including a cost benefit analysis based on the life cycle of traditionally used sidewalks versus porous sidewalks.

The following tasks will be performed to achieve the primary objective of this study:

1. Study and evaluate the various factors that influence the performance of porous concrete in sidewalks. These include hydraulic performance to meet DEP regulation and structural performance to meet typical sidewalk strength requirements.

2. Establish a selection of viable mix designs and narrowing them down through observing mechanical properties and durability of lab specimens created with different mix designs. In addition to the data from the experimental study, survey data from several state DOTs will be collected on the use and performance of pervious concrete in pavements and sidewalks

3. Perform benefit cost analysis comparing porous pavements for sidewalks to conventional concrete and asphalt alternatives, including environmental permitting, initial construction, and maintenance costs.

4. Evaluate local energy budget for slabs made from different pervious concrete mixes compared to conventional concrete mix.

5. Provide recommendations and guidelines to NJDOT on the use porous concrete for sidewalks and its anticipated maintenance issues and measures to mitigate these issues.

INTRODUCTION

Pervious concrete is a permeable material, often built with an underlying stone reservoir that temporarily stores surface runoff before it infiltrates into the subsoil. There are several benefits for using pervious concrete in sidewalks. One of the most important benefits is its effectiveness for storm water management; reduce puddling, reducing storm water runoff. It can also filter contaminants thus improving water quality. Several studies have quantified high removal rates of total suspended solids (TSS), metals, oil and grease, as well as moderate removal rates for phosphorous, from using pervious concrete [24,83]. They also can minimize the use of deicing chemicals and while they do not remove chlorides, the reduction of deicing chemicals use is an effective method for reducing chloride pollution [84]. However, pervious concrete has shown to clog with time without the proper periodic vacuuming, cleaning and maintenance. Pervious concrete can also ravel and fail if used in unstabilized areas and not properly designed, constructed, and maintained. Pervious concrete construction also requires skilled labor and has higher initial costs. Despite the increased use of pervious concrete in the area of storm water management, the true applicability in specific applications still needs further evaluation especially if there is potential for ground water contamination. According to the U.S. EPA [35], pervious concrete sites have had a high failure rate compared to conventional concrete (approximately 75%). Failure has been attributed to poor design, inadequate construction techniques, and soils with low permeability, heavy vehicular traffic and poor maintenance. A site investigation is critical to evaluate whether pervious pavements are an appropriate BMP for a site. The site investigation should be conducted with appropriate staff to be able to consider hydrology and hydraulic design, soil permeability, pervious concrete thickness design, and environmental considerations and regulations. Until more information is determined related to its field performance, maintainability, constructability, and improved benefit over other approved storm-water best management practices (BMPs), the inclusion of pervious concrete for sidewalks into NJDOT projects needs to be carefully considered. This study is intended to provide general guidance on the design and applicability of pervious concrete systems for NJDOT sidewalk projects. An experimental evaluation of the structural and hydrological properties of various porous concrete mixes well as life-cycle cost analysis of various sidewalk systems will be provided. The intent is to have consistent guidelines and standards, if a pervious sidewalk installation was ultimately chosen. When considering pervious concrete for storm water treatment, a project team should also evaluate the other approved BMPs and compare them to determine if pervious concrete would be considered the preferred BMP for a sidewalk. Although, pervious concrete has seen growing use in the United States, there is still limited performance data and practical experience with this measure. When using pervious concrete for sidewalks as BMP measure, its performance should be carefully monitored over its service life.

SUMMARY OF THE LITERATURE SEARCH

Pervious concrete's first use was in Europe in the 1800's. Later, in the 1920's, it was used in Scotland and England in residential construction. The first use of pervious pavement in the United States dates back to the 1970's. The Southeastern states began using pervious asphalt pavements in the 1970's. In 1977, pervious asphalt pavement was used for a parking lot in Walden Pond near Concord, MA [22]. Since then there has been many applications of pervious asphalt and pervious concrete pavements in the United States [83,108].

The main advantages of using pervious pavements include reduced water run-off, water treatment by pollutant removal, less need for curbing and storm sewers, improved road safety because of better skid resistance, and recharging of ground water. Potential disadvantages of using pervious pavements include clogging from run-off sediments and vegetation, higher rate of failure compared to regular pavements, risk of leaks contaminating groundwater, potential development of anaerobic conditions in underlying soils if the soils are unable to dry out between storm events. This may impede microbiological decomposition, and lack of skilled contractors in this type of pavement. According to the EPA [35], it is not advisable to construct porous pavement near groundwater drinking supplies, until more scientific data is available. The use of porous pavement does create risk of groundwater contamination. Pollutants that are not easily trapped, adsorbed, or reduced, such as nitrates and chlorides, may continue to move through the soil profile and into the groundwater, possibly contaminating drinking water supplies.

The main issues associated with the application of porous concrete are maintenance, durability, and cost. There have been many studies, reports, articles, and presentations that addressed the properties, application, and performance of pervious concrete. The NRMCA has published several reports on porous concrete, its application and maintenance [73, 74, 75, and 76]. Pervious concrete can become clogged, which directly affects the hydrologic performance and may indirectly affect other aspects of durability, such as freeze thaw resistance, deicer salt scaling resistance, and sulfate resistance. Abrasion resistance of pervious concrete is also of concern, particularly in locations that use snow plows or have turning traffic. Research done by Dong et al. [33] shows that smaller aggregate sizes and the use of polypropylene fibers and latex can increase abrasion resistance as tested by ASTM C944. Kevern [50] studied the freeze-thaw resistance of previous concrete made with various types of aggregates on. He found that certain types of aggregates did not perform well under freeze-thaw tests. The City of Olympia [87] built several sidewalks and bike lanes made of pervious concrete. Their firsthand experience and reporting is a very good resource when considering adopting porous concrete by an agency or municipality. Their experience at the time showed that pervious concrete could cost 3 times as much as conventional concrete pavements. They anticipated that with time and experience with pervious the cost will be less.

Izevbekhai and Akkari [49] reported that thermal gradients were lower for pervious pavement compared to PCC pavement. They also reported improved sound absorption was more in PC versus typical PCC pavements and that freeze-thaw cycles can be improved with less clogging. The CRMCA [32] (Colorado Ready Mix Concrete Association) published a Specifier's Guide for Pervious Concrete Pavement Design which provides detailed specifications for the production and quality control and maintenance of pervious concrete. A pervious concrete site at Villanova University was analyzed in terms of performance and durability after eight years of use [74]. Their evaluation showed that the strength of the concrete proved to be adequate for its intended use; however, significant variabilities in the measured porosity, unit weight, and strength values indicate inconsistencies in construction practices and material properties. Several factors that contributed to the decreased effectiveness of the pervious concrete were identified. Improper construction methods altered the desired pore distribution and significantly reduced the permeability of the sections, gradually leading to impervious surfaces. The reduced permeability decreased the effectiveness of the site to collect storm water, which further lead to reduced capacity to adsorb phosphorous. While the pervious surface allowed water ingress of 50% of its capacity in 2006, it became completely sealed by 2011. Additionally, raveling from freeze-thaw cycles played a key role in the eventual ineffectiveness of the concrete to allow infiltration into the ground, as verified by the inspection of particles locked in concrete pores. The varying porosity across the depth of the pavement was the result of improper installation procedures.

Drying shrinkage begins earlier in porous concrete compared to conventional concrete and the shrinkage strains are smaller. The specific values depend on many variables and they are about 50% the values of typical conventional concrete mixtures. The material's low paste and mortar content is a possible explanation. Approximately 50% to 80% of shrinkage occurs within the first 10 days, compared to 20% to 30% in the same period for conventional concrete. Often pervious concrete is made without control joints and allowed to crack randomly [86].

Types and Uses of Pervious Pavements

Several types of pervious pavement systems are being used to reduce storm water runoff. These systems include: 1) Pervious Concrete Pavement (PCP), 2) Pervious Asphalt Pavement (PAP), and 3) Pervious Interlocking Pavers [48] (PP). The selection of a specific permeable system depends on several factors such as pavement use, construction costs, maintenance costs, desired permeability, and aesthetics. Figure 1 shows a cross section of a porous concrete slab for a sidewalk. Figure 2(a) and 2(b) shows pervious paver and interlocking pervious pavers respectively.

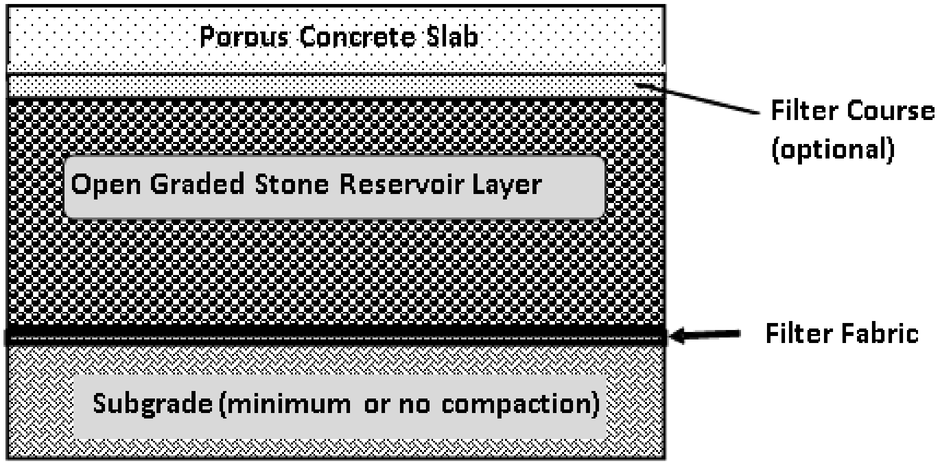

Figure1. Typical cross section of porous concrete sidewalk

Figure 2. (a) Pervious pavers (XeriPave,2016) (b)Interlocking pavers (Legacy pavers, 2016) http://www.xeripave.com; http://www.legacypaversllc.com/

Material Requirements and Mix Proportions

The literature review showed that the materials used in the mix design for pervious concrete pavements typically include Portland Cement Type I or Type II, 3/8 in, 1/4 in coarse aggregates, water, small amounts of fine aggregates, fly ash, slag, medium and high range water reducers (HRWR or MRWR), hydration stabilizers (HSA), viscosity modifiers (VMA), and air entrainment (AE). Some researchers reported the use of latex and polypropylene fibers. *A summary of the various material and mix proportions used to produce pervious concrete from various researchers, producers, associations, departments, and others are given in Appendix A. A summary of pervious concrete test results corresponding to those mixes are also given in Appendix A*. Mix designs of pervious concrete typically consists of single-sized local coarse aggregates mixed together with Type I cement and water. Air entraining and water reducing admixtures are also recommended. In some mixes fine aggregate as well fly ash are used. Typical void ratios range from 15% to 25% and infiltration rates between 250 in/hr to 1250 in/hr. High durability mixture proportions from Europe found 5 to 10% fine aggregate to be an optimal amount for strength and durability. Latex-based admixtures had been employed to improve the cement paste tensile strength. Most mixtures in the US .had relatively high porosity (15%-35%) and low strength, while European mixtures had lower porosity (15%-20%) and higher strength(50).

Bury et al. (23) evaluated the influence of admixtures on pervious concrete pavements. They tested several mixes with and without admixtures. Based on study, the use of a novel admixture system provides extended working time and facilitates the ease with which pervious concrete can be placed. In low compaction placement procedures, the use of the unique VMA provides an increase in both compressive and flexural strength of pervious concrete, the novel admixture help in the placement and consolidation of pervious concrete. The authors believe that additional research is necessary to further develop the compressive strength and effective void test methods Fine aggregates typically are not used in pervious concrete mixes. However, research results (63) showed that in severe cold weather, the addition of up to 6% of fine aggregates of the total weight of aggregates can improve durability. Huang et al. (44,45) and Kevern (50) found that the addition of polymer styrene butadiene rubber (SBR) enabled a higher strength to be obtained with lower cement content and it resulted in relative higher porosity. SBR also improved the workability, strength, permeability and freeze–thaw resistance of pervious concrete. Huang et al also found that with latex polymer, a permeability range of 10 – 20mm/s and compressive strength range of 5 -15 MPa could be obtained. Pindado et al (80) studied the effect of polymers on the fatigue behavior of pervious concrete. They observed that the fatigue resistance of pervious concrete could be improved with the addition of polymers but not significant for low stress ranges and larger number of cycles. They also observed the internal temperature of the concrete increased with the number of cycles. This increase was significantly higher than in conventional concretes. Moreover, the temperature distribution was not constant over the height of the specimen and the maximum temperatures occurred in the middle. They measured higher temperatures in the upper half of the specimen which they attributed to the lack of symmetry of the loading.

Several specifications from various agencies, departments and DOT’s are provided at the end of this section. These specifications include specific guidelines on the types of aggregates, the type of cementitious materials allowed and their percentages, fine aggregates and the maximum percentages allowed, void ratios, type of admixtures that can be used, as well guidelines on tolerances on densities and infiltration rates.

Mechanical and Hydrological Properties

The performance of pervious concrete pavements may be assessed in a number of ways, including monitoring changes in the permeability/porosity of the system (which would indicate clogging of the void structure), the presence of distress (both structural and surficial), and resistance to freeze–thaw damage. Void ratio and density are two of the most important properties of pervious concrete pavements that have a direct effect on its performance. Many studies have evaluated the effect of void ratio on permeability and strength as well as durability, sound absorption, thermal properties, constructability, and maintenance. There are limited long-term performance data from pervious concrete pavements, but generally performance of well-maintained pavements has been considered to be satisfactory. For example, a study in Florida indicated that pervious pavements that were 10 to 15 years old were operating in a satisfactory manner without significant amounts of clogging [(91)]. In another study [(76)], field inspections of twenty two projects located in freeze areas were conducted, with reported good performance and no visual signs of freeze–thaw damage (although all projects were less than 4 years old at the time of inspection). According to the Florida Concrete Producer Association (FCPA), Pervious concrete pavement shall not be used where heavy traffic loads are anticipated (e.g. average daily truck traffic is greater than two vehicles per day with truck gross weight equal to or greater than 80,000 lbs.).

Mechanical Properties

The compressive strength is a key property to establish the maximum allowable bearing stress of porous concrete. It is also a good indicator for the anticipated elastic modulus, flexural strength and tensile strength. Currently there is no ASTM test standard for compressive strength of pervious concrete. Therefore the interpretation of compressive strength results should be examined in conjunction with other acceptance criteria such as target void content and density measured by *ASTM C 1688 Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete'*. The flexural strength of porous concrete is critical for determining the maximum bending stress that can be applied on the pavement from traffic loads and other loads. Flexural strength in pervious concretes typically ranges between about 150 psi and 600 psi. Laboratory tests on flexural strength shows higher variability than compressive strength tests, thus design flexural strength values should be carefully selected (Tennis et al. 2004). Similar to the compressive strength, many factors influence the flexural strength, particularly degree of compaction, porosity, and the aggregate/cement (A/C) ratio, and water to cement ratio. Flexural strength and thickness determine the maximum allowable loads that can be applied to the pavement using the pavement design guidelines from AASHTO.

Hydrological Properties

Permeability is a key parameter for the evaluation of the effectiveness of using porous pavements in sidewalks, driveways and parking lots. This is achieved by creating sufficient voids so that water can readily pass through the system and into the subbase and subgrade layers. Building sidewalks typically triggers stormwater mitigation requirements. Sometimes the cost of creating the storm water mitigation for a new sidewalk can exceed the cost of constructing the sidewalk. Using porous pavements is one way to create sidewalks without triggering stormwater mitigation requirements. Passive pervious pavements are intended to reduce the area of impervious surfaces with pervious ones. It allows infiltration of initial rain and is not intended to accommodate run-off from adjacent impervious pavements. Active pervious pavements are intended to accommodate the total run-off from a larger area. It is used when pervious concrete system is intended to capture a sizeable portion of the runoff from other areas [75].

Several methods for determining the permeability of porous concrete systems have been proposed. Most studies utilize a falling-head apparatus (shown in Fig. 3) adapted from soils testing, although other methods have been used to measure permeability both in the laboratory and in-situ. The in-place infiltration test will be according to ASTM C1701.

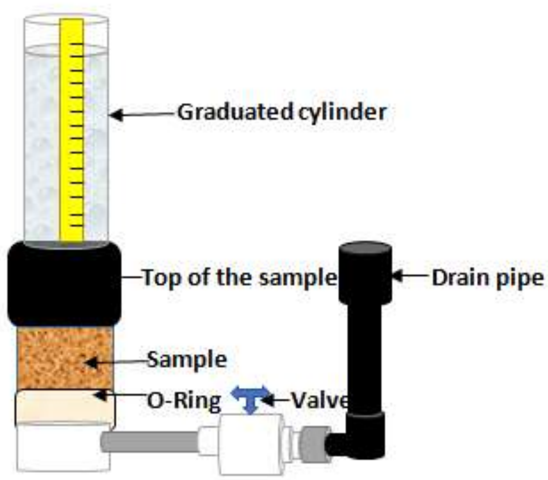

Figure 3. Falling head permeability test setup

NJ Stormwater BMP Manual

New Jersey Stormwater Best Management Practices Manual - Standard for Pervious Paving Systems provides the state requirements for pervious paving system to reduce storm-water runoff. There are three types of pervious paving systems: porous asphalt or concrete paving with storage bed; porous concrete pavers with storage bed; and porous pavers without storage bed. The first two types of design with storage bed can reduce stormwater runoff as well as provide significant stormwater quality treatment through the infiltration process. The porous pavers without storage bed achieve less runoff reductions than systems with infiltration base and for the same reason does not have the function of stormwater qualify treatment. The manual also provide a design criteria with storage volume, depth, and duration; permeability rates; stormwater quality pretreatment; runoff rates; overflow and emergency inflows design. For example, Porous paving and porous paver with storage bed systems must be designed to treat the total runoff volume generated by the system's maximum design storm; the minimum design permeability rate of the subgrade soils below a system's runoff storage bed is 0.5 inches per hour. The manual also presents the typical components of each type of pervious paving system as shown in the figure below. The manual also provides a general maintenance scheme for porous paving systems which must be vacuum and swept at least four times a year.

NJDEP Storm water Management Rules

NJDEP Stormwater Management Rules [(71)] at N.J.A.C. (7:8) define impervious surface as a surface that has been covered with a layer of material so that it is highly resistant to infiltration by water. The hydraulic process being protected is recharge, or the amount of water from precipitation that infiltrates into the ground and is not evaporated. NJDEP [(71)] sets minimum design and performance standards for groundwater recharge. Applicants are required to demonstrate through hydrologic and hydraulic analysis that the site and its stormwater management measures maintain 100 percent of the average annual preconstruction groundwater recharge volume for the site, or that the increase of runoff volume from preconstruction to post-construction for the two-year storm is infiltrated. Further, there are exceptions pertaining to highly urban areas as well as "areas of high pollutant loading", which may include industrial and commercial developments. In addition, NJDEP sets out additional instruction for the design engineer requiring an assessment of the hydraulic impact "so as to avoid potential adverse effects". It is critical to define "highly resistant" in order to garner NJDEP acceptance for using porous concrete as an option in mitigating net increases in impervious cover. N.J.A.C. 7:8-5.6 provides that the engineer select one of the prescribed methods to calculate runoff. NJDEP[(71)] Stormwater Management Rules at N.J.A.C. 7:8 established requirements and regulations for the stormwater quantity, quality and groundwater recharge management. In order to meet this requirements the Municipal Land Use Law and ordinances, *New Jersey Stormwater Best Management Practices Manual- Structural Stormwater Management Measures* presents specific planning, design, construction, and maintenance information about a range of structural stormwater management measures. The specific structural measures, also known as structural Best Management Practices (BMPs) include Bio Retention Systems, Constructed Stormwater Wetlands, Dry Wells, Extended Detention Basins, Infiltration Basins, Manufactured Treatment Devices, Pervious Paving Systems, Rooftop Vegetated Cover, Sand Filters, Vegetative Filters, and Wet Ponds.

Wisconsin Stormwater Regulations

The State of Wisconsin DNR [95] identifies permeable pavement systems as most effective in areas where subsoil and groundwater conditions are suitable for stormwater infiltration, and the risk for groundwater contamination is minimized. Permeable pavement systems may be used in areas where infiltration is prohibited by regulations or limited by soil or groundwater conditions when *liners* that inhibit infiltration, and subsurface drainage mechanisms, are installed. However, permeable pavement may not be used in industrial storage and loading areas or vehicle fueling and maintenance areas. Min void ratio 25% (Min); Min depth of aggregate. reservoir 12 in; and initial pavement surface infiltration rate of 100 in/hr. Table 1 shows average infiltration rates for various surfaces from the Wisconsin DNR Report [95].

Table 1. Average surface infiltration rates [95]

Permeable Pavement System	Average surface infiltration rate (inches/hour)	Reference
Permeable Interlocking Concrete Pavers (PICP) (no fines)	900	Bean et al. (2004)
PICP (with fines)	1.6	Bean et al. (2004)
Concrete Grid Pavers (CGP) (maintained)	3.5	Bean et al. (2004)
Permeable Concrete	1,835	Collins et al. (2007)
Permeable Interlocking Concrete Pavers with pea gravel (No. 78 Stone)	450	Collins et al. (2007)
Concrete grid pavers filled with sand	36	Collins et al. (2007)
Permeable Interlocking Concrete Pavers with pea gravel (No. 78 Stone)	125	Collins et al. (2007)

Energy, Thermal and Acoustic Properties of Pervious Pavements

Thermal behavior of pervious concrete was evaluated by Kevern et al. [52]
They studied the temperature behavior of a porous concrete pavements installed at Iowa State University. They describe construction and sensor installation for the Iowa storm water project. Results from their measurements showed that the pervious system as much warmer than the surrounding air temperature even during the winter months, suggesting further research was required to identify the heating mechanism. The results showed that over the course of the 2007 winter, the pervious concrete pavement and the aggregate base beneath the pervious concrete remained much warmer than the adjacent conventional concrete or the surrounding air temperature. The sensors were installed in the porous concrete pavement as well as the subbase material, and data was recorded during cold and warm weather. Cooling and heating rates for pervious pavements were found to be higher than conventional pavements which may lower heat island effects. According to Kevern et al. [52], light colored open-graded pervious concrete was significantly warmer than the surrounding air. These higher surface temperatures may be a result of lower solar reflectance of pervious pavements compared to conventional pavements. A study by Haselbach [42] found that the heat transfer for pervious concrete pavements was about 59% that of conventional concrete pavements. While Kevern et al. [52] reported higher surface temperatures; the work by Haslebach [42] may suggest that pervious concrete could still reduce the head

island effects in urban areas. Zhang et al. [97] tested solar reflectance of pervious concrete and compared it to traditional concrete. Their results showed that pervious concrete has an albedo of about 0.25 to 0.35 at density of 106 to 122 pcf. These values are about 0.05–0.15 lower than the albedo of the traditional concrete. Pervious concrete albedo linearly decreases with the increase of porosity because the cavities at the porous concrete surface are absorptive. This low albedo results in an additional solar absorption of 50–150W/m during the midday in summer. Therefore, it is cautious to develop pervious concrete to mitigate the urban heat island. Further experiments are expected to measure the albedo of pervious concrete with high reflectivity aggregates and colored cement in the mixture. Flower et al. [40] monitored surface and internal temperatures at pervious concrete, asphalt concrete, and regular concrete pavement sites. Their results showed that reduced temperatures at the PC site compared to asphalt. The results also showed that shaded regular pavement temperature were similar to those of pervious concrete. Kim and Lee [51] studied the effect of aggregate size and shape on the acoustic properties of pervious concrete. They found that aggregates of around 10-20 mm would be the most effective for the fabrication of porous concrete with high acoustic absorption properties. The value of the maximum acoustic absorption coefficient increases as the target void ratio increases, Their study showed that the target void ratio is as an important design factor affecting the acoustic absorption characteristics of porous concrete and that acoustic absorption properties are hardly affected by the aggregate shape when porous concrete is well compacted.

Solar Reflectance Index (SRI) and LEED Certification

Due to concerns about Urban Heat Island effect and the desire for energy efficiency, different land cover types including natural, agricultural, and most building materials, such as roofing have been studied extensively. Major infrastructure components, such as concrete and asphalt road surfaces, parking lots, and sidewalks have more recently become a topic of interest. Due to its dark color, asphalt is known to have a low albedo or low level of reflectivity, but the majority of albedo and solar radiation research conducted in the asphalt and concrete industry to date has highlighted freshly paved asphalt or concrete samples without accounting for changes in aged pavements, varying lift thickness, aggregate types, or structural parameters associated with widely varying asphalt mix designs. Standard concrete, on the other hand, is generally associated with higher reflectivity. The mix design parameters of either mix are known to affect the amount of light reflected, the amount of heat absorbed, the amount of heat retained, and the amount of heat expunged throughout the nighttime hours. Several studies have been completed to evaluate the benefits of more reflective surfaces, such as Portland Cement Concrete and chip seals using lightly colored aggregates [55].Another recent study was conducted to determine if “cool” pavements provided any benefit to the environment [54].

Unfortunately, urban heat island effect is not a problem that only New Jersey needs to be concerned with, but fortunately the issue has been gaining recognition around the country. The State of New Jersey currently holds over 39,000 miles of public roadways (of which 8410 lane miles (13534.58 km) are controlled by the state DOT), and 24 public use airports. As of 2007, the land cover of the state comprised of 800 sq. mi. of impervious surface which was increasing at a rate of 6.67 sq. mi. (1727.5 ha) per day [43]. This results in an 11% total impervious land cover as of 2007. Arnold and Gibbons [4] showed that an increase of 10% in impervious surface area results in an increase of land surface temperature by 1-1.5 deg C, which was expanded upon by Xu [96] in 2010. It should be noted that this relationship does not correlate with a linear scaling, but rather an exponential rate, resulting in a more rapid increase in temperature of urban areas than those of rural landscapes. Due to these NJ statistics, the need for research about the possibility of utilizing pervious surface instead of impervious surfaces, and how the design of each affects the albedo, and energy flux for asphalt and concrete pavements in New Jersey is paramount.

Typical new concrete has solar reflectance or albedo about 0.35 to 0.4. Regular new concrete normally meets the LEED SRI minimum requirement of SRI 29; pervious concrete pavements may or may not. Pervious pavements can be designed to meet the SRI 29 requirement. Pervious because of its uneven surface (with hills & valleys) creates shadows. This makes it appear somewhat darker than traditional concrete pavement. Tests on pervious concrete pavement have delivered SRI numbers both higher and lower than 29. Pervious concrete pavements with 25% slag replacement for cement have consistently tested above the 29 mark. White Portland Cement also significantly raises the SRI numbers. The soybean cure for pervious concrete has also successfully been seeded with a color agent when sprayed on the surface leaves a white film. It can be sprayed on a pervious pavement at any time for color addition or a refresher (C2 Products, Inc.).

Construction

Construction and installation of pervious concrete are critical factors in achieving the desired performance of pervious concrete pavements. Porous concrete pavement installations require expertise and special requirements during construction. Excavation usually must take place in order to install a gravel subbase and filter fabric or geotextiles. During this excavation, care must be taken to not over-compact the natural soil and reduce its infiltration capacity [60, 61]. Skill and experience is required for compaction which is achieved with a screed and steel rollers, and/or vibratory screed. The quality control is typically through visual inspection and preliminary test patches. Some specs [32] require test slabs prior to construction. Construction joints between pavement segments are typically placed between 15 ft to 20 ft using a joint roller to prevent and minimize cracks. Curing typically starts 20 min after placement using clear plastic cover for a minimum of 7 days. A hands-on-learning experience demonstration project at Auburn University to build pervious concrete pavements spanned over three years and involved students, faculty, university facilities and concrete suppliers [25]. The sidewalk was 6 in thick pavement over 6 in No. 57 crushed stone. Pervious concrete pavements in the environment and applications encountered in these projects, appears to work over long distances without in plane shrinkage cracks and the consequent need for control joints. A continuous pervious walkway five feet wide and over 160 ft long has been in service for eighteen months with no control joints and no signs of cracking. The use of water reducing admixtures in combination with viscosity modifying admixtures significantly reduced or eliminated most of the previous difficulties experienced placing pervious concrete pavements. Much of the hard physical labor was eliminated and the quality of the finished product was improved. This is a major milestone in facilitating successful placement of quality pervious concrete pavements. After some reflection, the collaborators believe that the compressibility issue was due to a miscalculation of compressible height. The 4 in. thickness was clearly less compressible than the 6 in. thickness for which the ¾" screed height had worked well in a previous project. Observations indicate that a ½ in. surplus elevation at screeding would have been successfully compressed by the roller. Chindaprasirt et al. [29] studied the effect of top vibration on the void ratio and strength of pervious concrete. They found that a top surface vibration of 10 s with vibrating energy of 90 kN m/m2 is effective in compacting porous concrete. This vibration energy produces variation in void ratio slightly less than 10% between top and bottom portions of cylinder.

Maintenance

Field sites should be monitored as surface infiltration capacity appears to reduce over time, and regular maintenance may be necessary. Plowing the surface may have an effect on surface infiltration capacity and should be monitored. Winter surface applications containing sand should be avoided, particularly when plowing is performed as regular winter maintenance. Applications containing only salt could be utilized instead. Continued field observations on constructed porous concrete facilities to determine changes in surface infiltration capacity over time. The type of cleaning equipment also plays an important role in the effectiveness of cleaning procedures. Vacuum dry sweeping is usually sufficient to restore 50% or more of initial flow rate. Pressure washing can restore 90% or more of initial flow rate and has been documented at a rate of 175 square feet per man-hour (www.concreteresources.net). A sprinkler can, a gallon of water, a tape measure and a stopwatch are used to ascertain whether the infiltration rate of the pervious concrete falls into an acceptable range

The Pennsylvania Aggregate and Concrete Association (PACA) issued guidelines on maintenance procedures for pervious concrete. According to the guide, *the most critical period to prevent clogging of pervious concrete pavement is during and immediately after construction. Many sites that have become clogged have become so from large amounts of nearby unstabilized soil running onto the pavement*. For winter maintenance, they recommend the following:

- No deicers containing Magnesium Chloride should ever be used.
- Calcium Chloride impregnated sand is al-lowed after the first year.
- Sand can be used as an anti-skid material with the understanding that vacuum cleaning will be performed after the winter sea-son.

- Snow plowing can be performed with trucks mounted with plows, but the plow should be fitted with a rubber cutting edge and/or set so that the steel edge is 1/2”-1” from the finished surface. Snow removal should not be performed using front end loaders or skid loaders by either scooping or back dragging.

According to the NRMCA [(74)], the frequency of the vacuuming is directly related to the amount of sediment that the surface receives over time. There are three levels of pervious concrete pavement maintenance: 1) routine maintenance that includes visual inspection of the pervious pavement to ensure that it is clean of debris and sediments (monthly), 2) periodic maintenance in areas that see freezing temperatures before winter to insure that the pervious concrete voids are clean and free of non-compressible materials to remove any anti-skid materials that may have been used. Proper cleaning procedures would include pressure washing and/or vacuuming the area with either a dry vacuum or a regenerative vacuum sweeper, and 3) deep cleaning/unclogging: if a pervious concrete pavement system is not periodically cleaned, the void structure system will become clogged with debris over time. Typically, an average infiltration rate decrease of 25% from the initial value, or an infiltration rate less than 100 inches per hour, triggers the need for deep cleaning/unclogging. McCain and Dewoolkar [(60,61)] studied the hydraulic conductivity (infiltration rate) of porous concrete and reported that the hydraulic conductivity ranged between 971 in/hr and 1,387 in/hr with an average of about 1,233 in/hr. These values were within the expected range found in the literature. They also reported that the reduction in the hydraulic conductivity was about 15% with the surface application of the sand-salt mixture. They also reported that the infiltration rate decreases over winter cycles and with less maintenance. Their measurements showed about 13.9% decrease in infiltration after one winter cycle. With minimum maintenance (maximum clogging), they measured about 30% reduction in surface permeability. When vacuuming was applied to clogged pavement, the reduction in the infiltration rate stabilized at 11.5%. Their results suggest that vacuuming can restore about 18% of original infiltration rate. According to their study, vacuuming can be used as an effective tool to rehabilitate porous concrete systems and improve their hydraulic conductivity and surface infiltration capacity characteristics. Field sites should be monitored as surface infiltration capacity appears to reduce over time, and regular maintenance may be necessary. Plowing the surface may have an effect on surface infiltration capacity and should be monitored. Winter surface applications containing sand should be avoided, particularly when plowing is performed as regular winter maintenance. Applications containing only salt could be utilized instead.

Luke and Beecham [(57)] presented results from an investigation of permeable pavements that have been in service for over 8 years. They reported that most sediments are retained in 2-5 mm bedding layer. They also reported that a maximum of 8.3% of the total sediments are retained in the fabric layer at the bottom and that over 90% of the sediments are retained in the pavement and aggregates bedding layers. Their results showed that the overall infiltration performance of the pavement was satisfactory after 8 years of service.

Table 2. Maintenance schedule [41]

Maintenance Activity	Schedule
Initial Inspection	Monthly for 3 mon after
Ensure pavement surface is free of sediments	Monthly
Ensure that contributing and adjacent areas are stabilized, mowed, with clippings removed	Monthly
Vacuum sweep pavement surface followed by high pressure hosing to keep pores open	As needed
Inspect pavement for spalling and deterioration	Every 3 months
Check that pavement can dewater between	Annually
Localized clogging can be mitigated by drilling 1/2 in diam. holes every 1 ft	Annually
Rehabilitate/Replace pavement segments and/or storage reservoir base	Upon failure

A fact sheet published on permeable pavement for the Howard County, Maryland owners provided a maintenance check list for permeable pavement using recommendations from several state publications (FL, MA, and CA).

Maintenance checklist for all types of permeable pavements
(Recommendations from FL, MA, and CA)

- Post signs identifying porous pavement areas.
- Keep landscape areas well-maintained and prevent soil from being transported onto the pavement.
- Clean the surface using vacuum sweeping machine or with high pressure hosing.
- Monitor regularly to ensure that the paving surface drains properly after storms
- Do not reseal or repave with impermeable materials.
- Inspect the surface annually for deterioration
- Potholes and cracks can be filled with patching mixes unless more than 10% of the surface needs to be repaired
- Spot clogging may be fixed by drilling 0.5” holes through the pavement layer every few feet.

Comparison of Pervious Asphalt and Pervious Concrete

Both porous asphalt and porous concrete provide basically the same function in reducing storm water runoff and promoting storm water quality, however, there are several key distinctions between the two materials. The most notable distinction is the ease of construction and cost difference in installing porous asphalt as compared to porous concrete. While the mix production of porous asphalt is a bit more difficult than that of porous concrete, porous asphalt is much easier to install than porous concrete. Most qualified installer can install porous asphalt, however, the installation of porous concrete requires trained and certified installers. If porous concrete is installed improperly, it can result in low infiltration rates and structural problems. Due to the need for highly trained installers, porous concrete can sometimes run up to 4 times the price of an equal area of porous asphalt for virtually the same benefit. While porous concrete does perform better in reducing the “heat island” effect in the summer due to its lighter color and ability to reflect (and not absorb the sun’s heat), it does not perform nearly as well as porous asphalt in promoting ice melt in the winter.

The key factors for comparing porous concrete with porous asphalt include: 1) Initial Cost, 2) Durability, 3) Performance (structural/hydrological), 4) Maintenance, and 5) Environmental Considerations (Heat Retention). Studies have shown that the initial cost of porous asphalt is about 15 % to 20% more than conventional asphalt and porous concrete is about 25% to 30% more than conventional concrete**.** Studies show that concrete typically lasts a decade or longer than asphalt before repairs are needed. Much more than concrete, asphalt is susceptible to raveling, or breakdown of the material. FDOT conducted long-term tests of various roadway materials, concluding that while pervious concrete was a good option, porous asphalt was not due to a high level of raveling. In addition, asphalt retains more heat than concrete and that heat can cause asphalt to break down. A study conducted by the National Center of Excellence at Arizona State University found that porous asphalt exhibited higher daytime temperatures than even traditional asphalt. Pervious concrete, on the other hand, actually has been shown to be cooler. The University of New Hampshire’s Storm water Center notes that pervious concrete has reduced daytime temperatures, thus minimizing the Urban Heat Island effect. Porous surfaces, whether concrete or asphalt, require different maintenance than standard surfaces. The UNH [88,89] recommends sweeping and pressure-washing and quarterly vacuuming of both types of surfaces, in addition to regular visual inspections. Standard concrete requires much less maintenance than standard asphalt, but there isn’t a huge difference between the pervious concrete and porous asphalt in regard to maintenance.

Based on the results of the literature review presented above, the following summary of recommended mix designs and performance properties from various researchers, departments, agencies, DOT’s, and others are presented [53,63,72,73, 75,and 76].

Recommended Mix Proportions for Porous Concrete (per cubic yard)
500 – 600 lbs of cement Type I/II
2500-2800 lbs of 3/8 in aggregates
Fine aggregates (maximum 6% of the total weight of aggregates)
Fly ash (maximum 15% weight of cement)
Slag (maximum 25% weight of cement)
0.25- 0.3 water/binder ratio
High Range Water Reducer (1.8 to 2.0 lbs)
Viscosity Modifier(1.8 to 2.0 lbs)
Hydration Stabilizer (1.8 to 2.0 lbs)
Air Entrainer (0.78 lb)

Recommended Properties for Porous Concrete
15% to 35% air void content (field studies show 18-25% average)
105 to 125 lb/ft^3 unit weight
2000 to 3000 psi strength*
Drainage rate 3-5 $gal/min/ft^2$ (equivalent of 275" to 450" of rain per hour)**

Recommended Construction Requirements for Porous Concrete
Construct test slab 200-225 ft2 at site, core sample, get approval from Engineer
Provide joints every 15 ft to 20 ft
Use 1/ 4 in to 1/2 in joint fillers
Begin curing within 20 min of placement
Cure pavement for 7 days-10 days minimum using plastic wraps

Recommended hydraulic design subgrade and storage reservoir
Subgrade compacted to 92%+/- 2%
Avoid subgrade overcompaction
Top 6 in of subgrade to be granular layer (sand with min amounts of silts or clay)
Subgrade infiltration rate 0.5-1.0 in/hr
Storage reservoir 6 in to 12 in in thickness; No. 57 stone; 40% void ratio

Structural Design – Recommended thickness of pervious slabs
4" for sidewalks/pathways
6" parking lots
6" residential driveways
8" residential streets
8" commercial driveways

***** *Compressive strength typically not used as acceptance criteria. Air void structure and unit weight are used instead.*
*******More than half of all rainfall is provided in rain events that total one inch or less*

SUMMARY OF THE WORK PERFORMED

Evaluation of Structural Properties

Pervious Concrete Mix Design

Twelve mix designs using New Jersey aggregates, two aggregate size, variable cement content and water to cement (W/C) ratios and admixtures were evaluated for structural and hydrological properties. These factors play important roles in the short and long-term performances of porous concrete. Table 1 shows a summary of the various mixes tested in this study. The aggregates and admixtures were obtained from a several suppliers in New Jersey. The aggregates came from Weldon and Clayton concrete suppliers and the admixtures were supplied by Euclid Chemicals and Sika Group. In the process of creating appropriate mix designs, several factors were taken into consideration such as the size and type of aggregates, the w/c ratios, cement content, and aggregate content. For pervious concrete mixes, care was taken in using the proper vibration during specimen preparation. Several trial mixes were made to evaluate the influence of vibration. Based on the results from these mixes, it was clear that vibration of pervious concrete mixes is a key factor that influences its performance. Excessive vibration causes most of the paste to accumulate at the bottom of the mix; while little or no vibration can result more voids and less cement paste around the aggregates, thus lowering the compressive strength and cohesiveness of the mix. Recommendations on the vibrating pervious mixes in the lab will be made based on the results of vibration evaluation. Mix PRC-1 included sand while mixes PRC-7 and PRC-8 included fly ash and slag respectively. Mix PRC-1 had higher strength due addition of sand. It seems that even a small amount of sand can affect the porosity of the hardened mix. In this study, two sizes of aggregates were used: 1 /4 in and 3/8 in stones, including crushed stones and river gravels depending on the mix design. Portland Type I Cement was used, with or without slag and fly ash. The remaining mixes had different w/c ratios, aggregate content and sizes. Mixes PRC-10 and PRC-11 had round river aggregate type. Mixes PRC-2, PRC-3, and PRC-9 were mixes used by concrete suppliers in NJ and PA. Due to the different geometry of the river gravel, the mixes using river gravels are likely to exhibit different performance compared to crushed stone. Their flowability, consistency, placement, physical properties, hydrological properties and long term were evaluated and compared to mixes with crushed stone.

Mid-range water reducing admixtures (MRWR) are used in the mix designs to allow for a lower water-to-cement ratio. Hydration stabilizer is used to improve workability and facilitate the ease of placement. The air-entraining admixture was added to improve the freeze-thaw performance of the specimens. In PRC-5, the viscosity modifier is used. Due to the lack of sand in pervious concrete mixes, these mixes tend to be difficult to mix and hydrate with reasonable uniformity. Viscosity modifiers help to improve to lubricate the mix and make for easier placement. Fly ash and slag were used in PRC-7 and PRC-8 respectively to compare workability and durability.

Table 3. Mix design proportions of selected porous concrete mixes

Mix	Cement	3/8 agg	1/4 agg	Sand	Fly ash	Slag	Water	w/c ratio	MR WR	HS	VMA	AE	No. of 6x6x18 beams	No. of 3x3x12 beams	No. of 2x2x12 beams	No. of 6x12 perm cyl	No. of 4 x 8in cylinders
PRC-1NV	635	2430	---	224	---	---	209	0.33	1.9	1.9	--	0.8	6	3	3	1	6
PRC-2 (Weldon)	864	2430	---	---	---	---	236	0.27	1.9	1.9	-	0.8	6	3	3	1	12
PRC-3 (Clayton)	600	2835		-	-	-	162	0.27	1.9	1.9	--	0.8	6	3	3	1	12
PRC-4	620	2700	-	-			168	0.27	1.9	1.9	--	0.8	6	3	3	1	12
PRC-5	620	2700	-	-			168	0.27	1.9	1.9	2	0.8	6	3	3	1	12
PRC-6	620	1380	1380	-	-	-	168	0.27	1.9	1.9	--	0.8	6	3	3	1	12
PRC-7 (Fly Ash)	525	2500			95		168	0.27	1.9	1.9	-	0.8	6	3	3	1	12
PRC-8 (Slag)	465	2500				155	168	0.27	1.9	1.9		0.8	6	3	3	1	12
PRC-9 (Silvi)	500		2700				165	0.33	1.9	1.9	--	0.8	6	3	3	1	15
PRC-10 (gravel)	600	2700					180	0.30	1.9	1.9	--	0.8	6	3	3	1	15
PRC-11 (gravel)	600		2700				180	0.30	1.9	1.9	--	0.8	6	3	3	1	15

The number of specimens and the specimen dimensions tested in this study are summarized in Table 4.

Table 4. Number of specimens and size for various tests

Spec'n	Flexural Tests	Comp Tests	Splitting Tensile	Permea-bility	Modulus	Shrinkage	Freeze Thaw
Dim	6 x 6 x18 in prisms	4 x 8 in cylinders	4 x 8 in cylinders	6 x 12 in cylinder	4 x 8 in cylinder	2x2x12 in prisms	3x3x 12 in prisms
No	3	3	3	1	2	3	11

Mixing and Placement

All lab specimens were mixed in the civil engineering laboratory under controlled environment. Mixing was performed using the mechanical drum mixer with the drum capacity of four (4) cubic feet. Few additional smaller specimens were mixed by a hand mixer in a five-gallon bucket. Each mix sums up to around four cubic foot and the mechanical drum mixer has sufficient mixing power and capacity to properly mix all mix types in this study. The lab specimens were prepared in accordance to ASTM C192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," with minor modifications because of the special characteristics of pervious concrete. For each mix, the proportions of materials are either measured one day prior or on the day of mixing. Before mixing, the inside wall of the mixing drum is wetted with water to avoid uneven mixing of materials and ease the process of cleaning. All materials are weighed out in five-gallon buckets ahead of mixing. The drum is rotated to about 15 degrees above parallel to the floor and locked before materials are placed. Half of the aggregates was first placed in the drum, and then sand (if applicable), cement, and the second half of the aggregates, to help make the mix more even. It is not recommended to place cement first because the fine cement particles can stick to the inner walls which can affect the consistency and uniformity of the mix. After placement of all dry materials into the mixer, the mixer was tightly closed with a lid, and dry-mixed for about one-to-two minutes. The dry mix was then inspected to make sure cement and coarse aggregate are evenly mixed, the rotating drum is turned on again without the lid. The liquid admixtures were pre-mixed with the water and slowly poured into the dry mix as the drum rotates. With the lid closed, the mixer ran for three minutes. Then the mix sat for two minutes before mixing for another two minutes to facilitate the chemical reactions between the materials. The procedure is similar to mixing conventional concrete. It is crucial to check the consistency of the mix constantly to make sure the mix is workable. When the mix is too dry, a small additional amount of water is weighed and added to the mix, and the additional water is recorded and was used to adjust the water-to-cement ratio. Figure 3 shows the various types of beam specimens and cylinder after casting.

Figure 4. Various types of specimens after casting

The mix was placed and rodded in two layers for minimal compaction. There are no specific guidelines or ASTM specifications that address the vibration or compaction of lab prepared specimens of pervious concrete. For PRC-1, one cylinder was selected to be vibrated after placement. A small vibrator was used to compact that cylinder with minimal vibration. Examining that cylinder the next day, it was shown that some cement paste has accumulated at the bottom, making the bottom of the cylinder almost impermeable. This resulted in a non-uniform mix and caused inconsistent texture in the hardened concrete mix. Based on the results from that cylinder, no vibration was used and only minimal rodding in two layers was used for the remaining mixes. Before casting the mix into molds, the fresh unit weight of the batch was measured using the steel cylindrical apparatus according to ASTM C1688. The dry density and unit weight of the specimen is taken after the curing period and compared with the fresh density and void content. Measurement of slump was attempted for few mixes but none of them could be measured.

For the placement of the 4”x8” and 6”x12” cylinders, the mixes were placed in two layers from experimenting with different casting methods, rather than the three-layer method as specified by ASTM for conventional concrete to minimize vibration and potential separation of the cement paste. Each layer was lightly rodded for about 10-15 times and gently tapped around the circumference of the cylinders. As the concrete compacts, more is added on top and again lightly rodded till the entire cylinder is filled. The top of the cylinder was then leveled using a flat steel surface. Achieving a top flat surface for the cylinder proved more difficult than for conventional concrete cylinder and something to be carefully done in order not to skew the compressive test results. The process for casting beams was similar; the concrete was placed into the mold in two layers and was lightly rodded across each layer several times and then the top of the beam was leveled. Casting beams required careful attention to filling corners of the mold to make sure each corner has the same consistency as the rest of the beam.

The shrinkage prisms were 2 in x 2 in x 12 in. Round screws of 1/4 in diameter and 2 in long were attached to the inside of the mold at each end prior to casting for the purpose of shrinkage testing. The length of the screw must penetrate the concrete mix so that the concrete can bond enough to the pervious concrete around the screws without leaving too much void. To secure the screws after casting, fast hardening cement (Portland Cement III) paste is placed around the surface of the beam around the screw and left to harden for at least 30 minutes before being placed in the curing room. This process also proved to be delicate as some screws did not bond enough to the pervious concrete because of the high void content. Certain mixes were observed to be less workable compared to others. Factors that influence workability not only include the materials and mix proportions, but also outside factors such as temperature and humidity.

The cylinders and beams were covered and left to cure for 24 + 8 hours. After that, the specimens were removed from the mold and placed into the curing room. Porous cylinders are difficult to remove from its plastic mold, and therefore it is suggested that cylinders be removed under water. After removing the specimens, they are placed into the moisture curing room. Specimens for each mix were tested at 7 and 28 days. All specimens are cured for 28 days before permanent removal from the curing room except for shrinkage specimens which are removed after 7 days. Initially, the cylinders were found often fail by crushing during compressive strength testing due to the uneven surface of the cylinder caused by the porous nature of the material. Similarly elastic modulus readings were also inconsistent. To ensure a leveled surface at the top of the cylinders, several methods of capping were attempted, including rubber, steel capping, as well as permanent sulfur capping. Sulfur capping was the best method and therefore cylinders were sulfur-capped prior to compressive strength and elastic modulus testing. Figure 4 shows a pervious concrete capped cylinder using sulfur compound.

All molds were made of steel and were cleaned using the microfiber cleaning device. Steel is the most ideal material for casting pervious concrete specimens because they are reusable and durable. It is not recommended to clean the molds with water to prevent the corrosion of the steel.

Figure 5. Sulfur-capped porous concrete 4”x 8” cylinder

Testing Procedure

Compressive, flexural, and splitting tensile strength tests, as well as elastic modulus tests were performed at 7 days and 28 days. Free-shrinkage tests were performed up to 70-day and freeze-thaw tests were performed up to 100 cycles. All tests are performed in a controlled laboratory environment.

Compressive Strength

Compressive strength tests were conducted in accordance to ASTM C39. Three 4”x8” cylinders from each mix were tested for compressive strength using 1000 kip Forney Testing Machine at 7 days and 28 days. At 7 days and 28 days, the specimens were taken out 24 hours prior to testing to be dried. Because of the high void content in pervious concrete, the specimen often were left to dry longer than 24 hours to achieve dry condition prior to testing. The moisture content in the air at the time of testing was found to effect the time needed for the specimens to dry. Some specimens were taken out from moisture curing rooms 36 hours ahead of time to ensure the proper drying of the specimen to obtain accurate results. After drying, the specimens were capped with liquid sulfur at 350 °F. When the sulfur capping completely hardened, the cylinders were placed and centered on the Forney compression machine and tested at a load rate between 300 and 500 lb/s. The load is recorded at 500 lb or 1000 lb increments until failure. The flatness of the capped faces of the cylinders as well as centering of the cylinders in the compressive strength testing machine are important to obtaining accurate results. The leveling process at the top of the cylinder using heavy flat steel plate and the sulfur capping proved to be sufficient to achieve uniform distribution of the applied compressive load. Figure 6. shows a 4 in x 8 in cylinder in the 1000 kip Forney testing machine. Figure 7 shows failure of 4 in x 8 in pervious concrete cylinder in compression.

Figure 6. Compressive strength test on 4”x8” sulfur capped cylinder

The coefficient of variance (C.O.V) is calculated using the equation:

$$C.O.V\ (\%) = \frac{Average\ Peak\ Load}{Standard\ Deviation}$$

Figure 7. Failure of 4 in x 8 in pervious concrete cylinder in compression

Flexural Strength Tests

Flexural strength tests were performed in accordance to ASTM C293. Three 6”x6”x18” beams were tested for flexural strength at 7 days and 28 days using the MTS Sintech 10/GL machine. The beam is set up as shown in Figure 8.

*

Figure 8. Porous concrete beam during flexural test (6”x6”x18” beam)

The test utilizes a four-point loading set up, a slight modification to the commonly used three-point loading. Initially, the three-point loading set up was used, following conventional flexural testing methods. However it was observed that some specimens failed by crushing at the supports. Therefore, the four-point loading method was used instead, to reduce stress at the supports to avoid failure by crushing. Each 18” beam is supported at each side 1” away from the edge of the beam and the two-point loading plate is centered, with the two loads spaced at 6” apart. The loading is recorded automatically by the MTS program and the peak load, cracking moment and flexural stress were recorded. Three specimens were tested for each mix design to ensure the consistency of the results, and the specimens were tested at 7 days and 28 days.

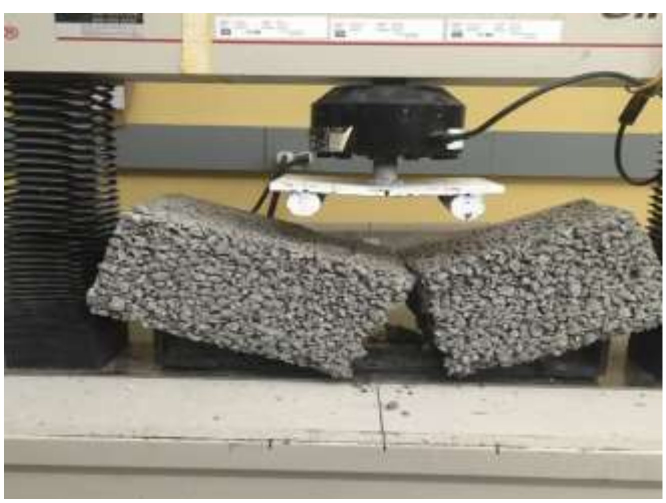

Figure 9. Flexural failure of porous concrete beam

Splitting Tensile Strength Tests

Splitting tensile strength was also tested using three 4”x8” cylinders per mix at 7 and 28 days using the Forney testing machine as shown in Figure 10 with a load rate of about 300 lb/s. The specimens were tested according to ASTM C496. Long wooden shims were placed at the top and bottom of the specimen as it is placed sideways in order to prevent the specimen from rolling off or going off center during the placement and testing of the specimens. The specimens for splitting tensile strength test were not capped. The peak load is recorded for each specimen at failure and three specimens were tested for each mix design to ensure the consistency of the test result. Figure 12 shows splitting tensile failure of 4 in x 8 in cylinder

Figure 10. Splitting tensile strength test of 4”x8” porous concrete cylinder

The splitting tensile strength is calculated with the equation:

$$T = \frac{2 * P}{\pi L D}$$

Where

P = failure load,

L = length of specimen (in),

D = diameter of specimen (in)

Figure 11. Testing machine used for the splitting tensile strength tests


Figure 12. Splitting tensile test failure of porous cylinder

Elastic Modulus Tests

Testing for elastic modulus was challenging and time consuming. The tests were conducted in compliance to ASTM C469, using a compatible compressometer with two yokes used for 4” x 8” cylinders. For measuring the modulus of elasticity, only vertical deformation was measured throughout the tests. Maintaining constant distance between the screws and the specimen, and keeping the top and bottom rings parallel to each other and to the horizontal surface are all key to obtaining accurate readings. After the compressometer is placed correctly onto the cylinder, the specimen must then be centered on the bearing plate of the Forney compression machine. It is then loaded to 40% of its failure load and unloaded, and the cage distances on the opposite sides are then measured. As the specimen is loaded again, readings are taken at 500 to 1000 lb intervals depending on the compressive strength of the cylinder. The loading rate is generally between 300-400 lb/s. Each specimen is tested first with the loading from one capped end, and then again with the load coming from the other capped end to ensure consistency of the test results. Figure 13 shows modulus test setup.

Figure 13. Elastic modulus test of 4”x8” sulfur capped porous cylinder

Free Shrinkage Tests

The specimens prepared for free shrinkage tests were 2”x2”x12” prisms with ¼ in diameter 2in long screws secured at each end using water and fast-setting cement. Three specimens were prepared for each of the selected mixes. Free shrinkage specimens were moisture-cured in a controlled environment for seven days after the prims are removed from the molds. Then readings are taken every 7 days up to day 70, for 10. Additionally during the first week while the specimen is moisture cured, the shrinkage is measured on day 4 as well while the specimen is still in the moisture curing chamber. The free shrinkage testing and measurements were made according to ASTM

C157. The test is taken on the length comparator and with a reference bar as shown in Figure 2.16. It is very important to maintain consistency in the orientation of the beam while taking the readings each time. After securing the specimen onto the device by the end screws, the specimen is gently rotated three times and oriented so the marked side of the specimen is facing the front. The top and bottom of the specimens are also marked so that the reading is never taken with the specimen upside down. Every detail of the process is essential to obtaining accurate and consistent results due to the high sensitivity of the pervious concrete specimens and the potential movement of the screws at both ends of the prism. In the experimental process, the first round of specimens returned inconsistent and inaccurate results that may have resulted because of inconsistencies in specimen orientation, variations in room moisture, or loosening of end screws. Therefore, during the second round of specimen casting and testing extreme caution was taken to ensure the consistency of the test results and minimize human errors and weather condition-factors.

Figure 14. Porous concrete prism placed in comparator for free shrinkage test

Freeze-Thaw Durability Tests

Freeze-thaw durability specimens were prepared and tested according to ASTM C666. The specimens were 3’x3’x12” and two specimens were tested from each mix. Figure 15 shows the freeze-thaw specimens with aluminum plate labels, connected to each specimen using thin metal wires. The method is used to prevent specimen confusion due to fading of the spray-painted labels in the process of freezing and thawing. The specimens are manually frozen and thawed using a five cubic foot freezer. The specimens were weighed after every ten cycles of freezing and thawing. One of the two groups of specimens was saturated with 4% salt solution in between freeze-thaw cycles to study the effects of salt on freeze-thaw resistance. The specimen is considered to fail when 10% or more mass is lost under freezing and thawing.

Figure 15. Freeze-thaw porous concrete specimens in freezer

Test Results and Discussion

Compressive Strength Results

The cylinders for compressive strength tests were tested at 7 and 28 days as mentioned earlier. The results as well as the coefficient of variance were calculated and recorded In Table 3.1. The 28-day compressive strengths range from 1,110 psi to 2,270 psi, with exception of mix PRC-2 which was higher. Generally, the compressive strength appears to directly correlated with the cement content of each mix, where the mixes with the most cement content has the highest compressive strengths, excluding PRC-1 which was the only mix containing fine sand. In the mixes PRC-10 and PRC-11, ¼" and 3/8" round river gravels were used. In these two mixes, the cement content was reduced due to the anticipation that river gravels are more workable compared to conventional crushed stone aggregates due to their round shape. Since PRC-10 and PRC-11 both showed compressive strength, it can be proposed that mixes containing river gravel generally increases the compressive strength while requiring less cement content.
In addition, PRC-7 and PRC-8 utilized partial fly ash and slag substitution for cement, respectively, to reduce the use of cement. Fly ash and/or slag to increase workability of the mixes due to their microstructural shapes. PRC-7 used 18% cement substitution with fly ash while PRC-8 used 33% cement substitution with slag. PRC-8 returned low compressive strength results despite the slag substitution. In contrast, the specimens of PRC-7 where fly ash substitution was used performed had an average compressive strength of approximately 1900 psi after 28 days. As seen in the table, the results of the

compressive strength have quite a range of variance. The nature of pervious concrete is quite variable due to the non-homogeneity of the mix, its high void ratio, and many factors causing difficulties in the testing process. Some of these factors could be attributed to its uneven surface, as well as the variability and effect of the microstructure of pervious concrete, which requires further research. Another likely factor could be the sensitivity of loading rate control on the 1000 kip Forney compression test machine which could cause the peak loads to have some variation. Table 5 shows the comparison of the 7 day and 28 day compressive strengths for all mixes.

Table 5. Summay of compressive strength results at 7 and 28 days

Mix I.D	f'c (psi)		C.O.V (%)	
	7-Day	28-Day	7-Day	28-Day
PRC-1 NV	1881	2271	6	3
PRC-2	1536	3414	4	5
PRC-3 (Clayton)	1665	2039	16	17
PRC-4	1574	1988	47	12
PRC-5	989	1116	6	18
PRC-6	1064	1291	7	10
PRC-7 (Fly Ash)	1449	1899	9	16
PRC-8	942	1326	11	15
PRC-9 (Silvi 1/4)	944	1166	5	2
PRC-10	1455	2061	11	2
PRC-11	1983	2308	3	3

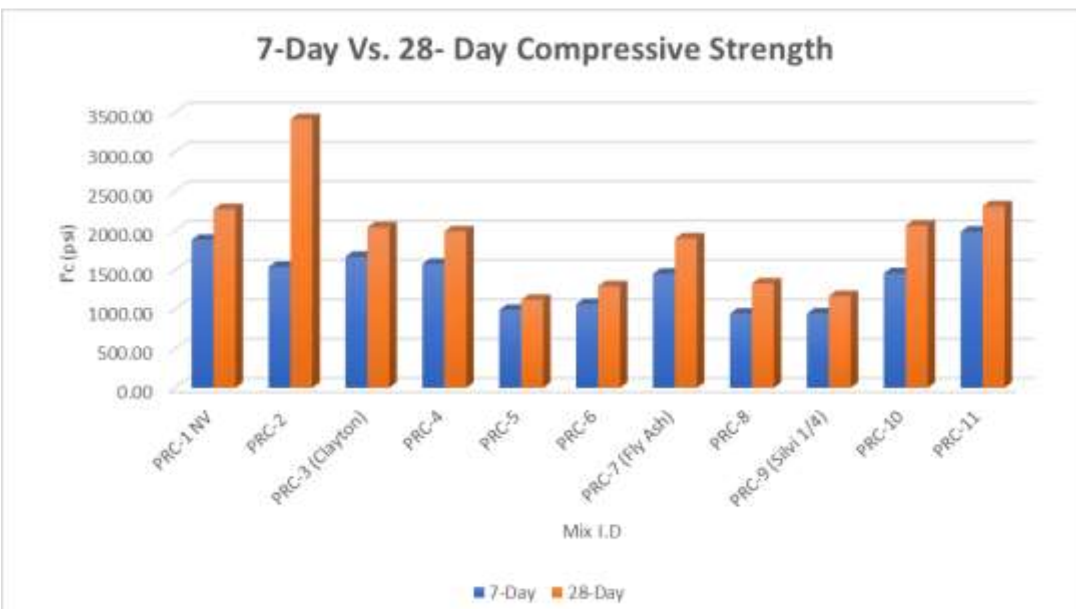

Figure 16. 7 days and 28 days compressive strength of various mixes

Splitting-Tensile Strength

The splitting tensile strength test was conducted at 28 days only. The trend of results of splitting tensile strength is in agreement with the compressive strengths mentioned in the last section. It has been noted that the coefficient of variances for the splitting tensile strength is much lower and more stable compared to the previous results. The set up used for the splitting tensile strength was also much more stable and the loading rate was more easily controlled; the results of the splitting tensile strength at 28 days for all mixes and their coefficients of variance are shown in Table 6.

Flexural Strength

The pervious concrete beam specimens were tested in flexure at 7 days and 28 days. The flexural tests were performed with four-point loading set up, a slight modification to the conventional three-point loading set up as mentioned previously. The results of the flexural strength test had less variation compared to the results of the compressive and splitting tensile strength tests. The coefficient of variance in these results was also consistent, with all values under 10%. The results of modulus of rupture of all mixes at 7 days and 28 days are summarized in Table 7. Table 7 also shows the coefficients of variation of these results.

Table 6. Average splitting tensile strength of various mixes

MIX ID	Average Splitting Tensile Stress (psi)	C.O.V (%)
PRC-1 NV	252	4
PRC-2	--	--
PRC-3	238	4
PRC-4	275	2
PRC-5	172	5
PRC-6	201	10
PRC-7	217	7
PRC-8	214	7
PRC-9	162	5
PRC-10	252	3
PRC-11	283	6

Table 8 shows the comparison between compressive strength, flexural strength, and splitting tensile strength. It can be seen that the ratio of modulus of rupture to compressive strength consistently ranges from 0.13-0.18. The last column of the table compares the ACI Code suggestion of the relationship between f’c and fr for normal weight concrete to the actual results. The results show that the actual relationship between f’c and fr in pervious concrete does not conform to that for normal weight concrete. Currently there is no standard relationship between the rupture strength and compressive strength of pervious concrete from the ASTM or ACI specifications.

Table 7. Summary of flexural strength (modulus of rupture) at 7 and 28 days

	f'r (psi)		C.O.V (%)	
Mix I.D	**7-Day**	**28-Day**	**7-Day**	**28-Day**
PRC-1 NV	333	370	8	4
PRC-2	381	415	3	7
PRC-3 (Clayton)	230	345	10	8
PRC-4	334	363	4	7
PRC-5	127	201	7	7
PRC-6	176	217	8	8
PRC-7 (Fly Ash)	192	238	3	4
PRC-8	188	220	6	3
PRC-9 (Silvi 1/4)	138	154	4	6
PRC-10	247	262	8	3
PRC-11	283	296	5	3

Table 8. Ratios of ft to f'c, fr to f'c and ACI prediction of fr in terms of f'c

Mix ID	**f'c (psi)**	**fr (psi)**	**ft (psi)**	**fr/f'c**	**7.5*(f'c)^0.5**
PRC-1 NV	2271	370	252	0.16	357
PRC-2	3414	415	--	0.12	438
PRC-3	2039	345	238	0.17	339
PRC-4	1988	363	275	0.18	334
PRC-5	1116	201	172	0.18	251
PRC-6	1291	217	201	0.17	269
PRC-7	1899	238	217	0.13	327
PRC-8	1326	220	214	0.17	273
PRC-9	1166	154	162	0.13	256
PRC-10	2061	262	252	0.13	340
PRC-11	2308	296	283	0.13	360

Modulus of Elasticity

The elastic modulus values had high variances. Research conducted at the University of Minnesota research team on elastic modulus tests on pervious specimens previously showed consistent results of elastic modulus values between 2,000 ksi to 3,000 ksi [(89)]. The test results shown in Table 9 for the elastic modulus showed that the results varied from 1000 ksi to 2500 ksi. While the majority of our pervious mixes had an elastic modulus of 1,700 ksi or higher, mixes PRC-1, PRC-8, PRC-10 and PRC-11 had low moduli of elasticity. Since modulus of elasticity in concrete depends largely on the proportions and types of binding materials and the aggregates, the void ratio, the variability in our mix designs in the w/c ratio and aggregate types may have contributed to the high variation of elastic modulus values for the different mixes. The effect of different aggregate types is especially apparent in PRC-10 and PRC-11, where round river gravel of ¼" and 3/8" were used instead of the conventional crushed stone, and these mixes had much elastic moduli lower than the other 9 mixes.

Table 9. Elastic moduli for various mixes

Mix ID	Elastic Modulus (ksi)
PRC-1	1,067
PRC-2	2,642
PRC-3	2,441
PRC-4	2,323
PRC-5	1,783
PRC-6	2,027
PRC-7	2,564
PRC-8	1,140
PRC-9	1,910
PRC-10	680
PRC-11	835

Mixes PRC-2, PRC-3, PRC-4, and PRC-7 had higher modulus values compared to other mixes as shown in Table 3.5. A complete set of the initial part of the stress-strain curves with the corresponding values of the elastic modulus values are given in Appendix E. These mixes had the highest amount of cement content except for mix PRC-7 which had part of the cement replaced with fly ash. Figures 3.2 through Figure 3.6 show the initial part of the stress-strain curves with the corresponding values of the elastic moduli for mixes PRC-2, PRC-4, PRC-7, and PRC-9, respectively. There are several factors that affect the elastic modulus. First and foremost is the percentage of voids in material. The strength of aggregates is also another factor that affects the modulus as well as the modulus of the cement paste. For pervious concrete, the void content is likely to be the most important factor that controls the value of the modulus of elasticity. A plot of the elastic modulus versus void ratio is shown in Figure 17. The results in Figure 19 show random results with no defined trend that relates the modulus to the void ratio. However, it is expected that the modulus of elasticity will decrease with the increase in void ratio.

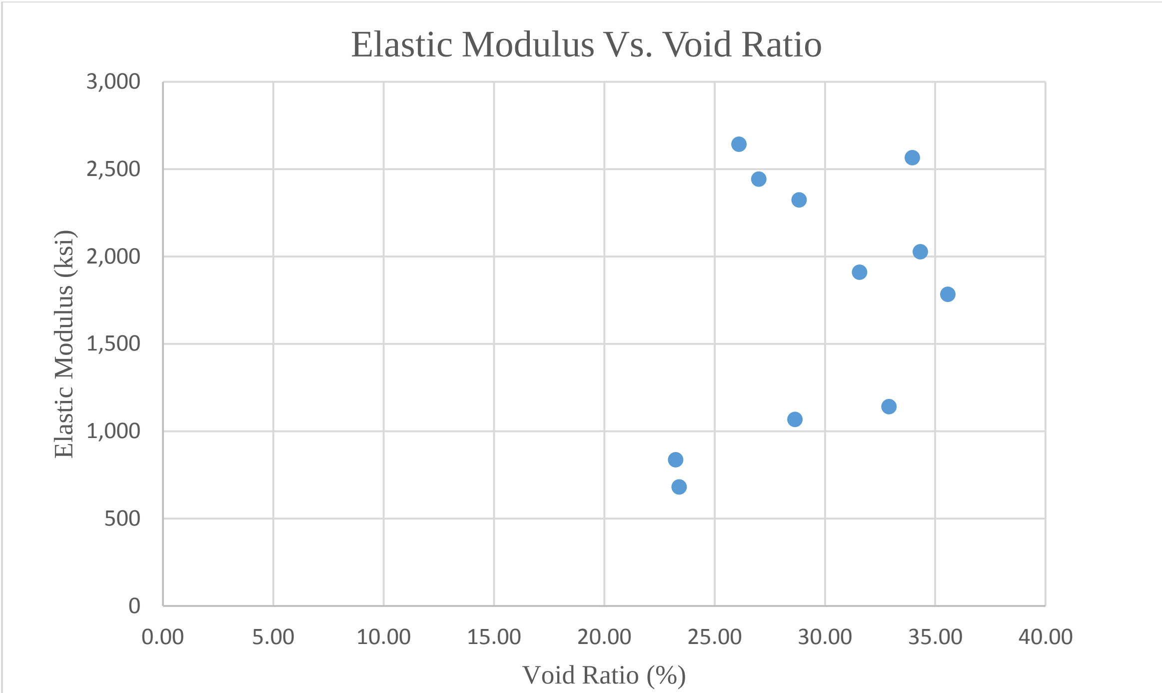

Figure 17. Elastic modulus versus void ratio of various porous mixes

Free Shrinkage Tests

The free shrinkage specimens require extremely careful curing and storing methods, and meticulous testing procedures. Many factors affect the accuracy and consistency of the results, including chipping of the specimen after the 7-day moisture curing period, the tightness of the screws at the ends of the specimens, the procedure and orientation of the specimens during test, and the humidity and temperature at the time of test. Therefore it is nearly impossible to pinpoint any major factors influencing the shrinkage of the mixes. After comparing the mix proportions and the shrinkage of the specimens tested, the proportion of cement as well as the w/c ratio appears to positively correlate to the free shrinkage of the specimens over time. As shown in the graphs in the section, the shrinkage increases linearly up to about 20 days and then decreases the rate of growth until it reaches somewhat of a plateau. The results show that the 70-day free shrinkage of pervious concrete is generally less than the shrinkage for impervious concrete mixes, which usually ranges between 600-700 µin/in between 60-80 days. From the graphs below it can also be observed that shrinkage results for pervious concrete can be very inconsistent due to difficulties introduced as mentioned previously.

During some days of testing, shrinkage values would be found lower than the previous cycle, even after careful confirmation that the specimens have been handled carefully and the test has been performed properly. After the first few observations of this occurrence, it was proposed that temperature and humidity might play a role in these results. Therefore, humidity was also tracked for a few cycles consistently for all specimens for the days when the shrinkage values were taken. It was found that humidity is a major culprit, causing shrinkage readings to be inconsistent. It was observed that pervious concrete is extremely sensitive to the change of moisture content in air and thermal changes in general. Therefore, the shrinkage results were a combination of free shrinkage and thermal expansion/contraction. Figures 20 and 21 show free shrinkage measurements with time for PRC-2 and PRC-9 respectively.

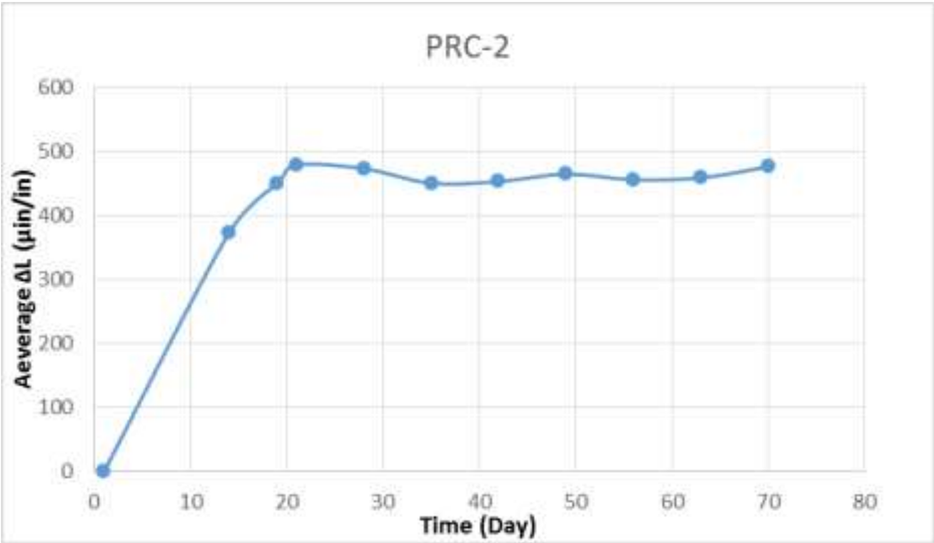

Figure 18. Free shrinkage strains versus time for Mix PRC-2

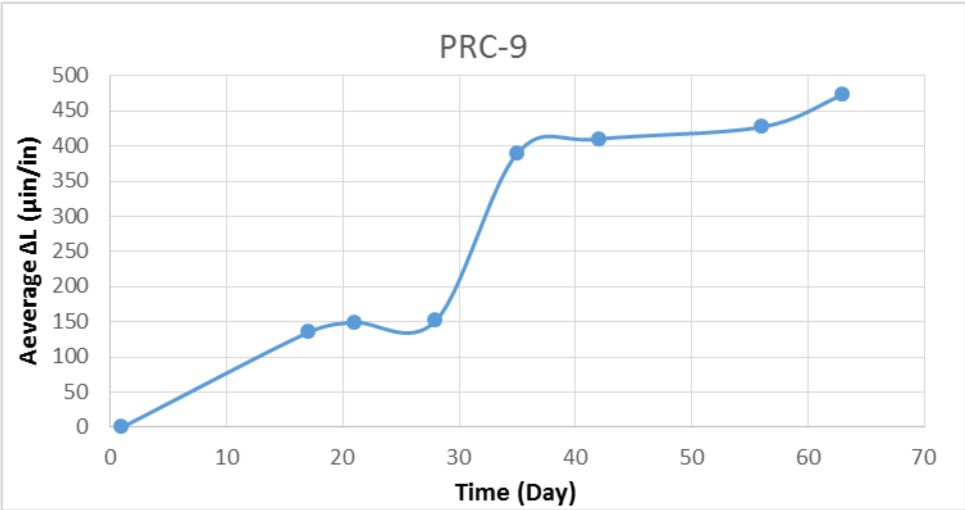

Figure 19. Free shrinkage strains versus time for Mix PRC-9

Freeze-Thaw Tests

The freeze-thaw test is simple yet tedious, requiring freezing and thawing for every cycle up to a total of 300 cycles. The test was carried out according to ASTM C666. The Freeze-thaw test results shown in Figures 22 and 23 are up to 70 cycles now. The test will continue up to 300 cycles. Based on the results so far, it is anticipated that at 100 cycles the loss of mass due to freezing and thawing will be less than 10% of the initial mass of the prisms. So far, the pervious concrete samples have performed well under freezing and thawing. The key for this durability test is the high void ratio of pervious concrete which allows water to drain quickly and not freeze in the specimen causing cracking and failure. Hence it is more important to prevent clogging of pervious concrete pavements to avoid retention of water within the pavement.

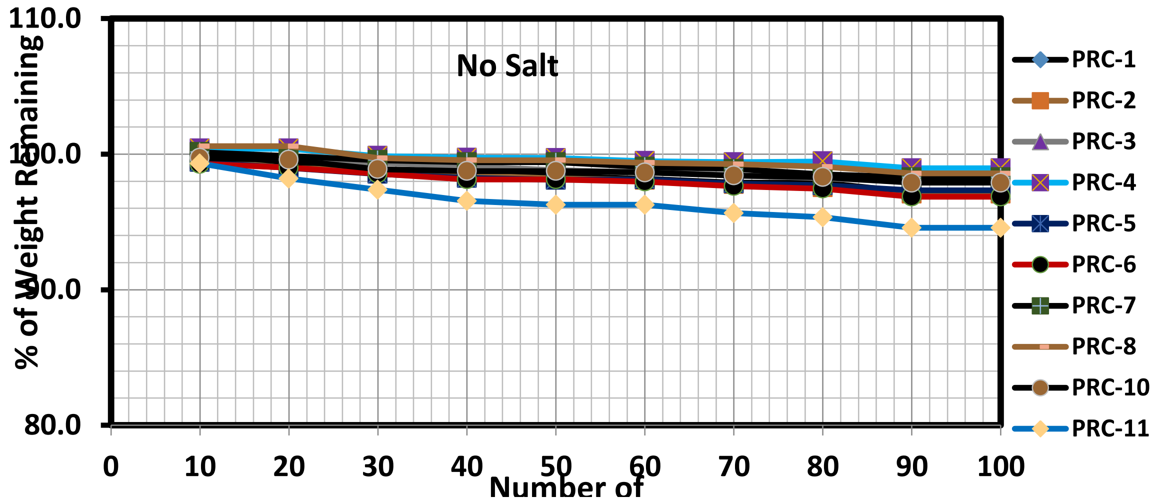

Figure 20. Freeze-thaw test results up to 70 cycles for specimens with no salt

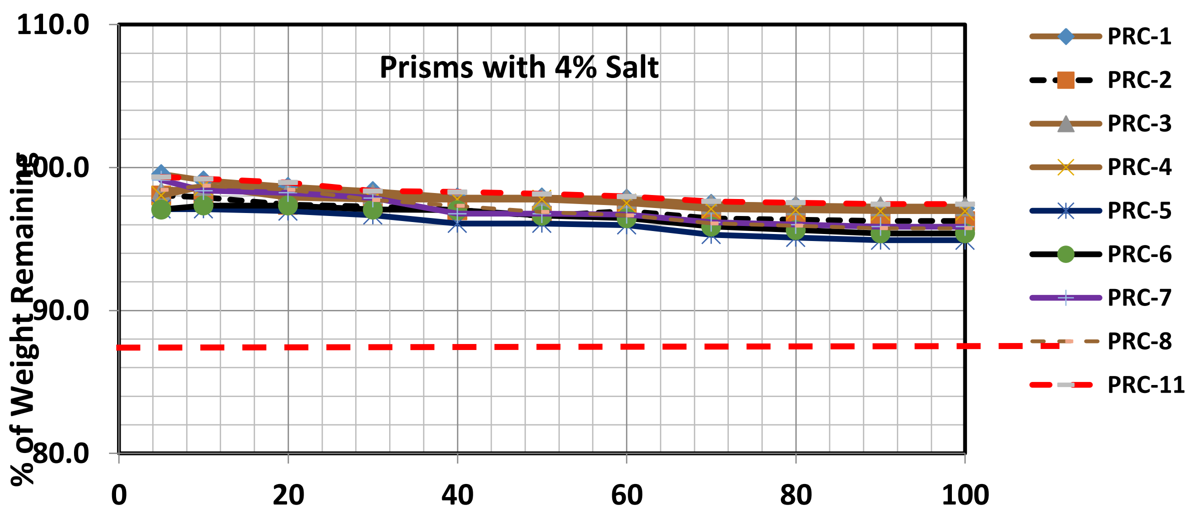

Figure 21. Freeze-thaw test results up to 70 cyvles for specimens with 4% salt

The samples with 4% salt seem to have slightly higher mass loss with freeze-thaw cycling compared to prisms with no salt up to 70 cycles. From the graphs, it can be noted that most samples have been experiencing similar and consistent rates of mass loss linearly overtime.

Evaluation of Hydrological Properties

Density Measurements

The fresh concrete density was measured according to ASTM C1688, “Density and Void Content of Freshly Mixed Pervious Concrete”. The density of the hardened concrete were measured according to ASTM C29 and ASTM D7063, using a vacuum packaging sealing device instead of the common submerged weight measurements due to the high porosity of pervious concrete. The fresh density is taken immediately after the mixing and before placing the fresh concrete. The 0.25 cubic foot aluminum unit weight bucket was used for the testing. First the weight of the empty bucket was recorded. Then the bucket is filled with the fresh mix in two layers, each rodded 20 times, distributing the rodding evenly across the surface of the mix. The bucket is filled such that the mix is overflowing. The surface of the consolidated mix must contain about 1/8in of excess pervious concrete protruding above the top of the bucket [17]. The weight of the full bucket is then taken again. The equation used to determine the fresh unit density is as follows:

$$\mathrm{D} = \frac{M_c - M_m}{V_m}$$

where

M_c = Mass of the measure filled with concrete
M_m = Mass of the weight bucket
V_m = Volume of the weight bucket

The dry density and effective void content of the pervious concrete was measured according to ASTM D7063, “Standard Test Method for Effective Porosity and Effective Air Voids of Compacted Asphalt Mixture Specimens”. Although the specification was written specifically for asphalt specimens, this testing method seemed more appropriate for the testing of pervious concrete specimens. The test specimens were around 2” in height and 6” in diameter. The specimen was first dried in the oven for 24± hours before being weighed for its dry unit weight. The weight of the vacuum sealing bag and the weight of the bag and the specimen together were also weighed. After the specimen is sealed using the vacuum sealing device, the air-tight mass of the bag and the specimen together is taken. Prior to vacuum sealing, the edges of the cut specimens must be rounded with wrenches or rodding devices by lightly tapping around the edges of the specimen. The failure to round-out the edges would cause puncturing of the sealing bag during the vacuum sealing process. After the specimen is taken out of the vacuum-sealing bag, is is then submerged in a water bath for 3 minutes, and then saturated. The submerged specimen weight and the saturated specimen weight are also taken. These weights are used in conjunction with the adjustment factors which accounts for the effect of temperature at the time of test to calculate the dry density and air void content.

The bulk specific gravity is calculated using the equation:

$$\text{SG1} = \frac{A}{B - E - \frac{B-A}{F_T}}$$

where

A = Mass of dry specimen in air (g)
B = Mass of dry, sealed specimen (g)
E = mass of sealed specimen underwater (g)
F_T = apparent specific gravity of plastic sealing material at 25 ± 1 ºC [77 ± 2 ºF], when sealed.

And the apparent specific gravity is calculated using the equation:

$$\text{SG2} = \frac{A}{B - C - \frac{B-A}{F_{T1}}},$$

where

C = Mass of unsealed specimen underwater, g
F_{T1} = apparent specific gravity of plastic sealing material at 25, ± 1 ºC [77 ± 2 ºF

The % porosity is calculated using this equation:

$$\%\ \text{Porosity} = \%\ \text{Effective Air Voids} = \frac{SG2 - SG1}{SG2}\ x\ 100$$

The theoretical density is calculated and compared to the measured densities. The theoretical unit weight is calculated according to this equation:

$$\text{D} = \frac{Total\ Mass\ of\ Mix}{Total\ Volume\ of\ Mix}$$

Hydraulic Conductivity (Falling Head Method FM 5-565)

The hydraulic conductivity tests were conducted on segments of 6 in x 12 in cylinders. After cylinders were cured for 28 days, they were cut into 1 ½ in to 2 ½ in segments and tested for permeability. The permeability tests were conducted using the Falling Head Method FM 5-565 in a controlled laboratory environment and were administered by a research associate being helped by research assistants. Figure 2.19 shows the specimens after they were cut into segments and Figure 2.20 shows the falling head apparatus used. The flatness of the cut face of the segmented specimens was important in order to conduct the permeability tests successfully.

Figure 22. Sample cuts from 6 in x 12 in pervious concrete cylinders used for air void and permeability measurements

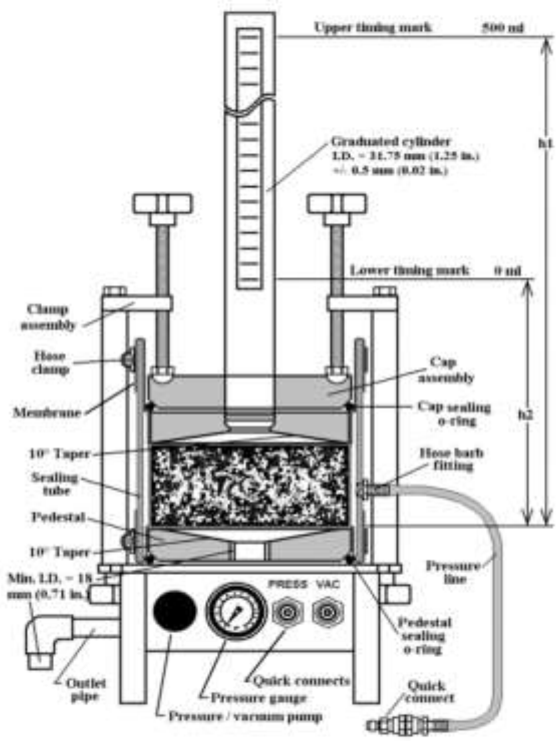

Figure 23. Falling head apparatus used for permeability tests (FM 5-565)

The coefficient of permeability was calculated with this equation:

$$k = \frac{al}{At} \ln\left(\frac{h1}{h2}\right) t_c$$

where

a = inside cross sectional area of the buret (cm^2)
L = average thickness of the test specimen (cm)
A = average cross sectional area of the test specimen
t = elapsed time between h_1 and h_2 (sec)
h1 = initial head across the test specimen (cm)
h2 = final head across the test specimen (cm)
t_c = temperature correction for viscosity of water where T = 20 ºC

PermeabilityTest Results

The permeability of various pervious concrete mixes were measured using the falling head test apparatus as described earlier. Figure 24 shows the correlation between hydraulic conductivity and air void percentage. The variability in the results could be attributed to the geometry of the interconnected pores, which can be further investigated. Figure 25 shows a bar chart of hydraulic conductivity factor k versus the various porous concrete mixes tested in this study. Table 10 shows the hydraulic conductivity values for various mixes with the corresponding void ratios.Table10 shows that mixes PRC-5 and PRC-7 have the highest permeability coefficients. However, PRC-5 has the highest void ratio and the lowest compressive strength of all 11 mixes. In contrast, PRC-7 has one of the highest compressive strengths, although also with a high void ratio. Permeability is related to the amount of voids in the mix but it also depends on how the voids are connected. Therefore any correlation of permeability with void content could be misleading.

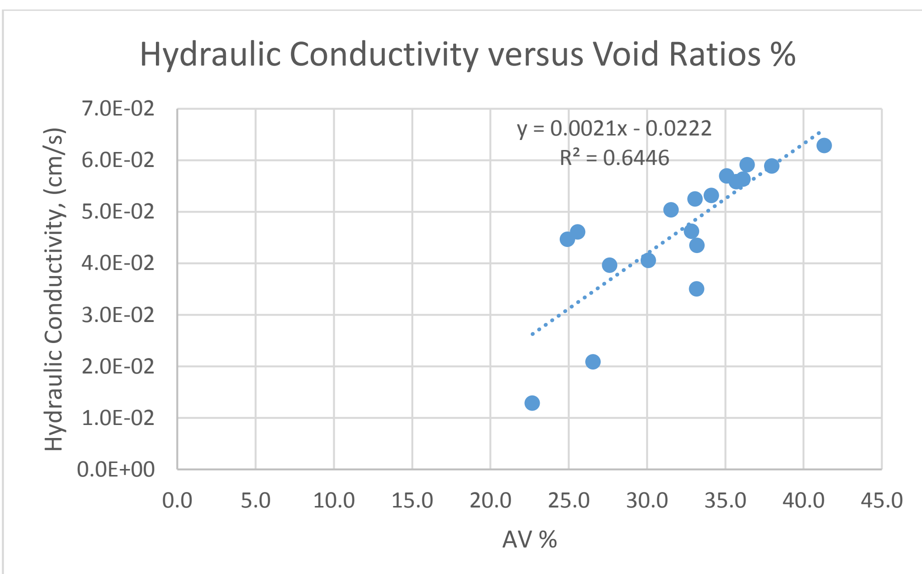

Figure 24. Hydraulic conductivity versus air voids for various porous mixes

Mix PRC-11 has the lowest permeability coefficient, as expected. Since the river gravels are more likely to compact and bind well due to the rounded shape, pervious specimens using river gravels were expected to be denser, containing less voids.

Table 10. Hydraulic conductivity and void ratio of various porous concrete mixes

Sample I.D.	Hydraulic Conductivity, k (cm/sec)	Void Ratio%
3A	0.041	30.1
3B	0.053	34.1
4A	0.040	27.6
4B	0.050	31.6
5A	0.056	35.7
5B	0.063	41.3
6A	0.052	33.1
6B	0.059	38.0
7A	0.059	36.4
7B	0.057	35.1
8A	0.056	36.1
8B	0.046	32.8
9A	0.035	33.2
9B	0.043	33.2
10A	0.046	25.6
10B	0.045	24.9
11A	0.013	22.7
11B	0.021	26.6

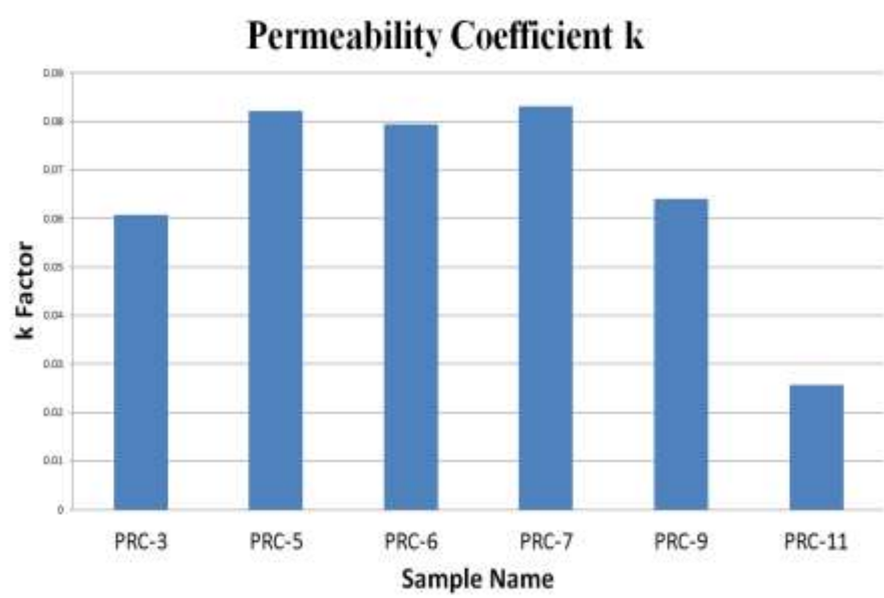

Figure 25. Permeability coefficient k from permeability tests for various mixes

Density and Void RatioTest Results

The theoretical unit weight (solid material without voids) of each mix was calculated based on the mass and volume of each mix, and compared to the fresh unit weight and the bulk density. While the theoretical densities of all the mixes were relatively similar, the fresh mix unit weight and bulk density were quite different compared to the theoretical unit weight. These discrepancies are not surprising considering the different methods of calculation for each value. It is important to note that the method used to calculate theoretical unit weights does not consider the void ratio of the mix, while the actual measured unit weights do. While this makes little difference in conventional concrete, which typically has a 4-6% void ratio, void ratio is one of the most crucial factors to fulfill the purpose of pervious concrete. The void ratio of pervious concrete is typically between 25-35% percent. Therefore, the measured densities of pervious concrete are much lower due to its porosity.

The percentage of air voids and the bulk density of the specimens are positively correlated with each other, while fresh mix unit weights and air void percentages do not seem to consistently correlate, as shown in Tables 11, 12, and 13 respectively. Although it would be logical to expect the fresh mix unit weights to be higher than the bulk density of the specimens since the water evaporates overtime, some specimens had lower fresh unit weights while others had higher bulk densities. The discrepancies in the unit weights of the mixes in different stages could be explained by the variations in the pore geometries of various pervious concrete; the microstructure of the pervious concrete and the definition of pores could change overtime while the concrete hardens. This would require further studies on the changes of the pore geometry of pervious concrete and pore structure as it hardens with time.

Table 11. Density measurements for various porous concrete lab mixes

Mix ID	Theoretical Unit Weight (lb/ft^3)	Wet Unit Weight (lb/ft^3)	Bulk Density (lb/ft^3)	Bulk Spefic Gravity
PRC-1NV	156.0	-	-	-
PRC-2	156.3	116.3	-	-
PRC-3	160.2	118.2	120.9	1.94
PRC-4	159.6	118.6	117.8	1.89
PRC-5	159.6	107.0	109.3	1.75
PRC-6	159.8	117.4	111.7	1.79
PRC-7	158.1	117.4	112.8	1.81
PRC-8	158.7	117.0	115.8	1.85
PRC-9	158.7	110.2	113.7	1.82
PRC-10	158.6	118.3	122.6	1.97
PRC-11	159.9	117.2	120.6	1.93

Table 12. Density measurements for various porous concrete field mixes

Date Casted	Mix ID	Weight Total (lb)	Weight Sample (lb)	Wet Unit Weight (lb/ft^3)	Theoretical (dry) Unit Weight
11/4/17	Control	37.75	29.75	119.00	154.28
10/28/17	PRC-3	36.60	28.60	114.40	160.12
10/31/17	PRC-7	38.00	30.00	120.00	158.73
11/2/17	PRC-9	34.75	26.75	107.00	158.73

Figure 13 shows the relationship between the air void and compressive strengths of the porous specimens. Clearly the porosity of concrete is inversely proportional to the compressive strengths. PRC-10, 11, and PRC-3 had the highest compressive strengths with the lowest porosities. As mentioned in the previous lit review, the porosity of pervious concrete typically ranges from 25-35%. Therefore, PRC-3 has the best combination of average void ratio to compressive strength based on the values shown in Table 13. Table 14 shows the comparison of air voids taken using the ASTM D7063 method and the falling head method.

Table 13. Void ratio (ASTM D7063) versus compressive strength

Mix ID	Average Air Void %	f'c (psi)
PRC-1	29	2271
PRC-2	26	3414
PRC-3	27	2039
PRC-4	29	1988
PRC-5	36	1116
PRC-6	34	1291
PRC-7	34	1899
PRC-8	33	1326
PRC-9	32	1166
PRC-10	23	2061
PRC-11	23	2308

Table 14. Voids ratios from ASTM D7063 and the falling head method

	Average Void Ratio (%)	
Mix ID	**ASTM D7063**	**Falling Head**
1	28.6	
2	26.1	
3	27.0	32.1
4	28.8	29.6
5	35.6	38.5
6	34.3	35.5
7	34.0	35.7
8	32.9	34.5
9	31.6	33.2
10	23.4	25.3
11	23.3	24.6

FIELD SLABS FABRICATION AND TESTING

Preparation of Pervious Concrete Slabs for Field Testing

Eight (8) field slabs consisting of two slabs for each selected mix designs were construced in the filed near the Asphalt Lab on Livingston campus at Rutgers Univresity. The selected mixes incldue three (3) pervious concrete mixes (PRC-3, PRC-7, and PRC-9) . The field slabs will be sued to evalauted thermal properteis and heat radiations. The slabs then will be cored to obtain cylinders for lab tests. The slab will then be cut to obtain test samples for flexural tests and for void ratio and premability measurements. The slabs were also built to simulate typical construction project conditions. The slabs were each 4' x 4' x 4". Two slabs were cast from pervious concrete using mix designs PRC-3, PRC-7, and PRC-9. The pervious mix designs (PRC-3, PRC-7, and PRC-9) were chosen for their strong compressive strength, workability, and variation of aggregates, as well as the chemical and cementitious admixtures used in these mixes. A three cubic foot capacity mechanical mixer was used, similar to the slightly larger mechanical drum in the lab. Two mixes were necessary to complete each slab due to the limited capacity of the mechanical mixer. Due to the thinnes of the slabs, they were only lightly compacted in one layer as much as to simulate field compaction. The surface finish was done suing trowels and flat beams across the surface of the mix. Figures 26, 27, and 28 show site preparation, and placement of 6 in aggregate reservior or storage layer, wooden molds, and completed slab. Figure 29 shows completed slabs and Figure 30 shows sensors placement and slab measurement scheme. The slabs were moisture cured for 7 days to simulate construction curing conditions. To determine the effect that pervious concrete sidewalk mixes as compared to conventional concrete sidewalk mixes, an energy balance study was determined to be beneficial. One conventional mix and three pervious mixes were selected for field evaluation. The field slabs were to be used for field aged structural analysis, field aged permeability, as well as the energy balance determination. Two slabs per mix for statistical evaluation were fabricated, backup in case of slab cracking, and to provide extra material for structural evaluation. To provide the most realistic evaluation, the samples were constructed following the NJDOT specification Section 606- Sidewalks, Driveways, and Islands, and Section 903 Concrete.

Figure 26. Preparation of subgrade and aggregate layer for field slabs

Figure 27. Placement of wooden molds before casting

Figure 28. Rodding and finishing of a porous slab

Figure 29. Completed 4 ft x 4ft x 4 in porous slab

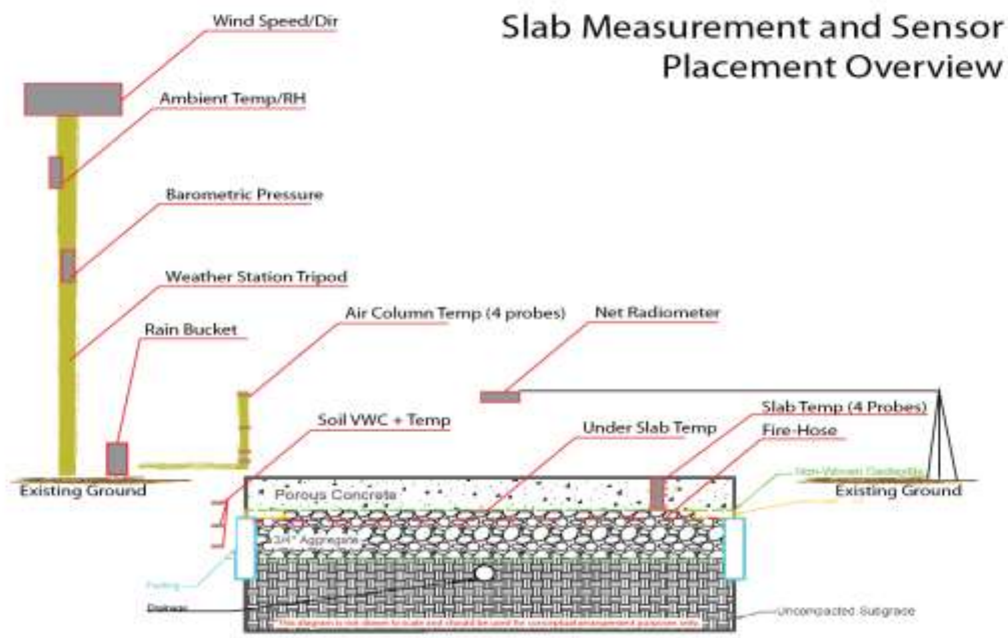

Figure 30. Slab measurement and sensor layout diagram

Results of Field Pervious Concrete Slabs

Albedo and solar radiation flux has been measured on asphalt pavements in earlier study utilizing two techniques, the solar spectrum reflectance measurement test, ASTM C1549, and the Pyranometer test method, ASTM E1918, the latter of which provides better measurements for pavement surfaces and gravel (Tran, 2009). Since the aggregates, mix designs, and climate are different from location to location, it is important to measure the solar radiation and albedo for state specific concrete parameters. This study was particularly designed to utilize a modified ASTM E1918 test with 3ft x 4ft (0.91m x 1.22m) sidewalk samples to evaluate candidate mix designs for pervious concrete mix applicable to New Jersey to determine how they would affect the local energy budget.

Albedo

The calculated albedo for this project ranged from 0.42 for PRC-C(conventional mix) as the most reflective, while PRC-9 (pervious concrete mix) had a measured albedo of 0.18, PRC-7 (pervious concrete mix) had a measured albedo of 0.24, and PRC-3 (pervious concrete mix) had a measured albedo of 0.19. The calculated albedo for each slab with standard deviation is plotted in Figure 31.

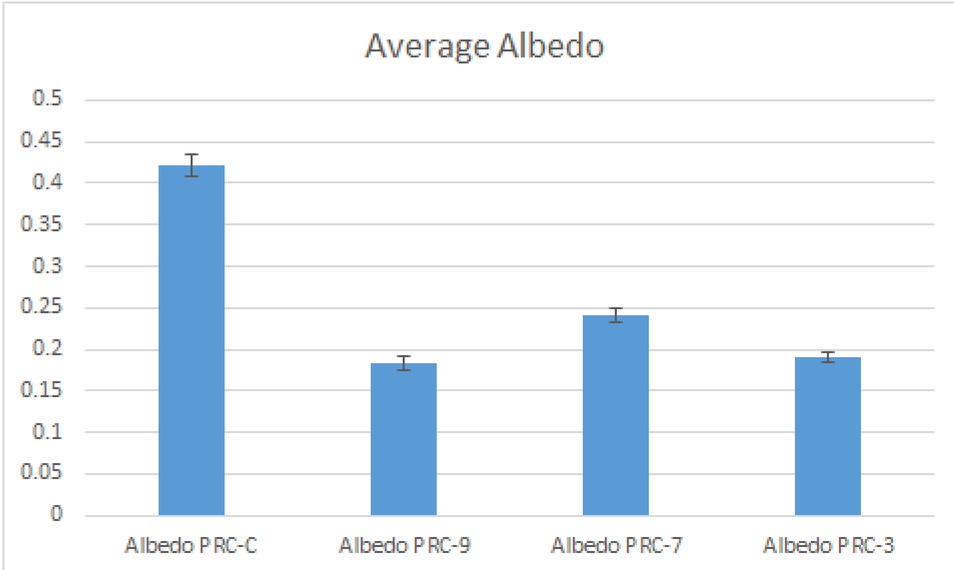

Figure 31. Albedo of conventional and pervious concrete slabs

Although this study of pervious materials was a fairly robust study, due to time constraints the measurement period was only effective between July 18, 2017 and August 22, 2017. It would be preferential to take measurements throughout each season to help create a better annual model. Additional research should be considered for additional pervious concrete mixes with different source aggregates of different color and size. Comparisons between conventional asphalt and concrete mixtures compared to pervious asphalt and concrete mixtures should be conducted. An on-site cloud meter, such as a passive cloud cover detector would help determine sky conditions better than deriving data from offsite. The load cell mass measurement to determine slab mass was a step in the right direction, because all other methods of determining slab moisture content or mass of water held within the slab are fundamentally flawed, but to increase the accuracy and precision of the slab mass calculations, additional research utilizing signal amplifiers and single-shielded extension wire should be utilized. Another approach to studying the energy budget of surface materials would be to experiment inside a controlled chamber to ensure the desired environmental conditions. Better research to determine specific heat and thermal conductivity of both pervious mix, conventional mix, source aggregates, and cementitious material should be conducted as well.

Life Cycle Cost Analysis of Porous Concrete

Basic Procedures

Life-cycle cost analysis (LCCA) is an engineering economic analysis approach evaluates the life-cycle economic efficiency between alternative options that equally satisfies the performance requirements. The purpose of conducting LCCA is to identify the lowest long-term cost among alternatives, providing information for decision making process. It is recommended that LCCA should be conducted as early as possible during the project design stage. The general procedures of conducting pavement LCCA include: 1) establish design alternatives; 2) establish analysis period that is long enough to cover at least on rehabilitation activity; 3) determine the performance life of pavement design alternatives and the timings of subsequent rehabilitation activates; 4) estimate agency costs; 5) estimate user costs; 6) develop expenditure stream diagrams and calculate the net present value; 7) evaluate results and reevaluate design strategies [90].

The net present value (NPV) of agency cost during the analysis period is computed using the discounted monetary value of future costs and salvages by transforming costs occurring in different time periods and salvages at the end of analysis period to a common unit of measurement (Equations 1 and 2).

$$\mathrm{NPV} = \mathrm{C} + \sum_{i=1}^{k} M_i \left(\frac{1}{1+r}\right)^{n_i} - S\left(\frac{1}{1+r}\right)^{N} \quad (1)$$

$$\mathrm{S} = \left(1 - \frac{L_A}{L_E}\right) \times C_s \quad (2)$$

Where, NPV is net present value or net present worth; C is present cost of initial rehabilitation activity; r is discount rate; Mi is cost of the i-th maintenance & rehabilitation (M&R) activity in terms of constant dollars; n_i is number of years from the present to the i-th M & R activity; S is salvage value (or residual value) at the end of the analysis period; L_A is difference between the year of the last maintenance activity and the year of termination of the life cycle analysis; L_E is expected life of the maintenance activity; C_s is cost of the maintenance activity having salvage value; and N is length of the analysis period in years.

The analysis period of this study is 40 years according to the lifespan of each alternative. The FHWA [36] suggests an analysis period of minimum 35 years for all pavement projects, while 30 to 40 years would be considered as a reasonable range[38]. The analysis period should cover at least one major rehabilitation activity for each alternative, while the number of maintenance is not required to be the same. Due to uncertainty of field performance and to avoid the arbitrary selection of life span of different pavement alternatives at sidewalk, sensitivity analysis of life span is considered in LCCA. Reconstruction is assumed when sidewalk pavements reach the end of pavement service life during an analysis period of 40 years. The real discount rate is used in LCCA accounting for fluctuations in both investment interest rates and the rate of inflation. The FHWA Report of Life-Cycle Cost Analysis in Pavement Design [38] indicates that the average real discount rate based on data released by the Office of Management and Budget (OMB) in USA from 1992 to 1998 is approximately 4%.

A study conducted by American Concrete Pavement Association (ACPA) in 2013 showed that 42% of states still used 4% as the real discount rate in transportation related project [93]. In this study, the discount rate used is 1.32% which is based on a 5-year average of the OMB released data from 2013 to 2017.

Design Alternatives

Porous pavement can reduce the negative environmental impact from surface runoff in the urban area. In order to reach the same performance level of storm water management, the impermeable sidewalk pavements with best management practices (BMPs) of storm water are comparable with porous pavement system. The subsurface drainage system is not considered for the sidewalk pavement in this study.
The design alternatives of sidewalk in this study include porous concrete, porous asphalt, and conventional concrete. Table 15 shows the structure design of conventional concrete and asphalt pavement at sidewalk. According to the New Jersey Standard Roadway Construction 2007, the conventional concrete sidewalk required 4-inch thick cement concrete surface with a slope 1/4” per foot.

Table 15 Conventional sidewalk structure design

Conventional Concrete Sidewalk Structure		
Surface Layer	Cement concrete	4”
Subgrade	Compacted earth	N/A

Porous pavement designs at sidewalk considered in the study include pervious concrete and porous asphalt. The reservoir layer of uniformly graded coarse aggregate is placed on soil subgrade with certain drainage requirement. One of the important benefits of porous pavement is the potential to reduce or eliminate the use of underdrain pipes. With the reservoir layer, more rainfall amounts can be temporally stored under the pavement until fully infiltrated into the ground, instead of collecting and discharging surface runoff into the nearby water bodies. The thickness of storage layer depends upon the required runoff storage volume and the typical rainfall amount of the area. The design of porous pavement follows New Jersey Storm Water Best Management Practices Manual - Standard for pervious paving system. Table 16 show the structure design of porous pavement at sidewalk.

Table 16. Porous asphalt and porous concrete structure design for sidewalk

Porous Pavement Structure		Thickness (in)
Surface	Pervious Concrete	4
	Porous Asphalt	4
Bedding	Choker Course -AASHTO No. 57	1
Reservoir Layer	Coarse Aggregate- AASHTO No.2	12
Filter Layer	Non-Woven Geotextile	-
Subgrade	Un-compacted Subgrade	-

Performance Life of Porous Pavement

The performance life of porous pavement is an important parameter in LCCA. Markow et al. [59] conducted a survey to investigate the management of transportation asset including sidewalk. The questionnaires were distributed to state agencies in the U.S. From the total of 35 respondents, the median life expectancy of sidewalk for concrete pavement is 25 years and asphalt pavement is 10 years [59]. At the same time, from the FHWA's Guide for Maintaining Pedestrian Facilities for Enhanced Safety [47], 25 years lifespan is considered for concrete sidewalk by many cities, while 80 years and 40 years life span are achievable for concrete and asphalt sidewalk if best practices are followed. The city of New York [31] collected information from different agencies and estimated that the life span of concrete sidewalk varies from 13 to 50 years. The City of Olympia, WA [31], designed porous concrete for bicycle and pedestrian traffic with 30 years lifespan. The durability of porous pavement has a wide range from literature review. Evidences show that porous pavements tend to be freeze-thaw resistant in cold weather, resulting in a longer service life in northern region [86]. FWHA suggests that an expected life span of 15 to 20 years if porous pavement is properly designed, constructed, and maintained. A report developed by the Low Impact Development Center [56] and EPA assumed a lifespan of 25 years for permeable pavement. After 25 years' service, it would be removed and reconstructed. In practice, several porous concrete pavements in North Carolina and Tennessee have been in service for more than 10 years [86].

It is noted that porous asphalt pavement has been used in travel lanes with heavy traffic, especially in Europe and Japan, In these cases, high-quality asphalt binder is required and laboratory performance testing is usually used to select the optimum mixt design, From a national survey conducted to assess the performance of open-graded friction course (OGFC) mixes in 2000, the average life of OGFC in the four states of Arizona, Georgia, California and Wyoming was 8.5 years as compared to an average life of 15 years of dense-graded mixture. The study summarized that open-graded mixtures in the North American had a life that is about one-half of that for dense-graded mixtures [46].

Cost Data from NJ Bid Reports

The primary data source is from New Jersey Department of Transportation Capital Contracts Bid Price History from 2013 to 2015. The summary of extracted cost data is listed in Table 17, including the bid item, the average, minimum, and maximum unit price for the related items. Figure 32 shows the box plots of the distribution of unit bid prices for conventional concrete sidewalk, porous concrete sidewalk, asphalt sidewalk, and porous asphalt sidewalk, respectively. The box plots graphically describe the data through five statistical indexes: the minimum sample value, the lower quartile, the median, the upper quartile, and the maximum sample value.

Table 17. Cost Data from NJ Bid Report 2013-2015 ($/square yard)

ITEM	AVR. UNIT PRICE	MIN	MAX
CONCRETE SIDEWALK, 4" THICK	93	32	300
CONCRETE SIDEWALK, 4" THICK, TEXTURED	90	90	90
TINTED CONCRETE SIDEWALK, 4" THICK	75	75	75
CONCRETE SIDEWALK, 5" THICK	120	120	120
CONCRETE SIDEWALK, 6" THICK	65	63	67
CONCRETE SIDEWALK, 8" THICK	123	50	210
CONCRETE SIDEWALK, REINFORCED, 6" THICK	111	72	150
CONCRETE SIDEWALK, REINFORCED, 8" THICK	180	180	180
PERVIOUS CONCRETE SIDEWALK	131	105	180
HOT MIX ASPHALT SIDEWALK, 2" THICK	59	52	75
HOT MIX ASPHALT SIDEWALK, 5" THICK	40	40	40
HOT MIX ASPHALT SIDEWALK, 5 1/2" THICK	39	35	42
NONVEGETATIVE SURFACE, POROUS HMA	38	23	64
NONVEG, POROUS HMA WITH BROKEN STONE	55	55	55
NONVEGETATIVE SURFACE, POROUS RESIN 2"	79	40	152

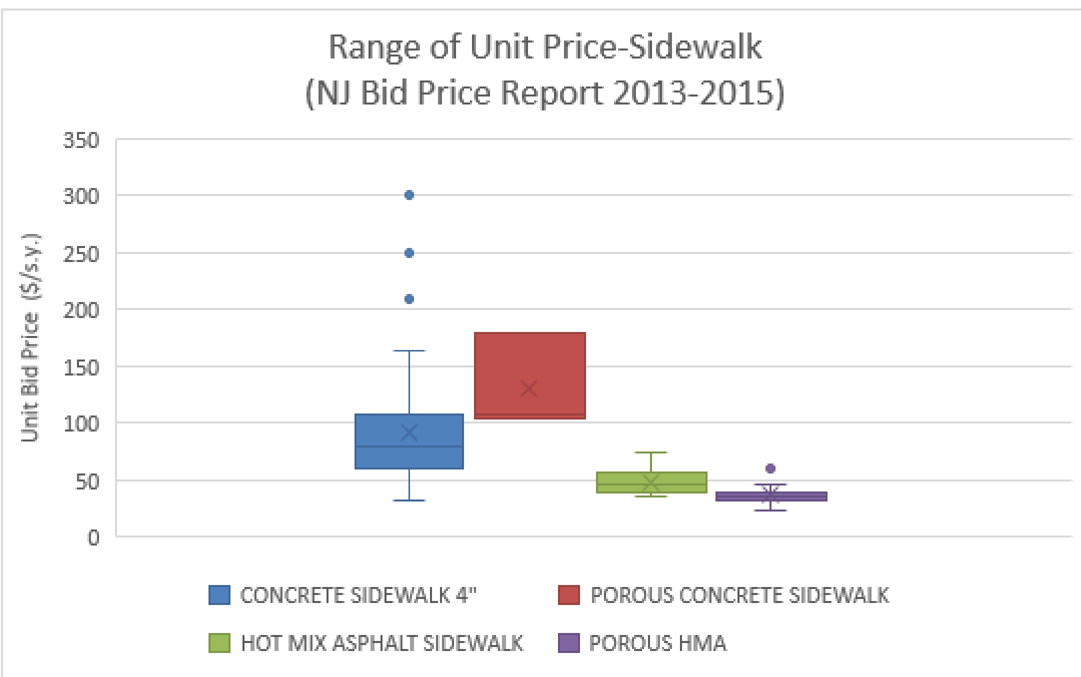

Figure 32. Range of Sidewalk unit price from NJ Bid Price Report (2013-2015)

The bid price reports include three pervious concrete sidewalk projects in the three years. The average bid price is $131 per square yard, and the price ranges from $105 to $180 per square yard (Refer to Appendix B for more information on these projects). The bid price data included about 90 conventional concrete sidewalk projects, in which the concrete layer thickness varies from 4 to 8 inches. A large variation of unit price data was observed. The bid price reports also include 31 porous asphalt projects, and the average price ranges from $38 to $79 per square yard. The results show that in general the price of concrete sidewalk is higher than asphalt sidewalk.
Figure 33 shows the variation of unit price with the quantity of construction for the conventional concrete sidewalk. It shows that large quantity of concrete sidewalk has relatively lower unit bid price around $50; but most projects have small quantity (less than 5000 square yards) and the unit bid price varies from $32 to $300. This implies that the bid quantity helps to explain part of the variation in the unit bid price. Other factors contribute to the variation of unit bid price might include locations of projects, sites conditions, mobilization cost, engineering designs, and contingency cost.

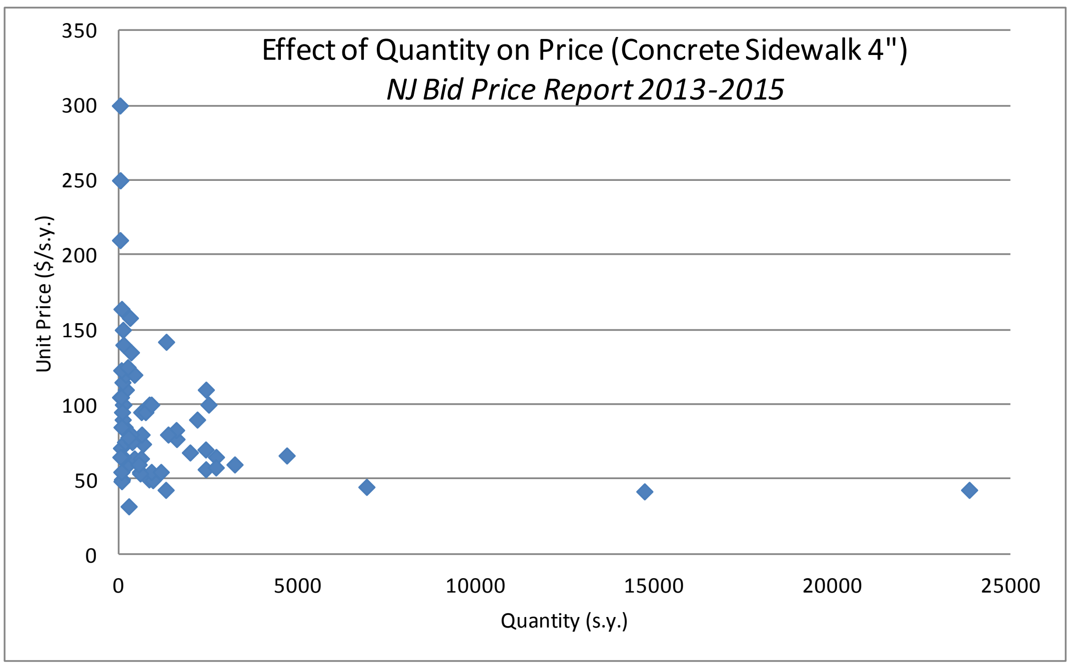

Figure 33. Effect of quantity on bid price of 4 in concrete sidewalk

Cost Data from Literature Review

Since pervious concrete sidewalk construction cost data from New Jersey bid price reports are limited to three projects, porous concrete cost from literature review is included in this study to better represent the average unit cost. Cost data from literature covers practices from 10 cities and 7 states including Florida, Philadelphia, Oregon, Washington, California, Wisconsin, New York City, and Virginia. Construction projects include using pervious concrete and porous asphalt on highway shoulder, light traffic residential street, sidewalk, bicycle lanes, and driveway. The construction costs range from $90 to $140 per square yard. The costs of maintenance activities including vacuum sweeping and pressure range from $0.09 to $3.69 per square yard per year. The average initial construction cost of porous concrete from literature review has an average of $103 per square yard. The detailed cost summary from literature review is shown in Table 18.

Table 18. Cost data from Literature Review

location	Component	Initial Construction Cost	source
Philadelphia, PA	Permeable Asphalt (Light Traffic)	$110 / sq. yard	Roadmap in NYC: Information in this case study was obtained in an April 5, 2012, interview with Peter Reilly, Civil Engineer at the Philadelphia Water Department.
Olympia, WA	Permeable Concrete Bicycle lanes & Sidewalk	Bike lane: $140 / sq. yard Sidewalk: $92.25 / sq. yard	Craig Tosomeen, P.E., Pervious Concrete Bicycle Lanes, City of Olympia, Public Works Water Resources, 2006
City of New York, NY	Porous Concrete	$78.03/sq. yard	NYC 2030 Sustainable Stormwater Management Plan Accessed March 2009
NC	Porous Concrete	$104.4/sq. yard	North Carolina Green Building Technology Database
Edison, NJ	Porous Concrete	$71.21/ sq. yard $60.75/ sq. yard	2009 EPA study Permeable Pavement Research – Edison New Jersey, Amy Rowe EPA National Risk Management Research Laboratory
Edison, NJ	Porous Asphalt	$48.4/ sq. yard $31/ sq. yard	2009 EPA study Permeable Pavement Research –Edison New Jersey, Amy Rowe EPA National Risk Management Research Laboratory Final proposed costs reported by Kirit Shaw, S Services, Inc, June 2009 (2)
City of Portland, OR	Porous Asphalt	$57.06/sq. yard	City of Portland, Bureau of Environmental Services,Willamette Watershed Program - Task Memorandum 4.1 August 2005
VA	Permeable Pavement-Pavers	$63.9 /sq. yard	Wetland Studies and Solutions, Inc; Virginia LID at WSSI 2007 [94]
-	Porous Asphalt	$61.2/sq. yard	http://www.3riverswetweather.org/green/green-solution-porous-pavement
-	Porous Concrete	$83.25/ sq. yard	http://www.3riverswetweather.org/green/green-solution-porous-pavement

Cost Data of Storm Water BMP's

The design of the storm water best management practices (BMP's) is based on New Jersey BMP calculator and Annual Groundwater Recharge Spreadsheet Version 2.0. The assumptions include the construction of one mile impervious sidewalk in Middlesex County is on a woods-grass combination land cover area. The average annual precipitation of 44.9 inches and the climatic factor of 1.43 are used to estimate the ground water recharge volume. After running the analysis, the results show that the post-development annual recharge deficit or the desired recharge volume is around 20,419 cubic feet, which is the annual BMP recharge volume. The BMP volume is about 313 cubic feet, with an area of 157 square feet and an effective depth of 24 inches. Table 19 shows the cost of construction and maintenance cost of BMPs from EPA Preliminary Data Summary of Urban Storm Water Best Management Practices (34,92). In order to understand the contribution of BMPs to the total life cycle cost of impermeable pavement, Delaware sand filter that has the highest cost among BMPs is selected. However, the real choice of type of BMPs depends on the specific field condition and project requirement. The construction cost is based on calculation of water quality volume. According to New Jersey Storm Water Management Manual, the water quality volume of one mile impermeable sidewalk is 1,821 cubic feet, which equals to 51.54 cubic meters. The detailed calculation of the storm water quality volume is shown in Hydrologic design section.

Table 19. Construction and maintenance costs of storm water BMPs (34)

BMP Type	Construction Cost Equation ($)	Annual Maintenance Cost (% of Construction Cost)
Retention Basins and Wetlands	7.75V^0.75	3-6%
Retention Basins	1.06 V	3-6%
Infiltration Trenches	$33.7V^{0.62}$	5-20%
Sand Filter	4V	11-13%
Bio-retention	5.3V*	5-7%
* V for total basin volume in cubic feet.		

Table 19 compares the calculated costs of different storm water BMPs using EPA equations to the costs obtained from other three sources, including the original dataset of pilot study in California, the data used by Maryland State Highway Administration, and the nationwide data. The national wide cost data is collected from a survey with five responses of raw data. It was found that the California pilot study had the highest initial construction cost of different BMPs, which was due to the relatively smaller project sizes with the smaller water quality treatment volumes compared to projects with the larger water volumes nationwide (25). At the same time, the national wide survey data, the data used by Maryland State Highway Administration, and the EPA's cost estimation are similar. Since the cost data from California pilot study might better be applied to estimate BMPs projects in California, the EPA's cost estimation is used for BMPs in this study.

Table 20. Comparison of unit cost of BMPs in 1999 dollars

BMP	Pilot study in California ($/m^3)	Nationwide survey ($/m^3)	Maryland State Highway Administration ($/m^3)	EPA equation ($/m^3)
Austin sand filter	74578	4226	1691	7760
Delaware sand filter	98544	10308	-	11398
Extended detention basin	30409	271	947	611
Infiltration trench	37779	2371	592	660-4400
Biofiltration swale	38758	457	-	-
Wet pond	89216	389	474	537-969
Wetland	-	237	203	537-969
Storm-filter	81021	979	-	-

Analysis Results

In this section, LCCA results were discussed without considering under drainage system for both conventional and porous pavement for sidewalk construction. Table 20 lists the initial construction and maintenance cost of conventional concrete and porous pavements for one-mile sidewalk. The average unit price for conventional concrete is based on NJ bid price, but the unit prices used for porous pavement are the mean values from the combination of literature data and NJ bid report due to the limited number of porous sidewalk projects in NJ bid reports. For storm water BMPs, Delaware sand filter that has the highest cost among BMPs is selected to understand the contribution of BMPs to life cycle cost of impermeable pavement sidewalk. It was found that the cost of BMP construction was about 6% of the initial construction cost of traditional concrete sidewalk. Porous concrete sidewalk has slightly higher initial construction cost than conventional concrete sidewalk, but porous asphalt has the lowest initial construction cost which is about 65% of conventional concrete sidewalk. The annual maintenance of porous pavement and BMPs are based on the cost equations of EPA Preliminary Data Summary of Storm Water Best Management Practices [34].

Table 21. Construction and maintenance cost for one-mile sidewalk

Initial Construction Cost (1-mile Sidewalk)	Avg. Unit Price (per s.q. yard)	Total Cost
Conventional Concrete	$93	$217,794
Porous Concrete	$102	$240,042
Porous Asphalt	$62	$144,397
Porous Pavement Annual Maintenance	-	$202/year
BMP Construction	-	$13,335
BMP Annual Maintenance	-	$1,368/year

From literature review, the lifespan of porous concrete sidewalk was found varying from 15 to 30 years, although the shorter life was observed at some locations. Thus, to avoid the arbitrary selection of lifespan of sidewalk for different pavement alternatives, sensitivity analysis is conducted by changing the lifespan assumptions of pavement at sidewalk.

Figure 34 shows the cost differences between porous concrete sidewalk and conventional concrete sidewalk based on 40-year life cycle cost analysis. The lifespan of conventional concrete sidewalk are fixed (15, 25, and 35 year); while the lifespan of porous concrete sidewalk varies in a wide range. When the service life of conventional concrete is 15 years, porous concrete sidewalk is required to have approximately the same lifespan as impervious concrete to have the same life-cycle cost. As the service life of conventional concrete become longer, the durability of porous concrete need to be extended accordingly to be economically competitive. For example, when the service life of conventional concrete sidewalk reach 35 years, porous concrete pavement need to be about 30 years to reach the breakeven point. This is because the saving of annual maintenance cost of storm water BMPs becomes more significant as compared to the increased reconstruction cost of pervious concrete at the end of its service life.

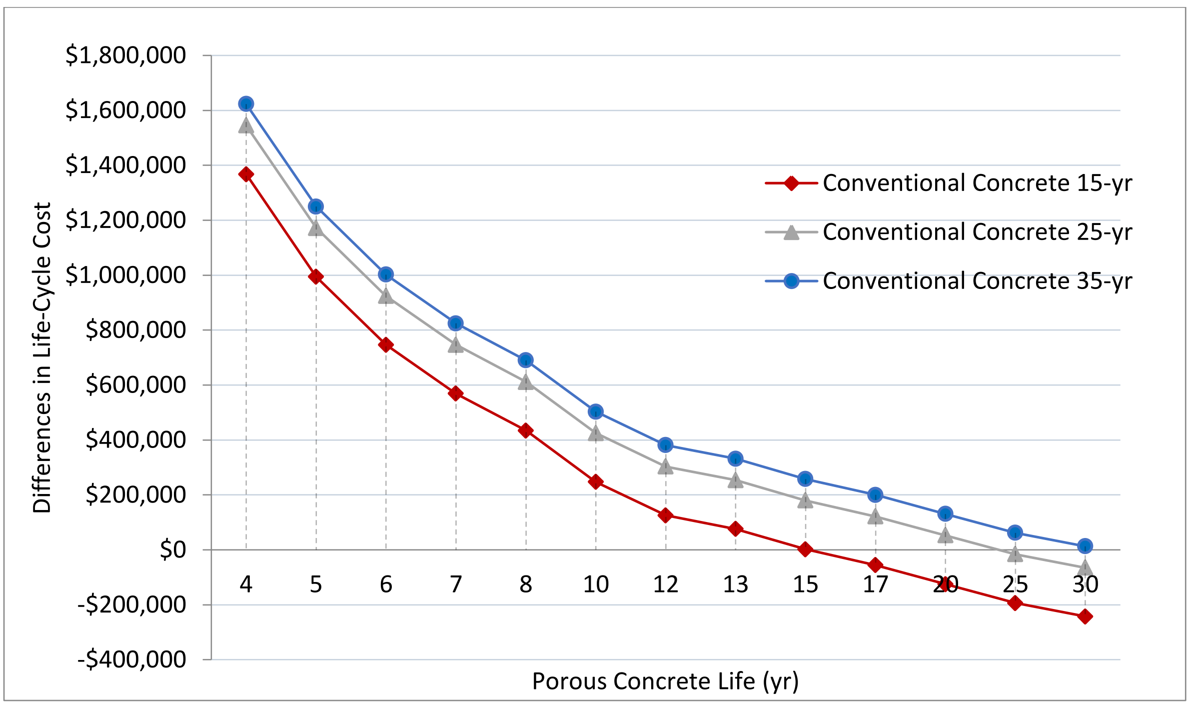

Figure 34. Cost differences between porous and conventional concrete Sidewalk

Figure 35 shows the cost differences between porous asphalt sidewalk and conventional concrete sidewalk based on 40-year life cycle cost analysis. When the service life of conventional concrete sidewalk is 15 years, porous asphalt sidewalk has smaller life cycle cost if it has a service life longer than 9 years. If the service life of conventional concrete sidewalk reach 25 years and 35 years, the breakeven points of the lifespan of porous asphalt is 13 years and 17 years, respectively. This is because the significant saving of initial construction cost for porous asphalt.

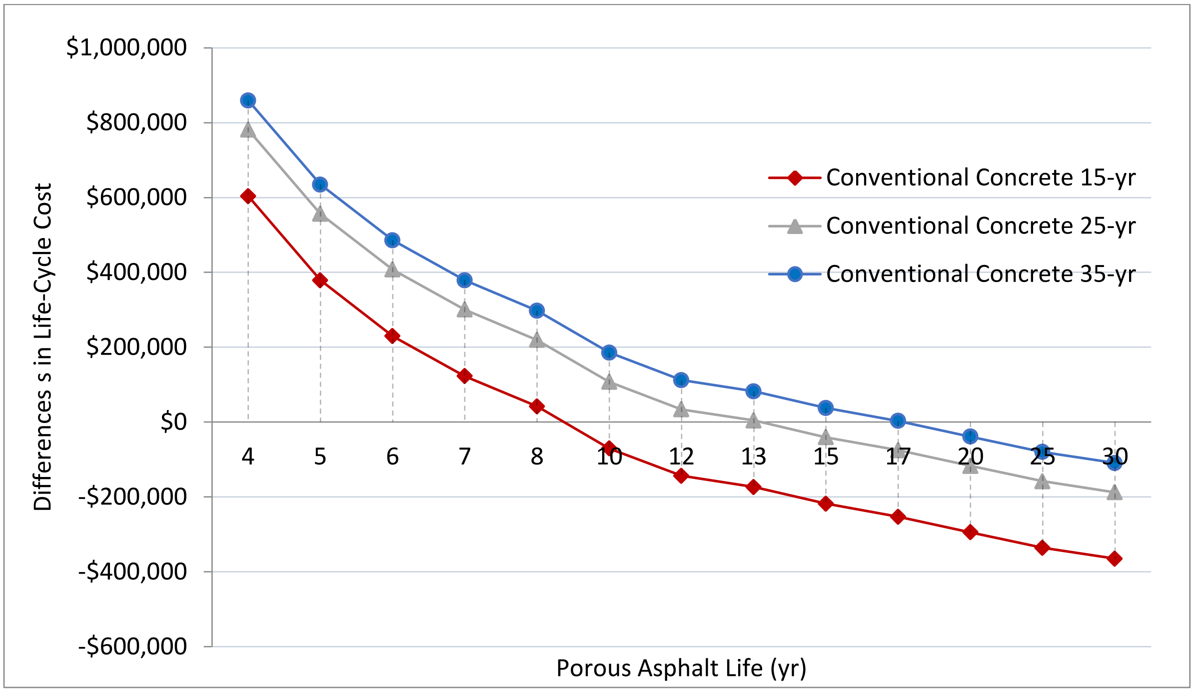

Figure 35. Cost difference between porous asphalt and conventional concrete sidewalk

Figure 36 shows an example of 40-yr life-cycle cost analysis for conventional concrete, porous asphalt, and porous concrete sidewalk. The lifespan of conventional concrete sidewalk is assumed 25 years; while the lifespans of porous asphalt sidewalk and pervious concrete sidewalk are assumed 15 years. The selection of service life does not reflect the real life in practice, but illustrates the comparison between design alternatives with different cost components. In this case, porous asphalt is the option with the lowest life cycle cost; while pervious concrete option has the highest life cycle cost. The distribution of cost components indicates that the service life of sidewalk pavement and the corresponding reconstruction cost contributes significantly to the total life cycle cost.

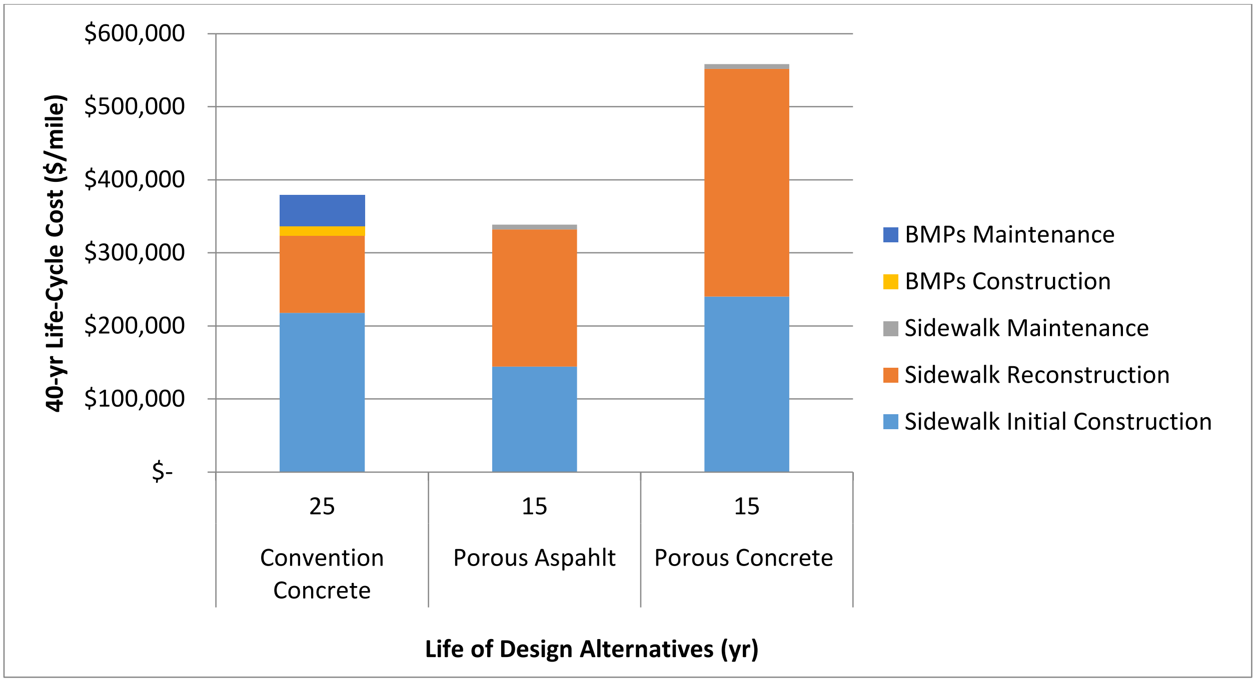

Figure 36. Life cycle cost for conventional concrete (25-yr life), porous asphalt (15-yr life) and porous concrete (15-yr life) sidewalk

Hydrologic Design of Porous Pavement

This section discusses the hydraulic design of porous pavement and its benefit in the removal of excessive storm water. The design of drainage system and the depth of reservoir layer underneath porous pavement surface depend on different storm events and the infiltration rate of soil that is the most hydraulically restrictive layer in the porous paving system. The typical permeability of each layer in the porous pavement system is shown in Table 22 .The ideal practice of porous pavement should retains and infiltrates 100% of captured runoff, which means no accumulated water on the surface. However, extreme heavy storm events or low infiltration rates of soil underneath might lead to spilling effect (surface runoff) if the water infiltration rate is beyond the drainage capacity of the designed porous pavement system.

In this section, the runoff curve number method developed by USDA Natural Resources Conservation Service (NRCS) is used to calculate the total runoff volume of porous pavement at different storm events. The NRCS method uses empirical equations to calculate the direct runoff volume from rainfall events. The most important component of the NRCS method is the Curve Number (CN), which is related to soil type and infiltration rate, land use cover, moisture, and the depth of water table. To fully comply with the NJDEP Stormwater Management Rules, quality design storm is used to analyze and design BMPs or structural stormwater quality measures. The quality design storm has 1.25 inches rainfall depth in 2 hours with a nonlinear accumulative rain fall pattern. The following steps follow the NJDEP Stormwater Management Rules [71].

Table 22. Typical permeability of each layer in the porous system

Layer	Description	Permeability (in./hr)	References
Porous Concrete Surface	19 mixture designs	18 - 90	Testing Samples from Rutgers Research Team
Choker Course	(AASHTO No. 57 – NJDOT Specification 901.03)	10000	Cedergren et al., (28)
Reservoir bed	(AASHTO No. 2 – NJDOT Specification 901.03)	60000	Cedergren et al., (28)
Geotextile	Non-woven AASHTO M288 Class 2 (NJDOT Specification 919.01)	k(fabric)>= k(Soil)	Huang (44)
hydrologic soil group permeability (Min Infiltration Rate)	A B C D	0.3 0.45 0.15 0.3 0.05 0.15 0 0.05	McCuen (62)

Step 1 Runoff calculations for quality design storm

As described in *New Jersey Stormwater Best Management Practices Manual (*NJ_SWBMP), the quality design storm of 1.25 inches in 2 hours is used to analyze and design structural stormwater quality measures.

Although the porous concrete pavement system retains and infiltrates 100% of captured runoff, it is assumed that the surface is impermeable in order to estimate the volume of rainfall collected by the system. So a CN of 98 will be assigned to the porous concrete surface. Using the NRCS methodology described in chapter 5 of NJ_SWBMP - *Computing Stormwater Runoff Rates and Volumes*, the water quality design storm runoff volumes were calculated as shown below:

Total drainage area=one mile sidewalk with 4 feet wide=21,120 square feet

Average surface runoff S = $\frac{1000}{CN} - 10 = 1000/98 - 10 = 0.204 \text{ inches}$

Average initial abstraction Ia=0.2S=0.2*0.204=0.041 inches

Runoff volume $Q = \frac{(P-0.2S)^2}{P-Ia+S} = \frac{(1.25-0.2*0.204)^2}{1.25-0.041+0.204} = 1.035 \text{ inches}$

Total Runoff Volume = $\frac{1.035\ in}{12\frac{in}{ft}} * 21120\ sf = 1820.847\ cubic\ feet$

Step 2 Storage volume and reservoir depth

a) Determine the maximum allowable reservoir depth

The storage bed under porous concrete surface is filled with AASHTO No.2 coarse aggregate with 40 percent air void. Assuming the sub-grade soil is extremely impermeable, the maximum allowable reservoir depth to manage the total runoff volume caused by the Quality Design Storm for the area is determined. The maximum reservoir depth for water quality storm runoff volume depends on runoff volume, percent of air void in reservoir layer, and storage bed area. Using the same method, the maximum reservoir depth corresponding to 1-year storm to 100-year storm event in 24 hours is determined. Table 23 shows the maximum reservoir depths at different storm events. The maximum reservoir depth is 2.59 inches for quality design storm and 21 inches for 100 year storm event, respectively.

$$\text{Maximum storage bed depth } = \frac{\text{water quality design storm runoff volume}}{\%voids * storage\ bed\ area}$$

$$= \frac{1821 \text{ cf}}{40\% * 21120 \text{ sf}/12\text{in}/\text{ft}} = 2.59 \text{ inches}$$

Table 23. Calculation of maximum allowable reservoir depth

Storm Events	Return Period (yr)	Duration (hr)	Rainfall Depth (in)	Total Runoff Volume(cf)	Maximum Reservoir Depth (in)
Quality Design Storm	-	2	1.25	1821	2.59
Middlesex County 24 hr. Rainfall Frequency Data	1	24	2.76	4452	6.32
	2	24	3.35	5486	7.79
	5	24	4.30	7153	10.16
	10	24	5.12	8594	12.21
	25	24	6.36	10774	15.30
	50	24	7.43	12655	17.98
	100	24	8.63	14766	20.97

b) Determine the minimum reservoir depth

However, except extreme clayey soil, the subgrade soil has different infiltration rates and helps to absorb runoff penetrated the surface course of porous concrete. To account for different permeability of soils, Natural Resources Conservation Service (NRCS) has divided soils into four hydrologic soil groups (HSGs). The minimum infiltration rate ranges from 0.3 to 0.45 inch/hour for type A soil, 0.15 to 0.3 inch/hour for type B soil, from 0.05 to 0.15 inch/mile for type C soil, and from 0 to 0.05 inch/hour for type D soil, respectively. The minimum reservoir depth is affected by runoff volume, percent of air void in reservoir layer, storage bed area, soil permeability, and storm duration. The following equations show the relationship between the parameters and the minimum reservoir depth. Table 24 shows the calculation results of four minimum reservoir depths for different infiltration rates of soil type A, B, C, and D. For example, soil type A refers to sandy soil that has highest infiltration rate resulting in 1.09 inches reservoir depth to manage quality design storm.

$$Min\ Reservoir\ Dept = \frac{Runoff\ Volume - soil\ Permeability * Area * Storm\ duration}{\%void * storage\ bed\ area}$$

$$= \frac{2253\ cf - \frac{0.375in}{hr} * \frac{\frac{21120sf}{12in}}{ft} * 2hr}{40\% * 21120\ sf/12in/ft} = 1.33\ inches$$

Table 24. Calculation of minimum reservoir depth under quality design storm

	Description	Duration (hr)	Rainfall Depth (in)	Total Runoff Volume (cf)	Max Reservoir Depth(in)	Min Reservoir Depth
Quality Design Storm	-	2	1.50	2253	2.59	
Hydrologic Soil Groups	A: Sand, loamy sand, sandy loam					1.09
	B: Silt loam or loam					1.84
	C: Sandy clay loam					2.34
	D: Clay loam, sandy clay, or clay					2.59

Step 3 Determine Drain Time and Use of Under Drain System

It is expected that subgrade soil is the most hydraulically restrictive layer in the permeable pavement system, which determines drainage time of different storm evens. For water quality design storm of 1.25 inches in 2 hours, the drain time ranges from 2 to 21 hours depending on soil type A, B, C, and D. According to NJ_SWBMP manual, the maximum drain time of permeable paving system is 72 hours, failing to meet the requirement may render the system infective. The reservoir layer should allow enough storage for the next rain event, and standing water may cause anaerobic conditions, odor, water quality and mosquito breeding problems. For the clay type soil, the drain time is estimated to exceed 72 hours, where drainage system is needed as the corrective action.

$$Drain\ Time = \frac{Water\ Quality\ Storm\ Runoff\ Volume}{Surface\ Area * Subsoil\ Permeability\ Rate} = \frac{2253\ cf}{21120sf * \left(\frac{1}{12}\right) * 0.3in/hr}$$

$$= 2.30\ hours$$

Table 25. Drain time for different Hydrological soil groups

Hydrologic Soil Groups	Soil Textures	Permeability (in/hr.)	Drain Time (hr.)	Use of Drainage
A	Sand, loamy sand, sandy loam	0.3-0.45	2 - 3	
B	Silt loam or loam	0.15-0.3	3 - 7	
C	Sandy clay loam	0.05-0.15	7 - 21	
D	Clay loam, sandy clay, or clay	0-0.05	> 21	√

Step 5 Reduced Curve Number

The reduced CN can be used to analyze the runoff volume for permeable paving surface, which is one of the indicators that quantify the potential benefit of porous paving system. The direct runoff leaving the permeable concrete surface is reduced by the runoff volume retained in the reservoir depth. Assuming the permeable paving system is designed to manage quality design storm, the retention volume of permeable paving system is equal to the direct runoff volume on impermeable surface. For porous pavement, there is no runoff volume leaving the paving surface which means rainfall will not accumulate on the permeable surface. For impermeable surface, the curve number is 98. After changing to permeable surface, the CN reduced to 65.

A NRCS curve number is related to soil type and infiltration rate, land use types, and depth of water table. For example, grass land in a fair hydrologic condition could be one of the land covers that get a CN of 65. By assuming that the maximum retention volume of permeable paving system is equal to quality design storm of 1821 cubic feet, a reduced CN of 90 can be obtained for 2-year returning storm, and a reduced CN of 91 for 50- year and 100-year returning storm, compared to CN of 98 for impermeable surface. CN values are shown in Table 26.

Table 26. Reduced CN at different storm events

Storm Event	Rainfall (in)	Direct Runoff Volume without Pervious Paving (cf)	Retention Volume (cf)	Runoff Volume Leaving Pervious Paving (cf)	Reduced Direct Runoff (in)	Reduced CN
Quality Design Storm	1.25	1821	1821	0	0	65
2-year	3.35	5486	1821	3665	2.31	90
50-year	7.43	12655	1821	10835	6.39	91
100-year	8.63	14766	1821	12945	7.59	91

NJDEP Requirements for Pervious Concrete

NJDEP Stormwater Best Management Practices Manual

The Stormwater Management Rules [(71)], N.J.A.C. 7:8 specify stormwater management standards that are mandatory for new major development. The New Jersey Stormwater Best Management Practices Manual (BMP manual) is developed to provide guidance to address the standards in the Stormwater Management Rules, N.J.A.C. 7:8. The BMP Manual is a developed by the New Jersey Department of Environmental Protection, in coordination with the New Jersey Department of Agriculture, the New Jersey Department of Community Affairs, the New Jersey Department of Transportation, municipal engineers, county engineers, consulting firms, contractors, and environmental organizations.

NJAC 7:8 requires runoff be addressed in one of three ways:

i. Demonstrate through hydrologic and hydraulic analysis that for stormwater leaving the site, post-construction runoff hydrographs for the 2-, 10- and 100-year storm events do not exceed, at any point in time, the pre-construction runoff hydrographs for the same storm events;
ii. Demonstrate through hydrologic and hydraulic analysis that there is no increase, as compared to the pre-construction condition, in the peak runoff rates of stormwater leaving the site for the 2-, 10- and 100-year storm events and that the increased volume or change in timing of stormwater runoff will not increase flood damage at or downstream of the site. This analysis shall include the analysis of impacts of existing land uses and projected land uses assuming full development under existing zoning and land use ordinances in the drainage area; or
iii. Design stormwater management measures so that the post-construction peak runoff rates for the 2-, 10- and 100-year storm events are 50, 75 and 80 percent, respectively, of the preconstruction peak runoff rates. The percentages apply only to the post-construction stormwater runoff that is attributable to the portion of the site on which the proposed development or project is to be constructed.

To fully comply with the NJDEP Stormwater Management Rules, stormwater runoff must be computed for three types of rainfall or storm events. These storms are associated with : 1) groundwater recharge, 2) stormwater quality, and 3) stormwater quantity .The latest update to the BMP revises Chapter 9, which provides general information on Structural Stormwater Management measures. Subchapter 9.7 addresses Pervious Paving Systems.

Chapter 9.7 Pervious Paving Systems

General Notes

- Pervious pavement is considered a stormwater management facility under NJDEP regulations.
- The system includes the pervious (porous) surface course, transition (intermediate) layer and a storage-bed layer of open-graded aggregate.
- BMP recognizes two pervious pavement systems (1) includes underdrain piping or (2) designed to infiltrate into the subsoil. Each comes with its own set of requirements.
- The BMP considers three types of surface courses: (1) porous asphalt, (2) porous concrete or (3) permeable interlocking paving units. Each also comes with its own set of requirements.
- The BMP primarily deals with closed developments and does not directly address linear development (roads, walkways, or bikeways).
- The document includes an in-depth section for designing pervious pavements.

Design Criteria

- Nonstructural stormwater management strategies design standard in the SWM rules must be addressed for all major development, pursuant to NJAC 7:8-5.3(a).
- Must be designed to meet the soil erosion and sediment control standards in NJ
    - Inflow to pervious pavement
- May be designed to meet Groundwater Recharge (Ch. 6)
- Must not be used where their installation would result in adverse hydraulic impacts such as exacerbating a naturally or seasonally high water table (resulting in surface ponding).
- Pretreatment only applies for vehicular surfaces. However, must minimize sediment and particulates in runoff by installing gutter guards, sumps and traps with maintenance access points in the conduits of the storage beds (where underdrain is planned)
- The minimum tested infiltration rate of any of these surfaces to be considered porous is 6.4 inches/hour. A system designed for quantity control must have a minimum infiltration rate of the surface course of 20 inches per hour.
- The BMP requires the treatment of the entire Water Quality Design Storm volume without overflow; Total Suspended Solid (TSS) removal rate of 80%.
- For stormwater quantity control, storage times in excess of 72 hours are not allowed.
- For systems designed for stormwater quantity control, emergency overflow catchments must be provided to direct surface runoff in excess of that generated by the maximum design storm.

- Where an outlet structure is included in the pervious pavement system, the effective opening of the outlet must be calculated as if it is partially obstructed by the rock screen and stone of the storage bed.
- Effects of tailwater must be analyzed for instances where the lowest outlet in the system is flooded by design flood or tide elevation.

Construction Requirements

- Must not construct during rain or snow, or when the subsoil is frozen
- Proposed area of pervious pavement must be kept free from sediment during the entire construction
- Excavation to the final design elevation of the storage bed must only occur after all construction within its drainage area is completed and the drainage area is stabilized. This prevents soil migration into pervious pavement system during its construction

Other Considerations

Soil characteristics

- County soil surveys may be used to obtain necessary soil data for planning.
- Site-specific soil testing is required for final design and construction.
- Soil testing should be compared with preliminary soil data used to calculate runoff rates and volumes and to design BMPs on-site to ensure reasonable data consistency.

Geology

- Karst topography, which is characterized by highly soluble bedrock is susceptible to infiltration of runoff that may lead to subsidence and sinkholes. Only use pervious pavements with underdrains in these areas.

Surface Course

- In order to minimize possibility of edge collapse, use of edge restraints in the design is strongly recommended. Edge restraints can be depressed curb, paver block, staking or strip edging.
- Vehicular intrusion deterrents such as planted shrubs, wheel stops and bollards are also recommended.
- Where pervious pavement is adjacent to traditional pavement, a full-depth dividing strip between the different pavements may be necessary to ensure that structural integrity is maintained and to prevent inadvertent saturation of the adjacent impervious pavement surface course
- Strongly recommends covering the pervious pavement with plastic film and held in place with timber until any adjacent landscaping is complete to discourage

traffic, vehicular access or storage of landscaping materials on the surface course.

- Clogged surfaces can be restored by use of high efficiency cyclone machines or other emerging technology (need to identify), which restores the infiltration capabilities. This should be included in the corrective maintenance measures portion of the maintenance plan.

Cold weather

- Locating pervious pavement in an area that receives full sun during the winter months may greatly reduce the need for de-icers.
- When using de-icing chemicals, take into consideration that some of the volume of commercially available products may contain magnesium or other damaging compounds without being declared in the product packaging. (Can we identify the damaging compounds to be avoided?)
- Strongly recommend the use of a silane based sealant as additional protection from chemical degradation by de-icing compounds as long as the sealant does not impair the rate of infiltration of the surface course.

Landscaping

- Where runoff cannot be redirected away from pervious pavement, a gravel strip or swale should be provided to filter and reduce intrusion from sediment.
- Use care in selecting the top dressing of surrounding vegetated areas. Particulates can be transported by wind or rain/snow, which could clog the surface course.

Maintenance plan

- This document requires a maintenance plan for all stormwater management facilities, including pervious pavement, on a major development.
- Pursuant to NJAC 7:8-5.8, there are a number of required elements in all maintenance plans in addition to the manufacturer's maintenance requirements. Covered in chapter 8 of the BMP. The document provides various key maintenance practices.

More details on the NJDEP requirements for porous concrete and porous asphalt are provided in the Guide Document for the Use of Pervious Concrete for Sidewalks

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The focus of this study was to evaluate mechanical properties and hydrological properties of various pervious concrete mix designs as well as life cycle cost analysis for use in sidewalks in New Jersey. Several mix designs were selected based on existing specifications and supplier's mix design, and modifications of them. The variables were cement content, aggregate content, water-to-cement ratio, the presence of sand, fly ash, or slag, and admixtures. Based on the results of this study the following conclusions can be presented.

Mechanical and Hydrological Properties

1. *Workability*: mixes PRC-10 and PRC-11 were the most workable mixes as expected. During both the mixing and placement process, mixes PRC-10 and PRC-11 exhibited appropriate consistency and the mixes were easy to work with. The round geometry of the gravel aggregates may have contributed to the good workability. The mix also hydrated well during placement showing no sign of bleeding with enough time or placement before it starts to set. PRC-1, PRC-2, PRC-3 and PRC-6 were also had acceptable workability but not as much as PRC-10 and PRC-11. Mix PRC-7 was drier and less workable, most likely due to the low cementitious material to water ratio in the mix design, although the mix performed decently over all. The addition of Viscosity Modifying Admixture in PRC-5 improved the workability of the mix.
2. *Placement and finishing:* care must be taken when placing pervious concrete in molds so as to avoid over-compaction which would alter its properties. The top surface of specimens (cylinders, prisms, and beams) needs to be carefully levelled to ensure uniform application of loads and avoid inconsistencies in testing data.
3. *Vibration*: There are no ASTM guidelines on vibrating of pervious concrete lab specimens or whether they should be vibrated. In this study, gentle rodding was used in two layers just enough to have uniform distribution to mix in the mold and avoid undesired additional voids due to placement. The length of vibration and type of vibrating equipment will have a major impact on the physical and mechanical properties of pervious concrete.
4. *Compressive strength:* As expected, pervious mixes exhibited much lower compressive strengths compared to conventional concrete due to its porous nature and the unique pore geometry each mix exhibits. The values of the compressive strength at 7 days varied from 942 psi to 1,893 psi and varied from 1116 psi to 3414 for the 28 day strength. It was also observed that there was more variability in the test data in comparison to conventional concrete.
5. Flexural strength: The 28-day flexural strength of the mixes of this study ranged from 154 psi to 370 psi. These values on average were about 30 % lower than those of typical conventional concrete. The variability in the test data for flexural strength was less than those of compressive strength. This may be attributed to potential uneven horizontal surface at top of the cylinders despite the use of sulfur capping.
6. *Hydraulic conductivity:* most mixes had a hydraulic conductivity k between 0.040-0.060 cm/s with the exception of PRC-11 which had very low k values. PRC-11 used ¼" river gravel aggregates, which are both more rounded in shape and smaller in size

compared to 3/8" aggregates, causing the mix to have more compaction, thus explaining the lower void ratio and lower hydraulic conductivity results.

7. *Elastic modulus: As expected, the modulus values of pervious concrete from this study were less than those of conventional concrete because of its high porosity and potential discontinuities in the microstructure. The modulus values ranged from 1000 ksi to 2800 ksi. These values were about 25% to 70% less than those of conventional concrete. The variability in the modulus values may be attributed to potential uneven top surface, variability in the microstructure and connectivity, aggregate type (gravel versus crushed stone), and water content.*
8. *Free shrinkage:* The tests for free shrinkage were difficult to perform because of the nature of the previous concrete mixes and the difficulty in bonding the end pins to the prisms. The tests were repeated several times. The inconsistencies in the readings are attributed to the adhesion of the pins at both ends of the specimens. The collected test results showed a range of free shrinkage staring between 300 to 500 micro-strains. Free shrinkage testing will be an going research to resolve the inconsistencies in readings.
9. *Freeze and thaw:* the prisms tested for freeze and thaw showed a small loss of mass up to 70 cycles. These tests will continue to 300 cycles however, based on the initial results and the recorded mass loss so far, the previous concrete specimens are performing well under freeze thaw cycles. <u>However, it is critical that the proper hydraulic design is performed for the particular soil type and the appropriate reservoir layer to avoid storm water reaching the porous slab and not draining down.</u>
10. *Surveys:* the goal of the surveys was to collect information related to DOT's experience with pervious concrete and its performance. Since only twelve responses were received, it will be difficult to make general conclusions on pervious concrete use and performance. However, based on the limited responses, several states mentioned concerns of maintenance and the durability of pervious pavements and potential failure and need of replacement. Four states had previous experience with pervious concrete. However, not much information could be provided on the maintenance and performance of these preexisting pavements because they are all relatively recent pavements. New York State has the oldest pervious pavements, which are about two years old, and the pavement is reported to have some raveling but overall is performing well and they did not need to replace the pavement.

<u>**Life-Cycle Cost Analysis**</u>

The life-cycle cost of three sidewalk design alternatives, including porous concrete, porous asphalt, and conventional concrete was investigated. Extensive literature review was conducted to consider the variation of construction cost and performance life of porous pavement at sidewalk. Based on the investigation, the following findings are summarized:

1. The initial construction cost of porous concrete is slightly greater than that of conventional concrete for sidewalks without subsurface drainage systems.
2. The initial construction cost of porous asphalt sidewalks is much cheaper as compared to conventional concrete.

3. The literature review shows that the service life of porous concrete varies and it may be shorter than of conventional concrete. Although there are cost savings from storm water best management practices, the life cycle cost of porous concrete sidewalk may be still higher than that of conventional concrete sidewalk due to the shorter pavement life.
4. If the life ratio of porous asphalt pavement compared to conventional concrete pavement is greater than 0.60, porous asphalt pavement would be the most economically competitive option among the three pavement alternatives at sidewalk. The service life of sidewalk pavement and the corresponding reconstruction cost contributes significantly to the total life cycle cost.

Energy Measurement

It would be preferential to take measurements throughout each season to help create a better annual model. An on-site cloud meter, such as a passive cloud cover detector would help determine sky conditions better than deriving data from offsite. The load cell mass measurement to determine slab mass was a step in the right direction, because all other methods of determining slab moisture content or mass of water held within the slab are fundamentally flawed, but to increase the accuracy and precision of the slab mass calculations, additional research utilizing signal amplifiers and single-shielded extension wire should be utilized.

Recommendations

1. There is a need to establish vibration and compaction criteria for preparation of lab specimens for compression, flexure, tension and modulus testing.
2. The addition of some sand to pervious concrete can improve its strength and may improve its resistance to raveling. There is a need to evaluate the effects of adding sand to mix and its effects on strength and porosity.
3. Establishing an optimum sand content for pervious concrete is worth investigation.
4. The resistance to raveling is very important for the long term performance of pervious concrete.
5. There is a need for research to evaluate the raveling resistance and factors than can influence this resistance (such as aggregate type, addition of sand, cement content and chemical additives).
6. There is a need for more data on field performance. Tests of cores from field can provide information on the effect of periodic maintenance or lack there-of on void ratio, density, permeability and strength of in-situ sidewalks.
7. Additional research should be considered for energy measurement additional pervious concrete mixes with different source aggregates of different color and size. Comparisons between conventional asphalt and concrete and pervious asphalt and pervious concrete should be conducted. Another approach to studying the energy budget of surface materials would be to experiment inside a controlled chamber to ensure the desired environmental conditions. Better research to determine specific heat and thermal conductivity of, the pervious mix, conventional mix, source aggregates, and cementitious material should be conducted as well.

IMPLEMENTATION AND TRAINING

Based on the results of this research, the following recommendation on implementation can be made:

Local Implementation

It is recommended that a porous concrete sidewalk and a porous asphalt sidewalk are constructed for monitoring. The proposed implementation of sidewalks in the field is needed to evaluate the short term and long term performance of porous sidewalks over time. The implementation plan shall include the following:

1. Identify implementation sites to build porous sidewalks.
2. Perform geotechnical evaluation of the subsoil layers for infiltration rates, and aggregate storage layer design
3. Perform hydraulic design and storm-runoff analysis
4. Identify special locations along the sidewalk that needs special attention during construction such as manholes, light poles, and others.
5. Select porous mix design for the sidewalks using NJDOT specifications and contractor recommendations.
6. Construct the sidewalks following NJDOT specifications and NRMCA and NAPA recommendations. Take sample prisms and cylinders for lab tests.
7. Curing and finishing to follow NJDOT specifications and NRMCA and NAPA recommendations.
8. Install signs alerting the public that the sidewalk is a porous concrete sidewalk and can't handle heavy loads and should be clean
9. Perform maintenance in accordance with NJDEP and NJDOT guidelines.
10. Perform regular inspection of the porous sidewalks.

National Implementation

Pervious concrete have been increasing in popularity as a potential solution to reduce the amount of impermeable surface area associated with sidewalks, reduce puddling, and potentially slow storm water surface high flow rates. As important as these benefits are to surface runoff mitigation, there are concerns with the ability of pervious concrete and pervious asphalt mixes to provide sufficient structural support and longevity for the expected service life of the sidewalks as well as life cycle costs. There are also concerns about the performance of the underlying soils and selections of the proper hydraulic designs. Given those issues and concerns, there is a need to provide the infrastructure community with a state-of-the-practice tool for the design of new and rehabilitated previous systems. Similar to the AASHTO Pavement ME, a state-of-the-practice design tool for pervious systems is needed- as well as an implantation phase. A pervious system ME would include environmental and weather data from MERRA for designing and modeling applications. MERRA provides continuous hourly weather data on a relatively fine-grained uniform special grid from 1979 to the present. Most MERRA data elements are fundamental physics-based quantities, many of which are not available from any ground-based or other conventional climate data source. Only a small subset of the MERRA data elements is needed to develop weather inputs for current infrastructure applications such as the Pavement ME and the proposed Pervious Systems ME. The broad range of MERRA data means that it will likely meet the climate data needs for future applications as well. The attention to quality and continuity in MERRA data eliminates the need to deal with temporal changes in position and/or measurement details of OWS histories. The close and uniform spacing of MERRA grid points also eliminate the need for improved weather data interpolation and use of VWS. MERRA also provides location-specific solar radiation measurement at every grid point. (FHWA PoolFund Study, 2014)

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Appendix A: Summary of Mix Design and Test Results from Existing Research

Table 27. List of mix designs of pervious concrete from literature review (lbs per cubic yard)

Producer/Researcher/ Department/DOT/Association	Cement Type I	3/8 in CA	1/4 in CA	FA	Fly ash	Slg	Water	w/b Ratio	a/b Ratio	AE	WR	HS	VMA
Silvi Conc. Products Inc. (PA)	500	-	2700	-	-	-	165	0.33	5.4	0.8	-	-	-
Clayton Companies (NJ)	600	2835	-	-	-	-	162	0.27	4.7	0.63	1.5	-	-
Weldon Industries (NJ)	864	2430	-	-	-	-	236	0.27	2.8	-	-	-	-
MDDOT Research Proj (2013)	620	2426	-	183	-	-	180	0.29	3.9	-	-	0.56	-
Bury et al (2006) Mix 1	600	2608					162	0.27			1.9	1.9	-
Bury et al (2006) Mix 2	606	2630					163	0.27			1.9	1.9	0.8
Bury et al (2006) Mix 3	600	2608					162	0.27			1.9	1.9	1.9
Bury et al (2006) Mix 4	616	2675					171	0.28			1.9	1.9	3.9
Kevern (2008) Field Mix	506	2575		135	68 [a]		155	0.27	4.5				
Kevern (2008) Abrasion Mix 1	455	2261		118	68 [a]		141	0.27	4.3				
Kevern (2008) Abrasion Mix 2	473	2362		118	68 [a]		146	0.27	4.35				
Kevern (2008) Abrasion Mix 3	473	2447		118	68 [a]		146	0.27	4.35				
UVM TRC Report(2013) Lab 1	630	2800					158	0.25	4.4	0.18	1.0	2.5	2.5
UVM TRC Report(2013) Lab 2	630	2800					185	0.29	4.4	0.18	1.0	2.5	2.5
UVM TRC Report(2013) Lab 3	630	2800					209	0.33	4.4	0.18	1.0	2.5	2.5
UVM TRC Report(2013)Mix4-7	600	2600			30-120		165	VAR	VAR	-	-	-	-
UVM TRC Report(2013)Mix4-7	603	2600[b]			-	-	165	0.27	4.3	0.06	1.1	-	0.8
Lim et al. (2013) Mix 1	620	2630					186	0.3	4.25				
Lim et al. (2013) Mix 2	408	2630					123	0.3	6.45				

Dong et al. (2010) Mix 1 (3/8)	555	2370		165			185	0.33	4.27				
Dong et al. (2010) Mix 3 (3/8)	518	2330		163			154 [c]	0.4 [c]	4.5				
Dong et al. (2010) Mix 1 (1/4)	556	-	2504	174			195	0.35	4.4				
Dong et al. (2010) Mix 3 (1/4)	546	-	2464	173			173 [c]	0.31 [c]	4.5				
Auburn U (2005), Sidewk	600	2391[d]		170			183	0.31			1.5		
Auburn U (2005), Parking	451	2605[d]		313	113 [a]		200	0.35			1.4		
Auburn U (2005), Arboret	600	2391[e]		170			183	0.31			1.5		
Auburn U (2005), Arboret	508	2410[d]		146	56 [a]		150	0.27			1.8[f]	1.1	1.8

a = Class C fly ash; b= recycled agg (0% to 100%); c = includes added 52 lb of latex; d = No. 7 gravel (1/2 in) ; e = No. 78 stone (1/2 in); f= MRWA g = Type F; h = includes 96 lbs of lime stone; i = Pea Gravel; j= Lime Stone; k= vinsol resin; l= olefin based;

Table 27. List of mix designs of pervious concrete from literature review (lbs per cubic yard) (cont'd)

Producer/Researcher/ Department/DOT/Association	Cemet Type I	3/8 in CA	1/4 in CA	FA	Fly ash	Slg	Water	w/b Ratio	a/b Ratio	AE	WR	HS	VMA
Zhang et al. (2012) Mix 1	410	2574	-	257	-	-	115	0.28	6.88	-	4.1	-	-
Zhang et al. (2012) Mix 1	417	2604	-	521	-	-	117	0.28	7.49	-	4.1	-	-
Zhang et al. (2012) Mix 3	421	2635	-	790	-	-	117.9	0.28	8.13	-	4.1	-	-
Zhang et al. (2012) Mix 4	427	2667	-	106[7]	-	-	119.6	0.28	8.74	-	4.1	-	-
Ong MTC Report (2016) Mix 1	639	2414	-	224	-	-	209	0.33	3.78	-	-	-	-
Ong MTC Report (2016) Mix 2	543	2414	-	224	96 [g]	-	209	0.33	3.78	-	-	-	-
Ong MTC Report (2016) Mix 3	543	2414	-	224	-	96	209	0.33	3.78	-	-	-	-
Ong MTC Report (2016) Mix 4	639 [h]	2414	-	224	-	-	209	0.33	3.78	-	-	-	-
Park&Ride parking VT (2008) 1	698	3090	-	-	-	-	244	0.35	4.4	0.15	0.9	2.2	2.2

Park&Ride parking VT (2008) 2	628	3090	-	-	70	-	244	0.35	4.4	0.15	0.9	2.2	2.2
Park&Ride parking VT (2008) 3	558	3090	-	-	140	-	244	0.35	4.4	0.15	0.9	2.2	2.2
Park&Ride parking VT (2008) 4	488	3090	-	-	210	-	244	0.35	4.4	0.15	0.9	2.2	2.2
Kevern (2008) PG 0	580	2570	-	130			157	0.27	4.65	-	-	-	-
Kevern (2008) PG AE-N1	580	2570	-	130			157	0.27	4.65	0.8 [k]	-	-	-
Kevern (2008) PG AE-N2	580	2570	-	130			157	0.27	4.65	1.6 [k]	-	-	-
Kevern (2008) PG AE-S1	580	2570	-	130			157	0.27	4.65	0.8 [l]	-	-	-
Kevern (2008) PG AE-S2	580	2570	-	130			157	0.27	4.65	1.6 [l]	-	-	-
Kevern (2008) LS 0	580	2400	-	130			157	0.27	4.36	-	-	-	-
Kevern (2008) LS AE-N1	580	2400	-	130			157	0.27	4.36	0.8 [k]	-	-	-
Kevern (2008) LS AE-N2	580	2400	-	130			157	0.27	4.36	1.6 [k]	-	-	-
Kevern (2008) LS AE-S1	580	2400	-	130			157	0.27	4.36	0.8 [l]	-	-	-
Kevern (2008) LS AE-S2	580	2400	-	130			157	0.27	4.36	1.6 [l]	-	-	-
Pindado et al. (Spain, 1999) M1[q]	355	2400	-	170	235	-	185	0.31	4.35	-	5.5	-	-
Pindado et al. (Spain, 1999) M2[q]	278	2535	-	178	185	-	144[m]	0.31[m]	5.86	-	-	-	-
Pindado et al. (Spain, 1999) M3[q]	470	-	2275[p]	150[p]	-	-	128[n]	0.27[n]	5.16	-	-	-	-
Pindado et al. (Sapin,1999) 4[o,q]	471	-	2582[p]	130[p]	-	-	160	0.31[o]	5.24	-	-	-	-

a = Class C fly ash; b= recycled agg (0% to 100%); c = includes added 52 lb of latex; d = No. 7 gravel (1/2 in) ; e = No. 78 stone (1/2 in); f= MRWA, g = Type F; h = includes 96 lbs of lime stone; i = Pea Gravel; j= Lime Stone; k= vinsol resin; l= olefin based; m=water includes 15% polymer; n= water includes 25% polymer; o=mix includes 47 lbs of microsilica; p= river gravel and river san; q= mixes were vibrated

Table 27. List of mix designs of pervious concrete from literature review (lbs per cubic yard) (cont'd)

Producer/Researcher/ Department/DOT/Association	Cement Type I	3/8 in CA	1/4 in CA	FA	Fly ash	Slg	Water	w/b Ratio	a/b Ratio	AE	WR	HS	VMA
Kevern (2008) GR. Ang (ME) [m]	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) GR. Ang (MN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) GR. Ang (NH)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) GR. S-Ang (GA)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) RG Round (IN)[n]	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) RG Round (IN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) RG Round (IN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) RG Round (IN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) RG Round (IN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) LS S-Ang. (FL)[o]	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) LS Ang. (IA)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) LS Ang. (IN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) LS Ang. (IN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) LS Ang. (TN)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) Cong Ang (CA)[p]	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern (2008) Quartz Ang(SD)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-
Kevern(2008)ShecheltAng(BC)	567	2565	-	135	-	-	153.1	0.27	4.76	0.8	1.6	-	-

m = granite Angular aggregates from Maine; n = river gravel round from Indiana; o = lime stone semi angular from Florida; p = conglomerate from California

Table 28. List of mix design properties of pervious concrete from literature review

Producer/Researcher/ Department/DOT/Association	Compressive Strength (psi)	Flexural Str. (psi)	Split Ten (psi)	Void Ratio (%)	Density (pcf)	Permeability (in/hr)	Freeze-Thaw Resistance	Shrinkage
Silvi Conc. Products Inc. (PA)								
Clayton Companies (NJ)	2000							
Weldon Industries (NJ)								
MDDOT Research Proj (2013)								
Bury et al (2006) Mix 1	1670	300		24.8	125.0			
Bury et al (2006) Mix 2	2120	430		26.4	125.0			
Bury et al (2006) Mix 3	1950	500		25.5	125.0			
Bury et al (2006) Mix 4	2200	490		28.1	127.0			
Kevern (2008) Field Mix	-	345		17.5	121.0			
Kevern (2008) Abrasion Mix 1				22.5	121.0			
Kevern (2008) Abrasion Mix 2				25.0	117.0			
Kevern (2008) Abrasion Mix 3				27.0	113.0			
UVM TRC Report(2013) Lab 1	910				114.6	1729		
UVM TRC Report(2013) Lab 2	1960				121.8	1460		
UVM TRC Report(2013) Lab 3	3170				130.2	454		
UVM TRC Report(2013)Mix4-7								
UVM TRC Report(2013)Mix4-7								
Lim et al. (2013) Mix 1	1988	442	-	23.4				
Lim et al. (2013) Mix 2	1230	-	-	30.0				
Dong et al. (2010) Mix 1 (3/8)	1306			28.0				

Dong et al. (2010) Mix 3 (3/8)	1741			27.0				
Dong et al. (2010) Mix 1 (1/4)	1451			29.0				
Dong et al. (2010) Mix 3 (1/4)	2177			23.0				
Auburn U (2005), Sidewalk								
Auburn U (2005), Parking Lot								
Auburn U (2005), Arboretum 1								
Auburn U (2005), Arboretum 2								

Table 28. List of mix design properties of pervious concrete from literature review (cont'd)

Producer/Researcher/ Department/DOT/Association	Compressive Strength (psi)	Flexural Str. (psi)	Split Ten (psi)	Void Ratio (%)	Density (pcf)	Permeability (in/hr)	Freeze-Thaw Resistance	Shrinkage
Zhang et al. (2012) Mix 1				35.0	106.0			
Zhang et al. (2012) Mix 1				30.0	108.3			
Zhang et al. (2012) Mix 3				25.0	113.0			
Zhang et al. (2012) Mix 4				20.0	120.2			
Ong MTC Report (2016) Mix 1	2285			25.0 [a]	117.0	340		
Ong MTC Report (2016) Mix 2	2120			22.7 [a]	119.6	369		
Ong MTC Report (2016) Mix 3	1858			25.6 [a]	115.9	624		
Ong MTC Report (2016) Mix 4	2045			23.2 [a]	119.4	354		
Park&Ride parking VT (2008)1	1600			35.2	123.9	1943		
Park&Ride parking VT (2008)2	1560			34.8	122.8	1671		
Park&Ride parking VT (2008)3	1370			35.1	121.6	1743		
Park&Ride parking VT (2008)4	1310			35.4	121.8	1687		
Kevern (2008) PG 0	2340		280	27.0	120	1375		

Kevern (2008) PG AE-N1	3340	340	23.0	124	439	
Kevern (2008) PG AE-N2	3530	410	20.7	124	283	
Kevern (2008) PG AE-S1	3340	335	21.2	125	85	
Kevern (2008) PG AE-S2	3450	345	15.3	129	28	
Kevern (2008) LS 0	2190	230	32.6	108	1446	
Kevern (2008) LS AE-N1	2020	205	31.7	107	1120	
Kevern (2008) LS AE-N2	1650	185	31.1	109	1049	
Kevern (2008) LS AE-S1	1740	215	25.9	107	624	
Kevern (2008) LS AE-S2	1390	245	24.7	107	354	
Pindado et al.(Spain, 1999) M1	3890			123.4		
Pindado et al. (Spain,1999) M2	2980			120.3		
Pindado et al. (Spain,1999) M3	3367			113.1		
Pindado et al.(Spain,1999) M4	2017			129.0		

Table 28.List of mix design properties of pervious concrete from literature review (cont'd)

Producer/Researcher/ Department/DOT/Association	Compressive Strength (psi)	Flexural Str. (psi)	Split Ten (psi)	Void Ratio (%)	Density (pcf)	Permeability (in/hr) [q]	Freeze-Thaw Resistance [r]	Shrinkage
Kevern (2008) GR. Ang (ME) [m]	2740		295	22.0	116.1	694	99	
Kevern (2008) GR. Ang (MN)	2330		270	18.5	113.2	581	99	
Kevern (2008) GR. Ang (NH)	2270		300	19.5	114.8	510	99	
Kevern (2008) GR. S-Ang (GA)	1600		265	15.2	120.1	468	98	
Kevern (2008) RG Round (IN)[n]	2960		425	16.2	125.2	340	17	
Kevern (2008) RG Round (IN)	3300		355	19.3	124.3	524	12	
Kevern (2008) RG Round (IN)	2240		270	30.0	109.2	1389	87	
Kevern (2008) RG Round (IN)	3340		335	21.2	120.0	85	66	
Kevern (2008) RG Round (IN)	3750		435	15.1	127.8	85	98	
Kevern (2008) LS S-Ang. (FL)[o]	1110		125	21.9	106.6	227	22	
Kevern (2008) LS Ang. (IA)	1740		215	25.9	107.1	624	58	
Kevern (2008) LS Ang. (IN)	2950		370	20.9	120.0	808	60	
Kevern (2008) LS Ang. (IN)	2800		380	26.9	116.5	1247	40	
Kevern (2008) LS Ang. (TN)	2990		290	21.8	117.2	609	95	
Kevern (2008) Cong Ang (CA)[p]	2770		325	25.2	110.3	1474	95	
Kevern (2008) Quartz Ang SD)	2540		295	21.6	114.3	822	97	
Kevern 2008)ShecheltAng(BC)	2740		255	17.6	121.7	539	98	

m = granite Angular aggregates from Maine; n = river gravel round from Indiana; o = lime stone semi angular from Florida; p = conglomerate from California; q = results for 4 in diameter samples; r = % mass remaining after 300 cycles

Appendix B: Cost Data Summary

Table 29. Cost data summary from various references

Component	Structure design	Drainage system	Construction cost	Maintenance schedule	Maintenance cost	Source	Note
Pervious Concrete shoulder (Highway Traffic)	Pervious concrete thickness: 10” Reservoir layer:12”	Two collection slotted pipes were placed to document runoff volume and water quality analyses	1.5 times conventional paving method due to skilled labor is needed to install the concrete layer	-	-	Florida Interstate Performance Assessment of portland Cement Pervious Pavement, 2007 http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_RD/FDOT_BD521_02_rpt4.pdf	
Permeable Asphalt (Light Traffic)	Asphalt Layer: 3”	-	$110 / sq. yard Full 8” including choker stone, Storage stone not included	-	-	Philadelphia, PA Roadmap in NYC: Information in this case study was obtained in an April 5, 2012, interview with Peter Reilly, Civil Engineer at the Philadelphia Water Department.	
Pervious Asphalt (Minimal Traffic)		Combination of traditional curbs channel to a receiving storm sewer and pervious asphalt	Cost of designing and installing was slightly higher than traditional pavement due to innovative engineering	annually Vacuum truck cleaning	Less than $400 entire project	Salem, OR Stormwater Solutions. “Case Study: Pringle Creek Green Streets.” 2012 http://www.ewashtenaw.org/government/drain_commissioner/dc_webWaterQuality/street-runoff-infiltration/presentations-and-case-studies/lid-casestudy-pringlecreek.pdf	

Permeable Concrete Bicycle lanes Sidewalk	Bike lane 5' wide Sidewalk 6' wide	Gutter slope and overflow basin to remove standing water into storm water facility	Pervious concrete lane: $140 / sq. yard Pervious Concrete Sidewalk: $92.25 /sy	Conventional sweeping and vacuum machines	-	Olympia, WA RW Johnson Boulevard/ 21st Ave. Porous Pavement Improvements, 2006 Craig Tosomeen, P.E., Pervious Concrete Bicycle Lanes, City of Olympia, Public Works Water Resources, 2006	30 year life with subgrade strength of 150-200 psi
Pervious Concrete Bike Lane			$140 sq. yd			Craig Tosomeen, P.E., Pervious Concrete Bicycle Lanes, City of Olympia, Public Works Water Resources, 2006	Bid Items for Pervious Concrete Components, City of Olympia
Permeable Concrete Sidewalk	1500' *5 1/2' sidewalk 917 sq. yard		$20/ sq. yard (bid price lower than expected) $10000 additional engineering cost	-	-	Olympia, WA North Street Reconstruction Project Summary of Porous Concrete Sidewalk, 1999	- 3/8'- No.10 washed round agg. - Aggregate to water ratio 0.32 - aggregate to cement ratio 4.5:1 - mix design: polypropylene fibers, air entrainment and water reducing admixtures
Pervious Concrete Sidewalk			$92.25 sq. yd			Craig Tosomeen, P.E., Pervious Concrete Bicycle Lanes, City of Olympia, Public Works Water Resources, 2006	Bid Items for Pervious Concrete Components, City of Olympia
Pervious Concrete Underdrain System			$63.50 cy			Craig Tosomeen, P.E., Pervious Concrete Bicycle Lanes, City of Olympia, Public Works Water Resources, 2006	Bid Items for Pervious Concrete Components, City of Olympia

Porous Asphalt			$61.2/sq. yard		3.69/sq/yr	http://www.3riverswetweather.org/green/green-solution-porous-pavement	New construction without under drain
Porous paver			$130.5/sq. yd		3.69/sq/yr	http://www.3riverswetweather.org/green/green-solution-porous-pavement	New construction without under drain
Porous Concrete			$83.25/sq. yd		3.69/sq/yr	http://www.3riverswetweather.org/green/green-solution-porous-pavement	
Concrete sidewalk and Driveway			$46.71/sq. yard		-	RSMeans Site Work & Landscape Cost Data - 28th Annual Edition (2009)	
Concrete Sidewalk and Driveway			$90/sq. yard		-	Residential Construction and Remodelling Estimates Accessed March 2009	
Concrete Sidewalk and Driveway			-		$0.261/sq. yard	City of Oxnard, California, Streets and Waterways Division. "Street Maintenance & Repair Funding." Accessed July 2005	
Permeable Pavement-Pavers			$47.7/sq. yard		-	Sikich, Andrew J. and Patrick D. Kelsey. "The Morton Arboretum's "Green" Parking Lot." Accessed July 2005.	
Permeable Pavement-Pavers			$63.9 /sq. yard		-	Wetland Studies and Solutions, Inc; Virginia LID at WSSI 2007	
Permeable Pavement-Pavers			$108/sq. yard		-	Rose Paving, email message to CNT, November 13th 2008	
Permeable Pavement-Pavers					$0.324/sq. yard	Southeast Wisconsin Regional Planning Commission. "Costs of Urban Nonpoint Source Water Pollution Control Measures." Technical Report Number 31.	

						June 1991.	
Permeable Pavement-Pavers					$0.09/sq. yard	Pelkonen, Peg. The Morton Arboretum Permeable Parking Lot Presentation at the US Cellular Field Lot L Paver Symposium April 8th, 2008	Life 15 years U.S. Department of Transportation, Federal Highway Administration. "Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring." Accessed July 2005.
Permeable Pavement-Pavers					$2.07/sq. yard	Low Impact Development Center, Inc; Low Impact Development for Big Box Manufacturers November 2005	Life Span 25 year
Porous Concrete & Porous Asphalt			$49.5/sq. yard		$2.07/sq.yard	Low Impact Development Center, Inc; Low Impact Development for Big Box Manufacturers November 2005Web Link	Life Span 25 years
Porous Asphalt			$57.06/sq. yard			City of Portland, Bereau of Environmental Services,Willamette Watershed Program - Task Memorandum 4.1 August 2005	Life Span 20 year
Porous concrete & porous asphalt					$0.81/sq. yard	California Stormwater BMP Handbook; Pervious Pavements Factsheet January 2003	Life span 40 years Southern California Ready Mix Concrete Association & California Cement Promotion Council Concrete Pavement

Porous Asphalt			$73.17/sq. yard		$1.71/sq. yard	PlaNYC 2030 Sustainable Stormwater Management Plan Accessed March 2009	
Porous Concrete			$49.5/sq. yard		$2.07/sq.yard	Low Impact Development Center, Inc; Low Impact Development for Big Box Manufacturers November 2005Web Link	Life Span 25 years
Porous Pavement			$104.4/sq. yard		-	North Carolina Green Building Technology Database; Friday Center Park & Ride Lot, UNC-Chapel Hill Accessed March 2009	
Porous Pavement			Design cost =24% porous pavement construction cost		-	North Gay Avenue Portland, Oregon, 2005	Life More than 20 years
Porous pavement			$54.764/ sq. yard	Four inspections each year with jet hosing and vacuum sweeping treatments.	$200/sq. yard	Storm Water Technology Fact Sheet Porous Pavement EPA 1999	Construction cost include: excavation cost, filter stone, filter fabric, porous material, overflow pipes, observation well, grass buffer, erosion control, contingencies.
Porous Asphalt			$48.4/ sq. yard $31/ sq. yard			2009 EPA study Permeable Pavement Research –Edison New Jersey, Amy Rowe EPA National Risk Management Research Laboratory Final proposed costs reported by Kirit Shaw, S Services, Inc, June 2009 (2)	
Porous Paver			$114.8/ sq. yard $104.32/ sq. yard				
Porous Concrete			$71.21/ sq. yard $60.75/ sq. yard				

Additional data on the three pervious concrete sidewalk projects in New Jersey

2015 Pervious concrete sidewalk

Item: 606017p, Number of contracts: 1, units: square yard, total quantity: 1,124.0,

dp # 15134, Description: Route 9 Northfield sidewalk re, reg: s1, County: Atlantic, bid date: 09/29/15, work type: 6, unit price: 180

2014 Pervious concrete sidewalk

Item: 606017p, Number of contracts: 1, units: square yard, total quantity: 1,728.0,

dp # 14130, description: Route 38, Route 295 to Route 206 contra, reg: s1, County: Burlington, bid date: 07/17/14, work type: 4, unit price: 105

2013 Pervious concrete sidewalk

Item: 606017p, Number of contracts: 1, units: square yard, total quantity: 507.0,

dp #13135, description: Route 21 Tichenor Park, reg: n1, County: Essex, bid date: 07/18/13, work type 11, unit price: 108

Notes:

There were no data available on the performance of these sidewalks. The research team proposed additional work to investigate field performance of pervious asphalt and pervious concrete sidewalks in New Jersey including visual observations, field permeability tests, and coring. The proposed work was not pursued as part of this project but can be part of a local implementation project.

APPENDIX C: Complete Survey Sent to State DOT's

Q1. Did your department use pervious concrete pavements in sidewalks, bike paths or shoulders? [ ] Yes [ ] No

<u>If the answer is No, Please go to question 20</u>.

Q2. Where did your department use pervious concrete?
[ ] Sidewalks, [ ] Bike paths , [ ] Shoulders

Q3. What was the typical thickness of pervious concrete used?
[-----] inches (Sidewalks), [-----] inches (Bike paths) , [----] inches (Shoulders)

Q4. What was the typical thickness of reservoir (storage) aggregate layer used under the pavement?
[-----] inches (Sidewalks), [-----] inches (Bike paths) , [----] inches (Shoulders)

Q5. What was the spacing of joints of the pervious pavements?
[ ] 15 ft [ ] 20 ft [ ] 25 ft [ ] 30 ft
[ ] Other (specify) ----------

Q6. What was the approximate bid cost of pervious pavement system?
[-----] $\$/ft^2$ (Sidewalks), [-----] $\$/ft^2$ (Bike paths) , [----] $\$/ft^2$ (Shoulders)

Q7. If you needed to replace previous pavements, typically, how long was that after construction?
[-----] years (Sidewalks) [-----] years (Bike Paths) [-----]years (Shoulders) [----] N/A (specify)

Q8. If you have experienced distress or failure in pervious pavements, the reason for it was: [ ] minor cracking [ ] major cracking [ ] structural failure
[ ] severe clogging [----] Raveling

Q9. When do you normally perform the initial inspection of the pervious pavement?
[ ] after three months, [ ] after six months [ ] after first major storm [ ] after one year [ ] after first clogging

Q10. What is the frequency of cleaning of pervious pavements?
[ ] once every year, [ ] 2 times a year, [ ] 3 times a year, [ ] depends on clogging

Q11. Have you used an auxiliary drainage system with the pervious pavement to mitigate the storm water runoff?
[ ] Yes [ ] No

Q12. Would you consider precast pervious concrete slabs instead of cast-of-place?
[ ] Yes [ ] No [ ] Not sure

Q13. Do you specifications require contractors build test pervious slabs before getting approval to build the contract slabs?
[ ] Yes [ ] No

Q14. If the answer to Q12 is yes, the required minimum area of the test slab was?
[ ] 100 ft^2 [ ] 200 ft^2 [ ] 225 ft^2 [ ] 250 ft^2

Q15. Do you require the subgrade to be compacted?
[ ] Yes [ ] No

Q16. Do your specs allow the use of sand in the pervious concrete pavements?
[ ] Yes [ ] No

Q17. Do your specs allow the use of fly ash in the pervious concrete pavements?
[ ] Yes [ ] No

Q18. Do your specs allow the use of slag in the pervious concrete pavements?
[ ] Yes [ ] No

Q19. Do your specs prescribe a minimum pervious pavement infiltration rate?
[ ] Yes [ ] No

Q20. Comparing conventional concrete pavement to previous pavement, you would say the performance of pervious pavement is overall:
[ ] better, [ ] worse, [ ] about the same, [ ] Not enough data

Q21. Based on your experience with pervious concrete in your area, the reaction of the public to the use of pervious concrete compared to conventional concrete has been: [ ] positive, [ ] negative, [ ] about the same, [ ] Not enough data

Q22. As a BMP for storm water runoff, the EPA in our state considers pervious concrete pavements as: [ ] Acceptable, [ ] Not Acceptable, [ ] Acceptable but with certain conditions* [ ] Not sure

If available, please provide the following information of the pervious mix that was used in your pervious pavement?

Mix Design

Cement Content = lbs/cu yd
Aggregate content = lbs/cu yd
Max aggregate size = inches
Sand content = lbs/cu yd
Fly ash content = lb/cuyd
Admixture used, please provide type (s) ------------------

Specified Properties of Porous Concrete (or typically values if no specs are available)

Void Content = %
Density = lb/cuft
Permeability= in/hr

Table 30. Survey responses from various state DOT's

		Maine	*Nevada*	*New York*	*Washington*	*Virginia*
1	*Previous Experience with Pervious Concrete?*	Yes	Yes	Yes	Yes	No
2	*Where did your department use PC?*	Shoulders	Shoulders	Sidewalks and Shoulders	Shoulders	Park and Ride (Exp)
3	*What was the typical thickness of PC used? (in)*	5	6	4 (Sidewalks), 6 (Shoulders)	8.5	5-6
4	*What was the typical thickness of reservoir (storage) aggregate layer used under the pavement?*	24	8 (sand)	Varies based on storage capacity need	21-30	18
5	*What was the spacing of joints of the pervious pavements? (ft)*	5 (prefab modular panels)	15	20	20 max	12 or less
6	*What was the approximate bid cost of pervious pavement system? ($/sq ft)*	15	Unknown		N/A	
7	*If you needed to replace previous pavements, typically, how long was that after construction?*	Unknown (est 2014)	Has not been replaced yet. Some maintenance on raveling at edge.	Locations that have lasted have not been replaced yet but are clogged with fines and do not perform as intended (6-7 years old). Locations that failed were replaced in less than a year (see comments at end of survey)	N/A (installation recent)	
8	*If you have experienced distress or failure in pervious pavements, the reason for it was:*	Raveling To date not on this project, but City of Bangor ME had severe raveling and clogging	Raveling	Raveling		
9	*When do you normally perform the initial inspection of the pervious pavement?*	(N/A) Responsibility of third party	After 3 months			Imm. Post construction and annually
10	*What is the frequency of cleaning of pervious pavements?*	depend on clogging	depend on clogging	Should be a minimum of 2 times per year, but some that have been in place several years have never been maintained. Other locations (see comments at end of survey) did not last long enough to clean.		
11	*Have you used an auxiliary drainage system with the pervious pavement to mitigate the storm water runoff?*	Yes	Yes	Some		

		Maine	Nevada	New York	Washington	Virginia
12	*Would you consider precast pervious concrete slabs instead of cast-of-place?*	Yes	Not Sure	Not Sure	Not Sure	Not Sure
13	*Do you specifications require contractors build test pervious slabs before getting approval to build the contract slabs?*	Yes	No	Yes	Yes	Yes
14	*If the answer to Q12 is yes, the required minimum area of the test slab was(sq ft)?*	100 ft^2		100	225	225
15	*Do you require the subgrade to be compacted?*		Yes	No	Yes	No
16	*Do your specs allow the use of sand in the pervious concrete pavements?*	No, Manufacturer did	Yes	No	No	Yes
17	*Do your specs allow the use of fly ash in the pervious concrete pavements?*	No, Manufacturer did	Yes (20% of Ce	Yes	Yes (35% cement)	Yes
18	*Do your specs allow the use of slag in the pervious concrete pavements?*	No, Manufacturer did	Yes (15% of Ce	Yes	Yes (30% cement)	Yes
19	*Do your specs prescribe a minimum pervious pavement infiltration rate?*	No, Manufacturer did	Unknown	Yes (100 in/hr)	Yes (100 in/hr)	Yes (100 in/hr)
20	*Comparing conventional concrete pavement to previous pavement, you would say the performance of pervious pavement is overall:*	not enough data	worse	not enough data	not enough data	
21	*Based on your experience with pervious concrete in your area, the reaction of the public to the use of pervious concrete compared to conventional concrete has been:*	negative	not enough data	not enough data	about the same	
22	*As a BMP for storm water runoff, the EPA in our state considers pervious concrete pavements as:*	acceptable	Not sure	Not sure	acceptable but with certain conditions	acceptable
	MixDesign Provided?	No	No	Yes	Yes	No

Table 31. Additional comment responses from various state DOT's

State	Comments
Colorado	The Colorado Ready Mixed Concrete Association constructed a few parking lots in the Denver Metro area. Because of Colorado's extreme freeze/thaw environment, the pavement did not fare well and the CRMCA has not pursued further projects. The CRMCA can be contacted at 303-290-0303 for information on their demonstration projects. Pervious pavement sounds great in theory for BMPs, but reality they do not meet the requirements for strength and durability to handle traffic in a freeze/thaw environment. In Colorado, the pavement the can experience two or more freeze/thaw cycle per day. That coupled with deicers and sand make the maintenance cost prohibitive. This type of BMP may work great in places not subject to freeze/thaw cycles. Using pervious pavement can also create issues with the subgrade creating long term structural performance issues for PCCP and HMA by saturating and weakening the subgrade. From a pavement design perspective, water should be removed or kept from entering the roadway prism for best performance and thinner more sustainable designs. Again the theory sound great from an environment and drainage perspective, but in reality does not meet structural requirement for durable and sustainable pavements.
Florida	Currently, the FDOT does not have an active specification, nor approved mix designs for pervious concrete pavement approved for use on the State Highway System. Most pervious concrete applications are limited to County, City and private applications.
Kansas	KDOT has no pervious concrete. Period. In fact, we are taking steps to make our concrete mixes less permeable. The last thing we want is to invite moisture into the system, which can exacerbate the influence that freeze/thaw cycles have on our pavements.
Louisiana	LADOTD has not completed any pervious concrete work, but the City of New Orleans has completed several large projects where pervious concrete was specified and used for street construction. I would suggest getting ahold of the New Orleans City Engineer to discuss their efforts._
Maine	Product was precast pervious concrete panels http://www.storm-crete.com preapproved by my predecessor on our PreQual Product list and in the one application. I have my reservations for application in high traffic area subject to high winter salt application, but I am monitoring the product. Peter Newkirk PE Senior Environmental Engineer
Nevada	We have placed one test section of pervious concrete on a shoulder. The section is at 6600" elevation near Lake Tahoe. It is subjected to snow fall and salt and sand, but not snow removal. The section began to ravel almost immediately and appeared to be low in paste content, even for pervious concrete. A second test section has not been placed.
New York	NYSDOT and some local municipalities have had some cast-in-place installations that have lasted several years, but then other that have raveled so severely that they needed to be torn out in less than a year. Investigations into the failures contribute the raveling to high concentrations of road salts or other de-icing materials. Due to this NYSDOT is only recommending cast-in-place installation at locations where the use of salt and other de-icing materials will not be used. This prohibits parking that are not fully pervious (vs. pervious PCC parking stalls with conventional PCC driving lanes), sidewalks
Virginia	We are planning to place pervious concrete in two projects in 2017; in parking stalls. Therefore, we did not answer many of the questions; however, we attempted to fill some even though we do not have the installations.
Washington	WSDOT has only constructed a few permeable concrete installations so the answers to this survey are based on limited data. WSDOT published a report Pervious Concrete Parking Strips documenting the construction permeable concrete on shoulders. (http://www.wsdot.wa.gov/research/reports/fullreports/852.1.pdf)

Table 32. Mix designs provided by New York and Washington State

STATE	NY (Size 1 agg)	NY (size 1A Agg)	Washington
Cement (lb/cu yd) =	520	580	400
Aggregate Content =	A/C ratio 4:1 ~ 4.5:1		2920
Max Aggregate Size =	Size 1	Size 1A	3/8
Sand (lb/cu yd) =	0	0	0
Fly Ash (lb/cu yd) =			100
Admixtures			VMAR (.1-100 oz/cwt)
Admixtures			D-WRA & RET (.10-20 oz/cwt)
Void Content %	15-25 (ASTM)		
Density (lb/cu ft)=	+/- 5 lb/ft^3 as designed		131.12
Permeability (in/hr) =	100	100	100

APPENDIX D: Energy Budget Evaluation of Field Slabs

Construction Environmental Conditions

Throughout the mixing and testing of the field slabs the environmental conditions were recorded.

Soil Characterization

The soil found at the laboratory test site is predominantly shale, listed by the USDA as Klinesville-Urban land. The soil map provided by the USDA web soil survey. While the soil type, permeability, and structural capacity have a direct impact on the stormwater design, structural design, and mix selection for a given area, the location of this project was predetermined by availability of space and funding. Developing a knowledge of local soil parameters is strongly advised by the authors when considering the use of pervious concrete mix and how the underlying structure is designed based on the desired outcomes. Pervious structures can be built to either encourage local source-site infiltration, or they can be built with underlying drainage but each has its limitations.

Equipment

Test Setup

The test setup for this project consisted of a global sensor array to catch close proximity environmental conditions, as well as mix specific sensor arrays to capture data related to each slab specifically. Two weather-stations were utilized, one positioned on the roof of the laboratory and one positioned on the ground next to the field slabs. Each weather-station included barometric pressure, wind speed, wind direction, ambient temperature, relative humidity, and rainfall measurement equipment. Air column temperature, soil temperature, and soil moisture content was captured globally as well, where a single set of probes was outfitted near slab 4 and the data was utilized for each of the slabs measurements. Finally, each slab was outfitted with load cells to measure slab mass, a temperature probe at the bottom of the slab to measure the under slab temperature, four thermocouples to measure slab temperature, and a net radiometer above the slab to measure the incoming and outgoing solar radiation.

Equipment Setup

The equipment/sensors were all wired in the laboratory. The first step in the procedure was to determine if each piece of equipment was functional. Each piece of equipment was connected to a data logger separately and tested to verify it was functioning properly. The number of wires required to connect each to the data logger was recorded. The total length of standard wire that came with each unit was recorded as well. Items that were broken were replaced or repaired as applicable. The majority of the repairs required cutting broken wire and soldering new wire to ensure proper connection. The second major repair was resoldering terminal connections that had become loose. One of the Young Anemometers was missing a 6 pin plug, which was replaced with a new plug. After each piece of equipment was tested, a wiring/data logger plan was developed to determine the applicable sensors that could be connected to each data logger. Once the wiring plan was developed, a siting plan was developed for each of the six data loggers and two multiplexers. The rough siting plan was used to determine the required wire length that each of the pieces of equipment required to reach each field test slab. The wiring for each piece of equipment was conducted as thoroughly as possible to alleviate any possible mechanical or electrical error within the sensors and measurements. All solder joints were coated with individual heat shrink tubing, then the entire line was covered in a larger heat shrink tubing. Finally an outside sheath was placed around the outside of the line to prevent water damage. Roughly 500 solder connections were made throughout repair, testing, and the extension of signal lines.

Due to budgetary constraints, the extension wires utilized for this project were limited to wire-on-hand. The load cell extension wires caused the majority of the load cell noise, as they utilized a 24 stranded JX extension wire, where four load cells all ran through the same line. Two load cells per line utilized the Iron wire while the remaining two utilized the Constantan wire. While evaluating the functionality of the load cells with this extension wire, there appeared to be no difference in the signals. When the extension wire was placed outside though, two sources of noise became overwhelming to the load cell signal; the number of wires over the signal distance caused excess noise within the line while the solar flux and heat caused noise along the distance of the line. The authors would recommend the use of single shielded, environmental grade line per sensor with the addition of a signal amplifier per line to ensure the environmental noise be kept to a minimum when evaluating such small loads over such a long time period. Aside from that extension wire issue, extreme care was taken to ensure that the final length of the signal wires matched within 6in (15.24cm). The wiring diagrams for each Campbell data logger as well as extension wires can be found in the appendix. The DAQ wiring and placement will be covered in the equipment orientation section of this paper.

Equipment Location and Orientation

Rooftop Weather Station

To provide local weather conditions, two weather stations were utilized. The first of which was placed at 33ft (10m). To accomplish this, the weather station was erected on the roof of the laboratory. The roof weather station assembly is shown in Figure 37.

Figure 37. Rooftop weather station

The rooftop weather station was not allowed to be connected to the building or roof in any way. Bolts were recessed on a double layer of ¾" (19mm) plywood to hold the tower while not scratching the roof. Pull tests were conducted on the ground to determine the appropriate ballast weight to withstand a 150mph (67m/s) wind. The rooftop weather station was set up to measure wind speed and direction, precipitation, ambient temperature, relative humidity, and barometric pressure. It is customary to not conduct these measurements so close to the roof, but the data provided a valuable backup for the ground weather station data and was used for additional data verification.

Ground Weather Station

The ground weather station was set-up very similarly to the roof weather station but in close proximity to the ground. This was considered important for this study since the pervious slabs were part of the ground and surface condition. The ground weather station is shown in Figure 38, in on the left of the foreground.

Figure 38. Ground weather station (left foreground)

Type-E Air Column Thermocouples

The Type-E air column thermocouples were located above slab 4. The data from the close-proximity air column thermocouples was utilized for each of the slabs. The four type E thermocouples were placed at logarithmically spaced intervals increasing in height from the surface of the slab.

Slab Temperature Probes

The slab Temperature probes were located at the Northeast corner of each slab. Each probe had four type K thermocouples which were attached to a 0.9in (22.9mm) diameter silicone filled PVC pipe using electrical tape. Care was taken to ensure each thermocouple was lying flat against the PVC pipe and taped with the end of the thermocouple at the appropriate measurement depth.

Figure 39. In-Slab temperature probe location

Net Radiometers

The net radiometers utilized for this experiment were located at the center of each slab at a height of 18in (45.7cm) above the slab surface. The radiometers were held in place by tripods with extension booms to reduce the shadow effect the sensors would have on the surface. The sensors surface was made level with bubble levels and a handheld level if possible. The position of the net radiometer can be seen in Figure 40.

Figure 40. Net Radiometer location

Measurement Protocol

The final layout of sensors per DAQ is shown in Figure 30. When arranging the equipment layout, there were several considerations that were required to mitigate. Each DAQ required power and communications to deliver data back to the main computer interface. Power cables were created to extend power to the two environmental containment boxes utilized. The sensors with the shortest extension wire were placed in the outside environmental containment boxes where the longest wire run measured approximately 40ft (12.2m) and the shortest run measured approximately 15ft (4.6m). The Campbell CX3000 Load Cell and AM16/32 multiplexer were located in the outside containment boxes, along with the CR1000 TDR DAQ. The second CR3000 utilized to measure type K thermocouples, the AM25T multiplexer, and two final CR1000s were mounted to a wall inside the laboratory near the main computer.

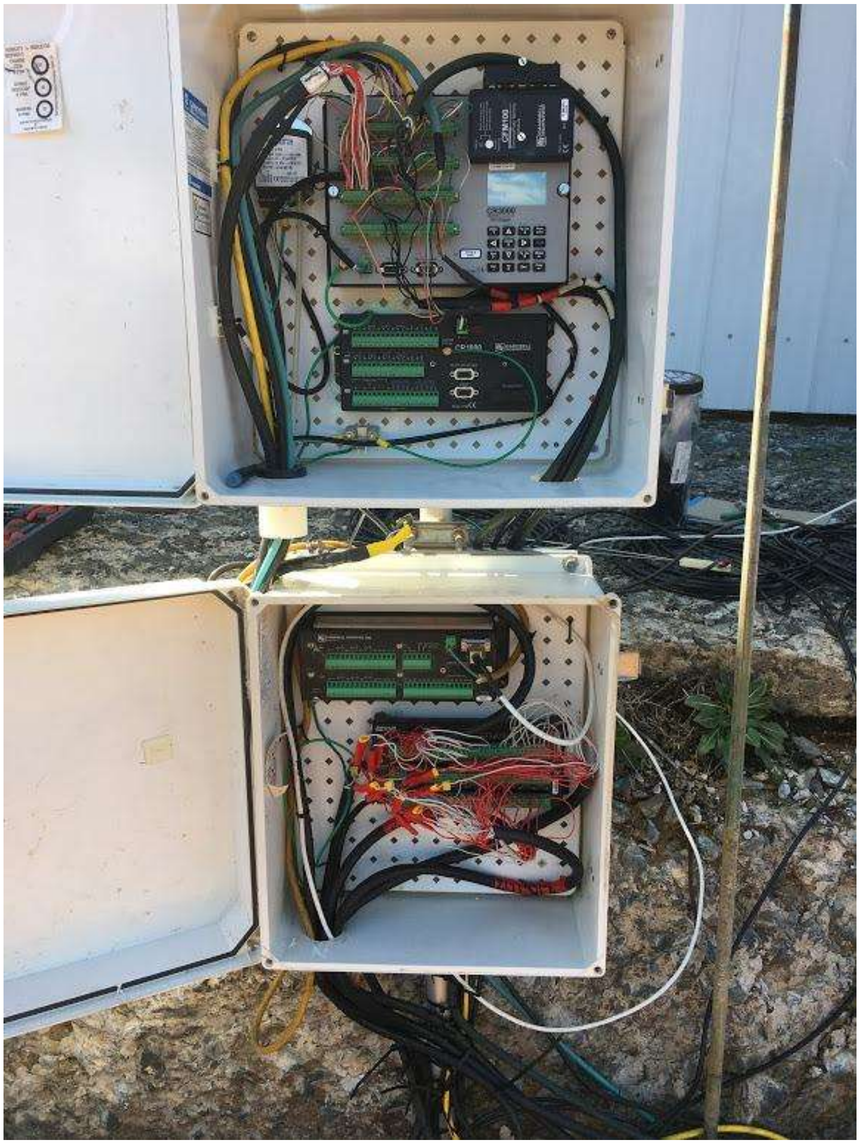

Figure 41. Wiring configurations inside environmental containment boxes

The completed wired data loggers inside the environmental containment boxes are shown in Figure 41 below. The data loggers mounted inside the laboratory were mounted to a vibration resistant panel to ensure vibrations from the vibratory brick compactor on the adjacent wall would be dampened as well as to provide a separation from any moisture that might accumulate on the wall. The in-lab setup is shown in Figure 41. All of the power requirements for DAQs was handled by a dedicated Electro Industries Digi 360 regulated DC power supply, which was capped at 2 amps of output at 11.75 volts. The communications were supplied through USB to RS-232 adaptors into a standard Dell Computer which ran Windows 64-bit Professional. Due to the harsh laboratory conditions typically found where this computer was situated, it was determined to be necessary to add an additional cooling fan to ensure the computer would remain functional throughout the duration of the project.

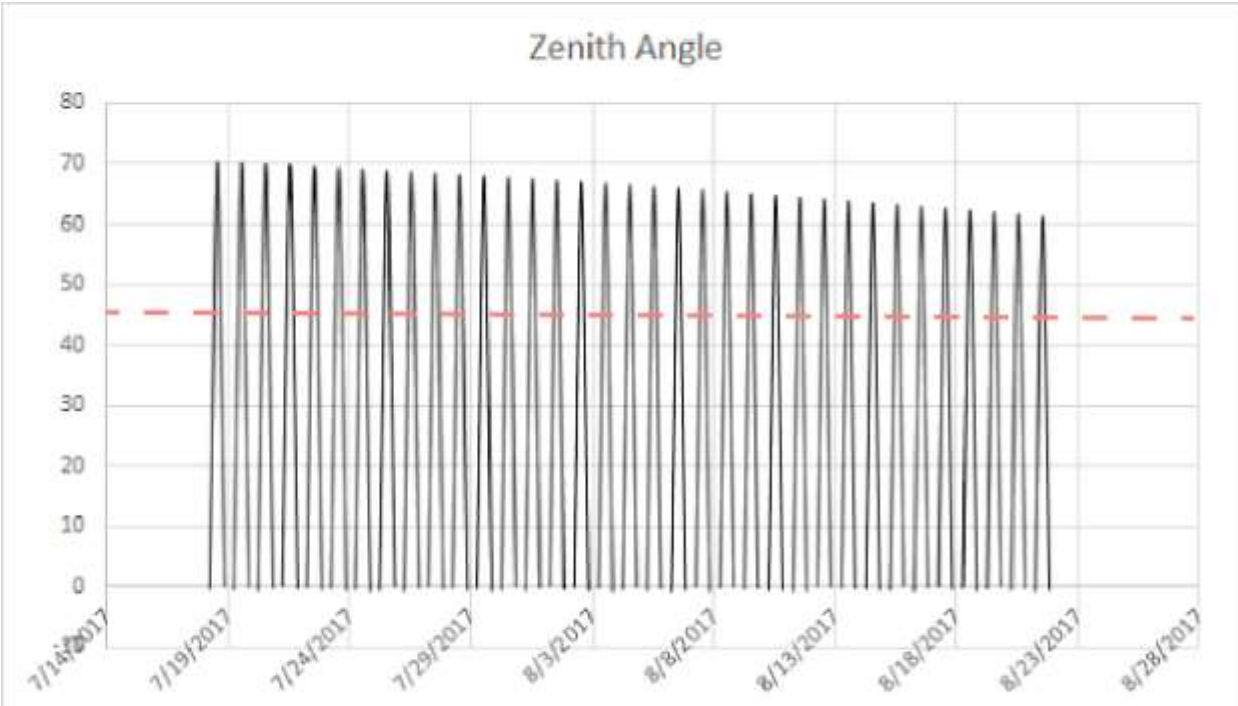

Figure 42. Zenith angles used for albedo measurements

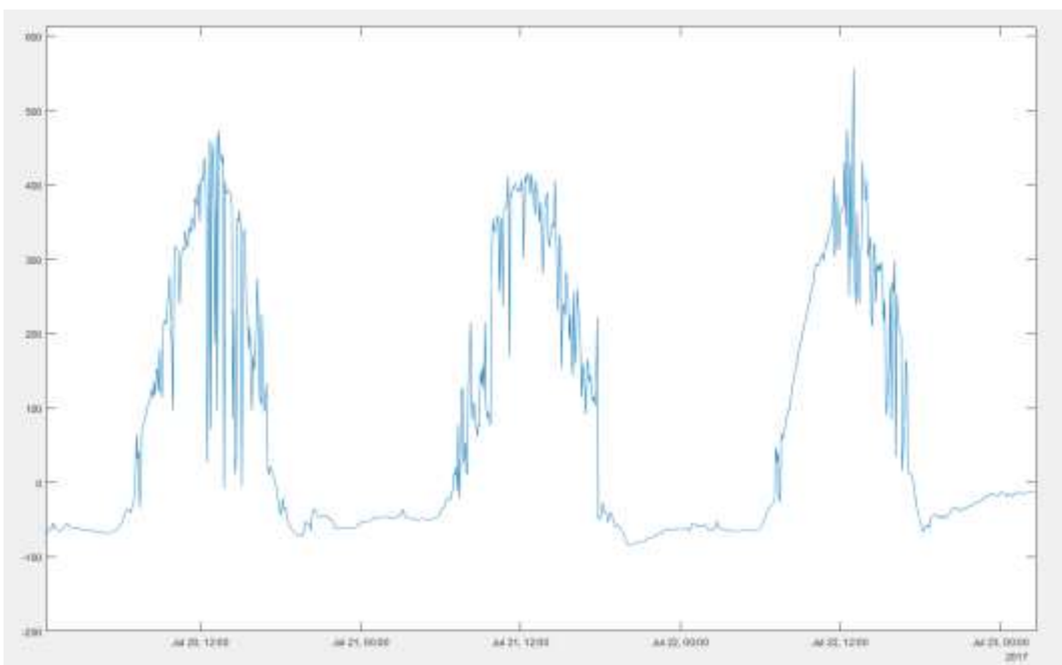

Figure 43. Net Radiation for July 20 - July 22, 2017 at Slab 1

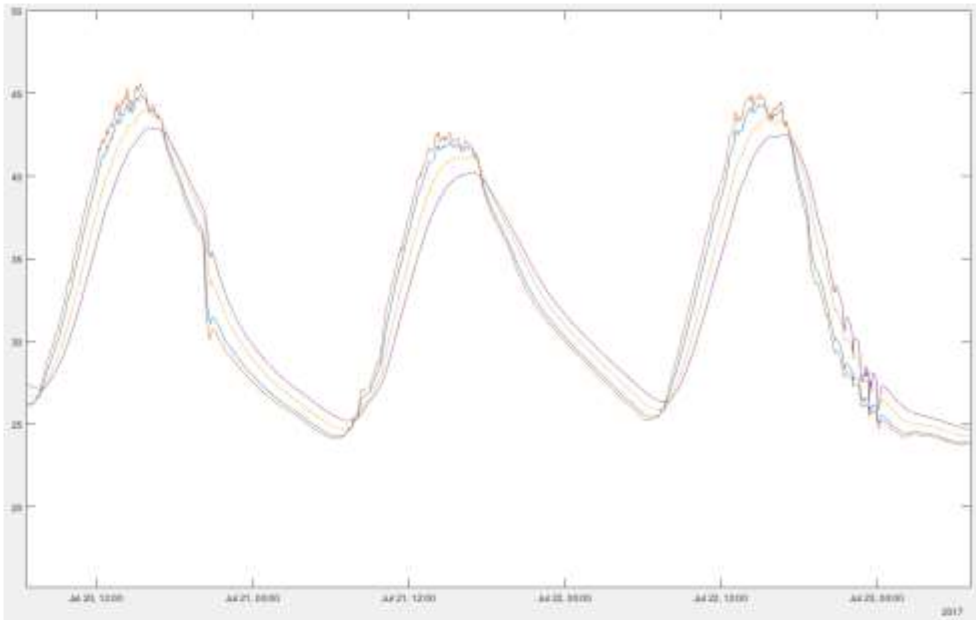

Figure 44. Soil VWC unfiltered from 7/20-7/22

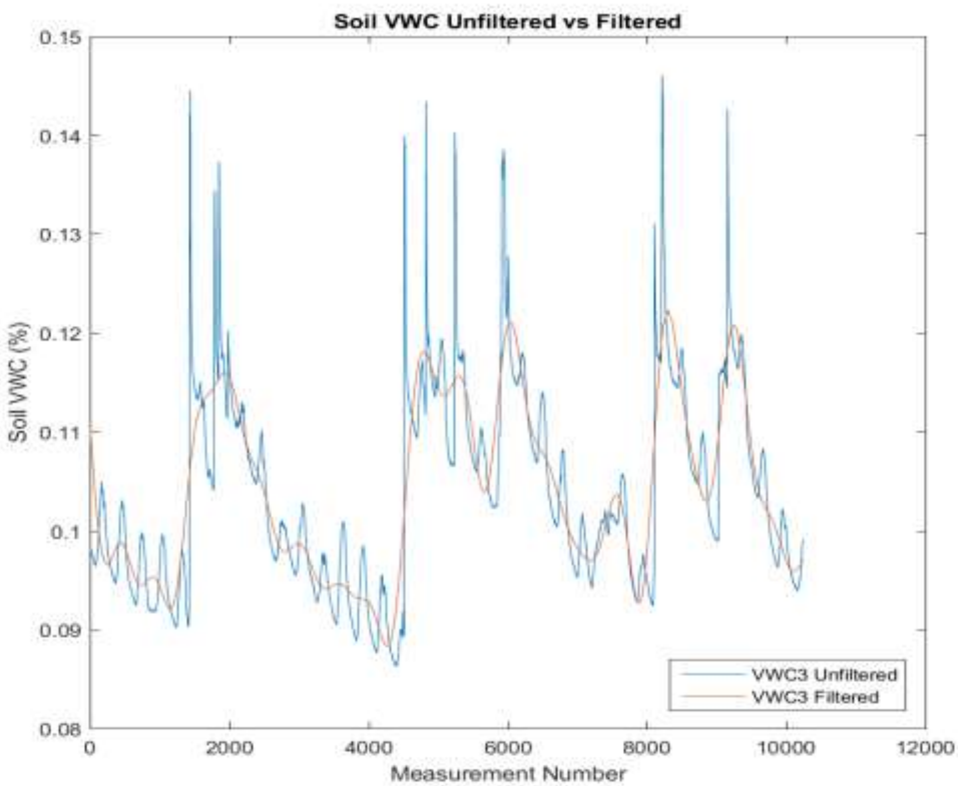

Figure 45. Soil VWC 3" filtered versus unfiltered measurement

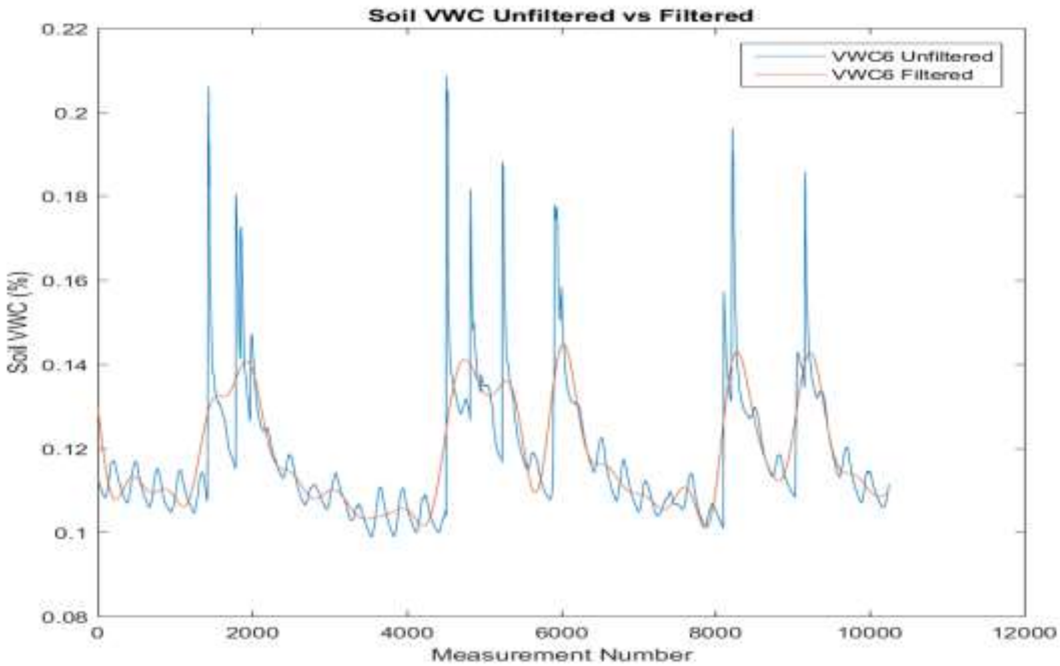

Figure 46. Soil VWC 6” Filtered vs Unfiltered Measurement

Load Cells

The load cells utilized for this experiment posed the most complicated problems during data reduction. This is likely due to the extension wire utilized as well as the lack of signal amplifiers. The raw load cell results were extremely noisy and required a filtering procedure to be developed. The first step in the process was to examine the fit between the rain bucket data as compared to the load cell data. Each signal was compared to the rain bucket data to show the fit of the load cell response to the recorded rain events at the site. Only one rain bucket was available at the site due to equipment malfunction, so the results for that rain bucket compared to each load cell are shown below Load cells 1, 2 and 4 versus rain is shown in Figures 47, 48 and 49 respectively with, the load cell response in lbs on the left y-axis, rain bucket data in 0.01” increments on the right y-axis, and measurement number (consecutive date) on the x-axis. Load cells 9, 10, 11, and 16 versus rain are shown in Figures 50, 51, 52, and 53 respectively. The figures show the load cell response in lbs on the left y-axis, rain bucket data in 0.01” increments on the right y-axis, and measurement number (consecutive date) on the x-axis.

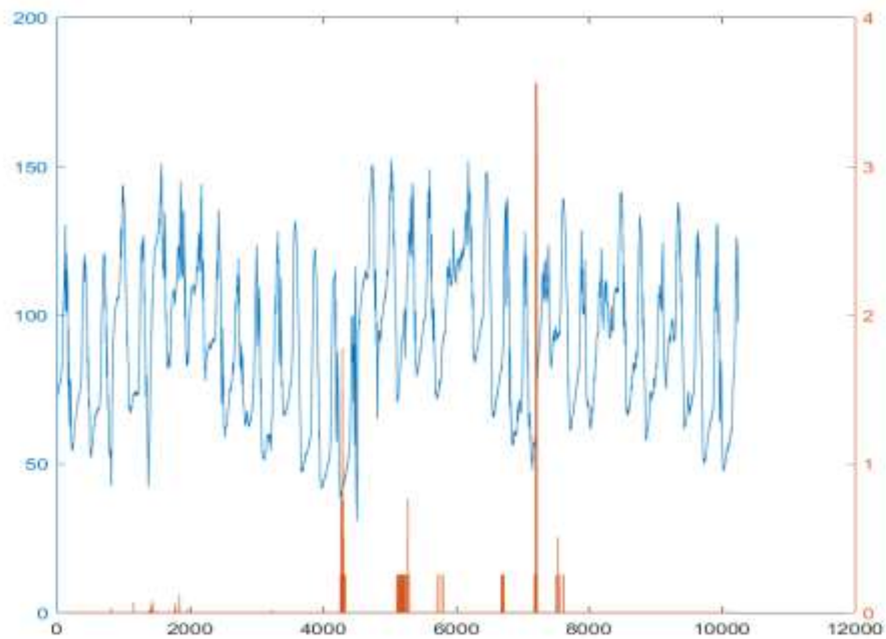

Figure 47. Load Cell 1 response versus measured rain events

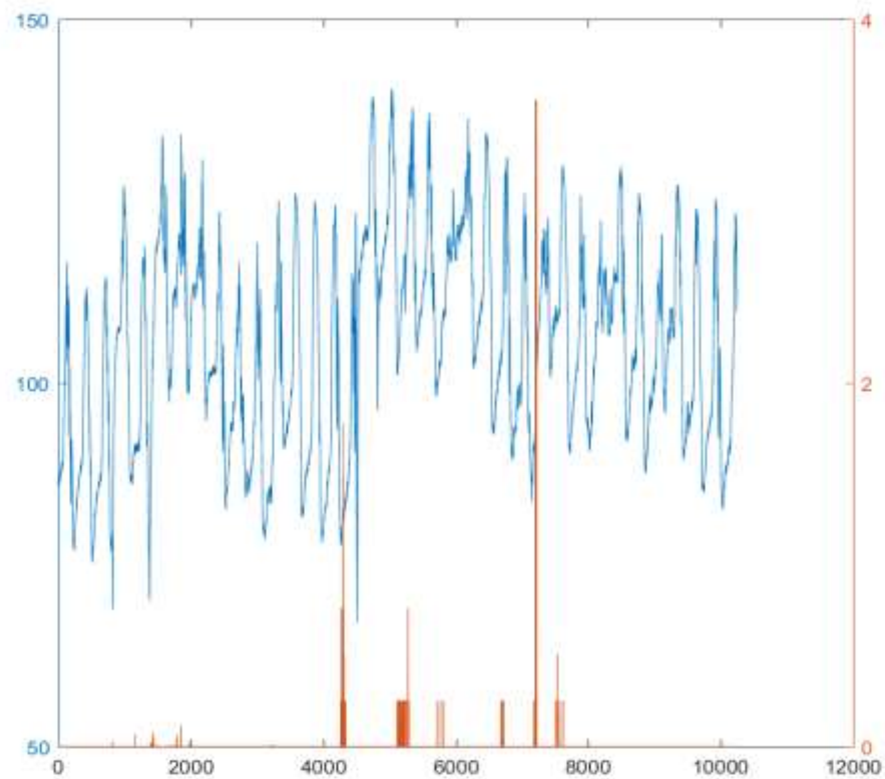

Figure 48. Load Cell 2 response versus measured rain events

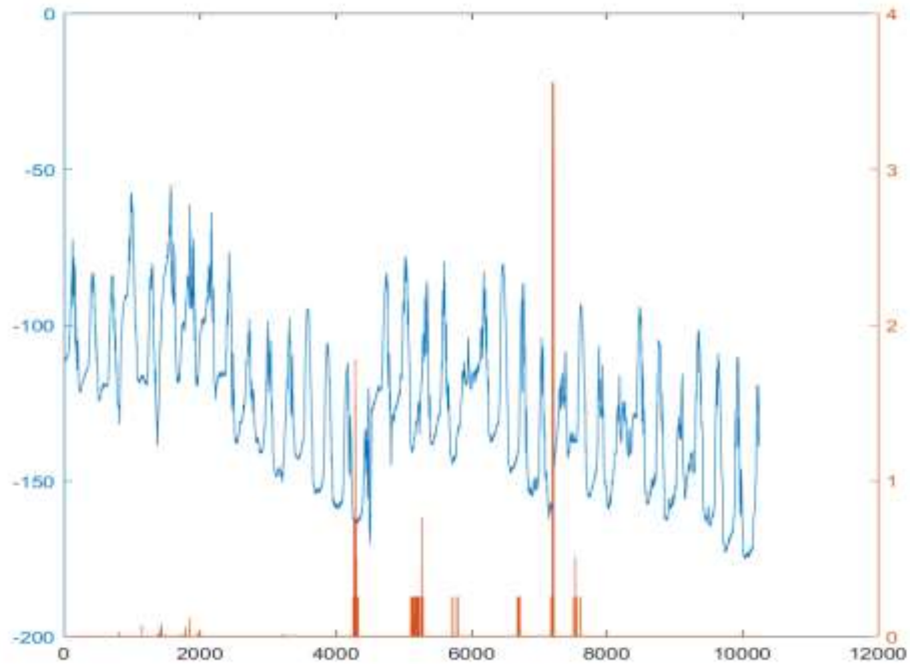

Figure 49. Load Cell 4 response versus measured rain events

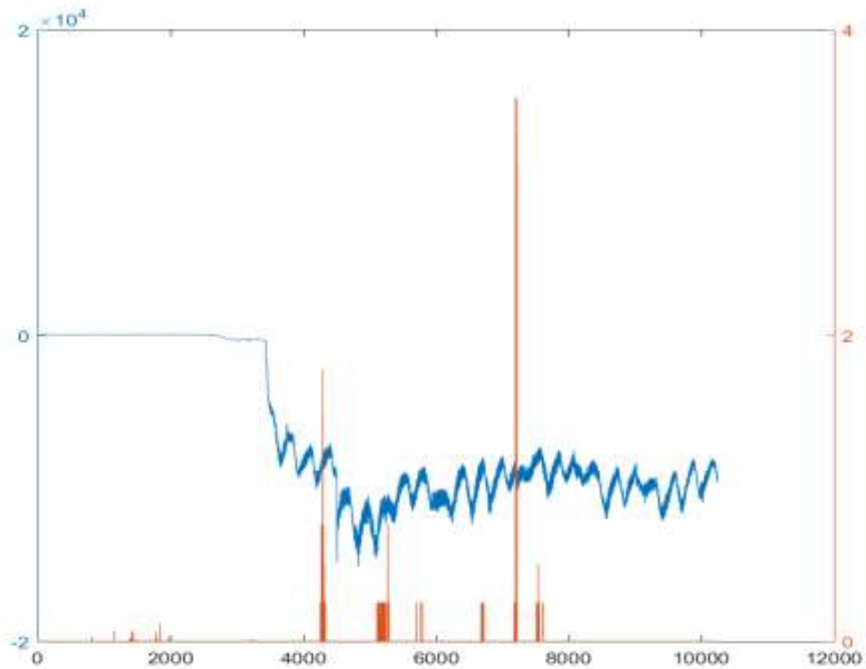

Figure 50. Load Cell 9 response versus measured rain events

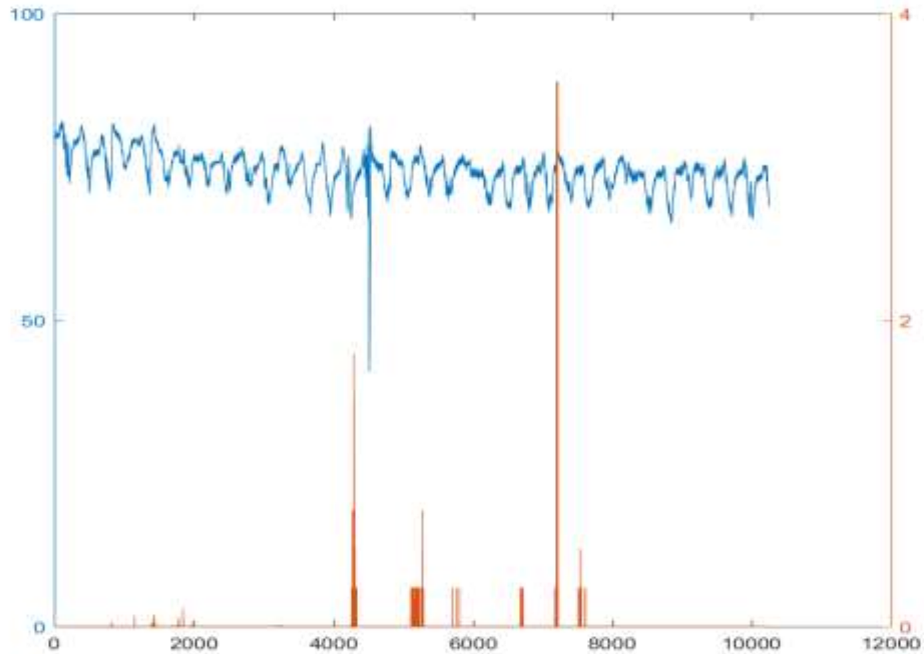

Figure 51. Load Cell 10 response versus measured rain events

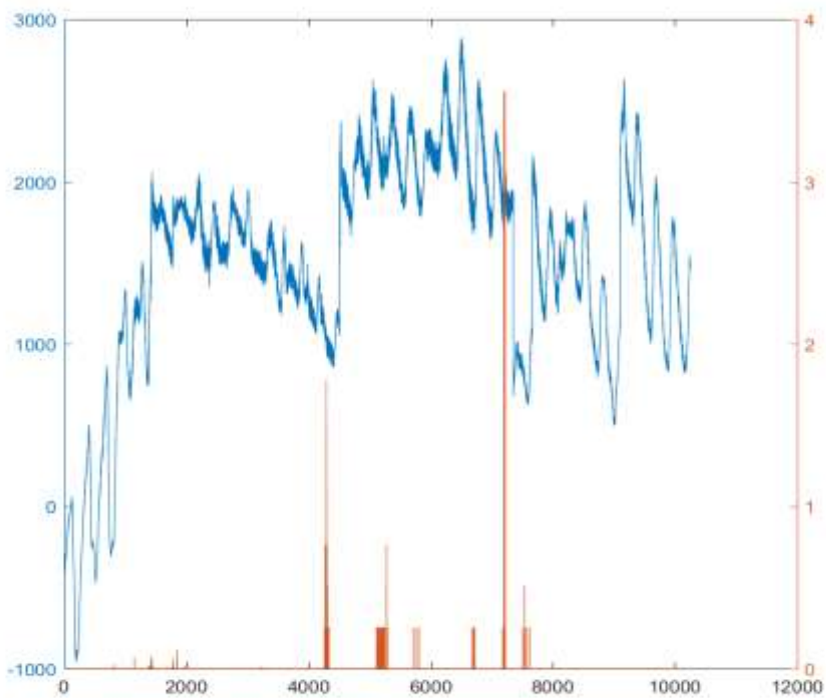

Figure 52. Load Cell 11 response versus measured rain events

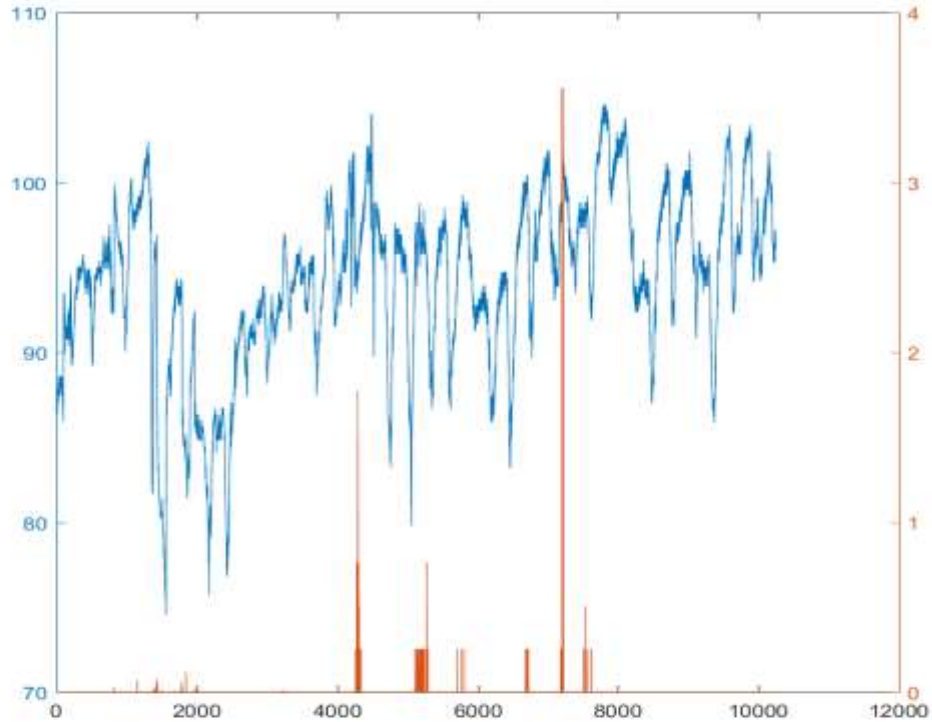

Figure 53. Load Cell 16 response versus measured rain events

To filter the load cells, first the signals were each taken separately, extended using the signal wavelet transformation (SWT) application in Matlab. Since signal denoising was the intended goal, the extension method utilized was a right extension for SWT filtering. The signals were extended to the maximum extension offered, where the original signal length measured 12047 measurements and was extended to 16384 providing 6137 additional points for filtering analysis. Once each filter was sufficiently extended, the SWT denoising portion of the Wavelet application was utilized to transform each signal with a 14 part db wavelet with 8 level decomposition. The thresholds were determined utilizing a soft medium penalization mode, with the sparsity dropped to the lowest level available for each signal. The thresholds for each filter were determined manually and independently for each load cell signal. Once the thresholds were determined, the filtered signal response was overlaid over the original load cell signal to show the adequacy of fit. After the fit was confirmed to be sufficient, the improved filtered signals were cropped by 6137 points from the right to return the signals to original length. The filtered response of load cell 1 compared to the original signal is shown in Figure 54. The filtered response of load cells 2, 11, 15, and 16 compared to its original signal are shown in Figures 55, 56, 57, and 58 respectively.

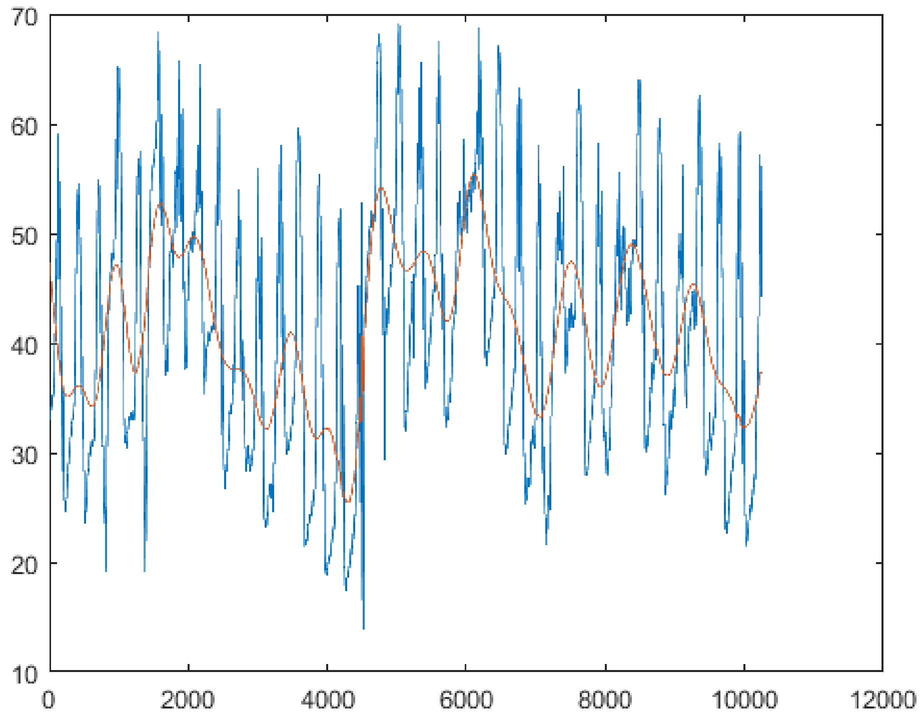

Figure 54. Load Cell 1 unfiltered versus Load Cell 1 filtered

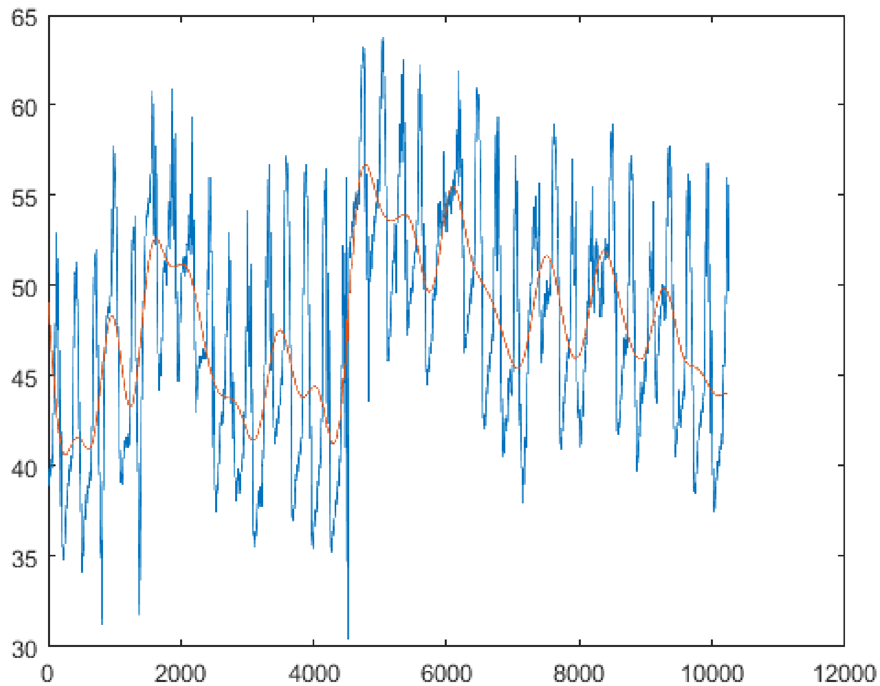

Figure 55. Load Cell 2 unfiltered versus Load Cell 2 filtered

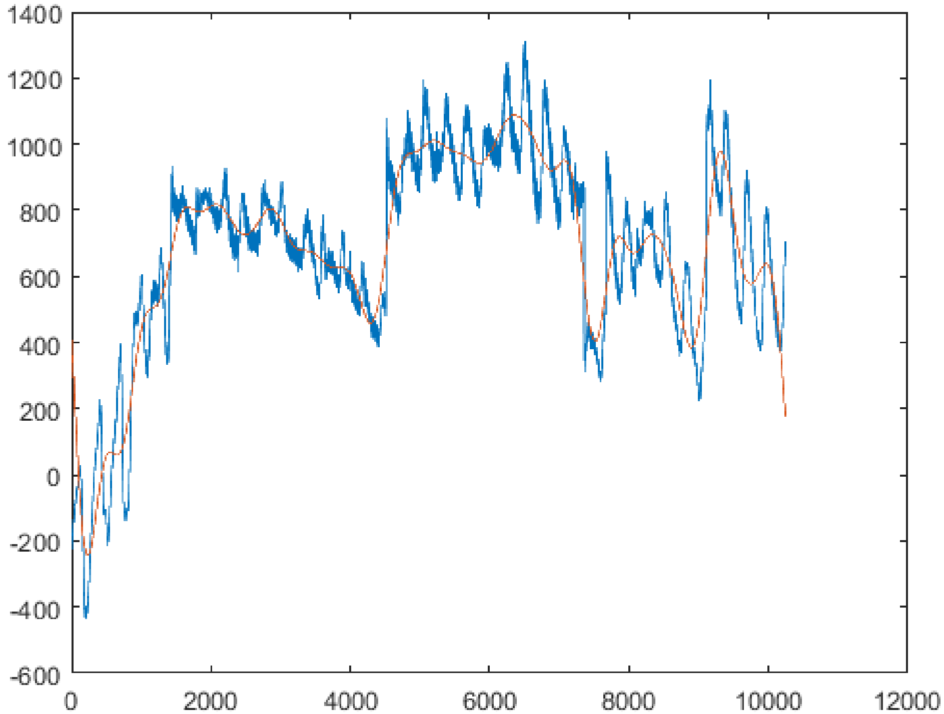

Figure 56. Load Cell 11 unfiltered versus Load Cell 11 filtered

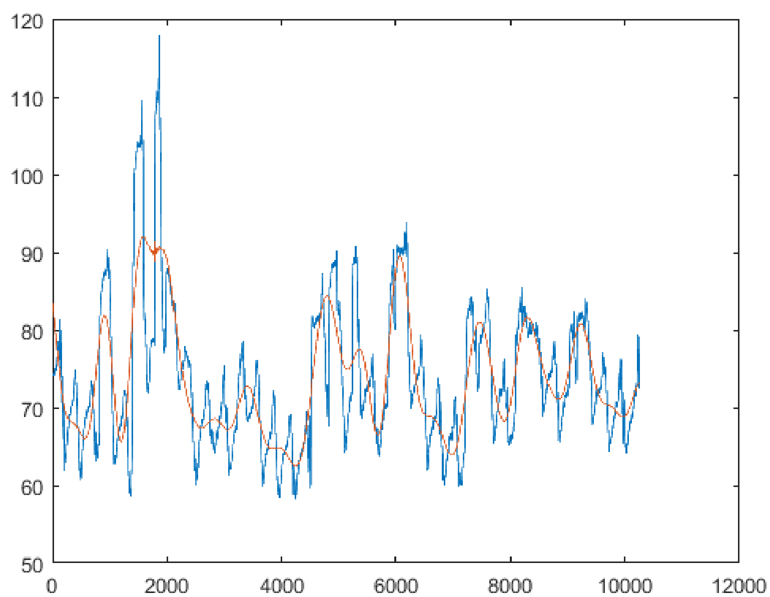

Figure 57. Load Cell 15 unfiltered versus Load Cell 15 filtered

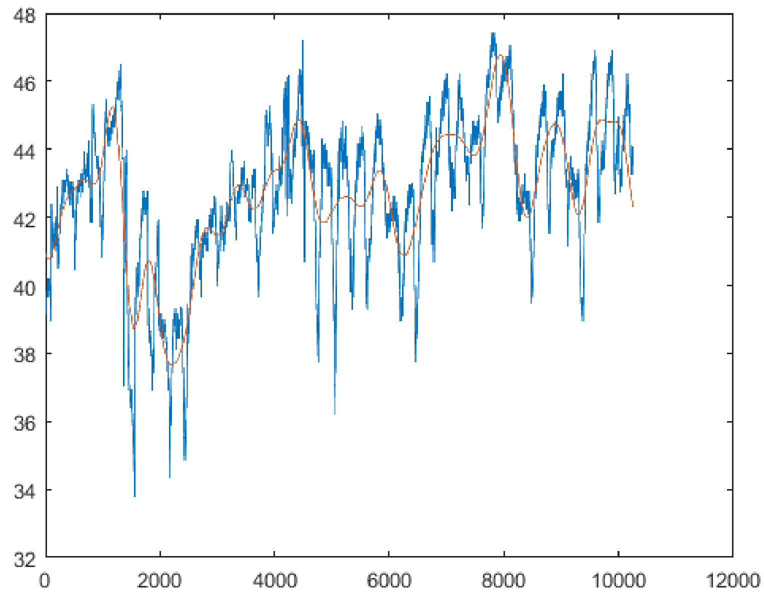

Figure 58. Load Cell 16 unfiltered versus Load Cell 16 filtered

After the load cell filtering procedure, the next step was to assign load cell values to slabs. Two load cells were used per slab in the sensor layout, but after evaluating the load cells compared to the measured rain events, it was clear that some of the load cells performed more closely to the expected response, where the mass increases after a rain event. The best signals were chosen to represent each slab. If both load cells were utilized for each slab, the average of each was utilized, otherwise the load cell with the better fit was chosen to represent that slabs mass for the purposes of this experiment. The result of this procedure determined that the mass of the slabs utilized from this point forth would be relative mass, which worked out well due to the poor quality of the load cell data and the poor fit determined by some of the load cells as shown above. Once the load cells were assigned to slabs, the next objective was to limit the load cell response to meaningful levels. The minimum of each load cell was set respective to the dry mass of the measured sample. The maximum of each load cell was set respective to the maximum modified saturated surface dry value, which was found in Table XX, utilizing the procedure outlined in the density determination section of this report, by using the ratio of the (Dry Mass/Wet Mass)/(LCsigmin/LCsigmax). The corrected slab 1 and 8 masses as compared to the original filtered results are shown in Figures 59 and 60 respectively.

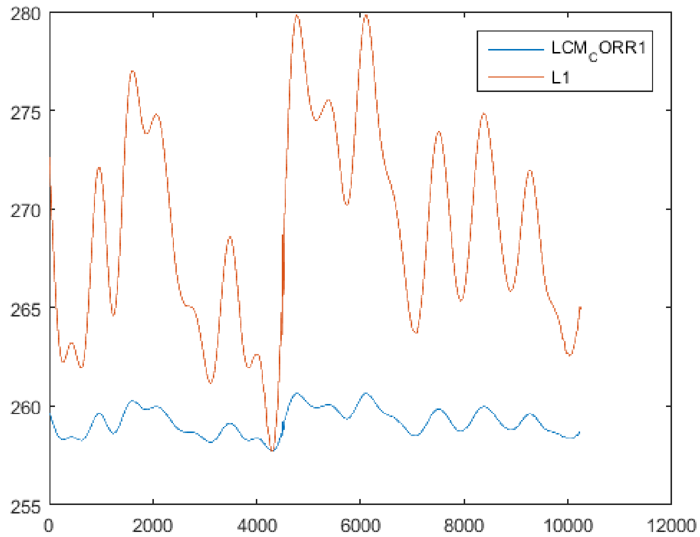

Figure 59. Slab 1 mass original versus corrected measurement

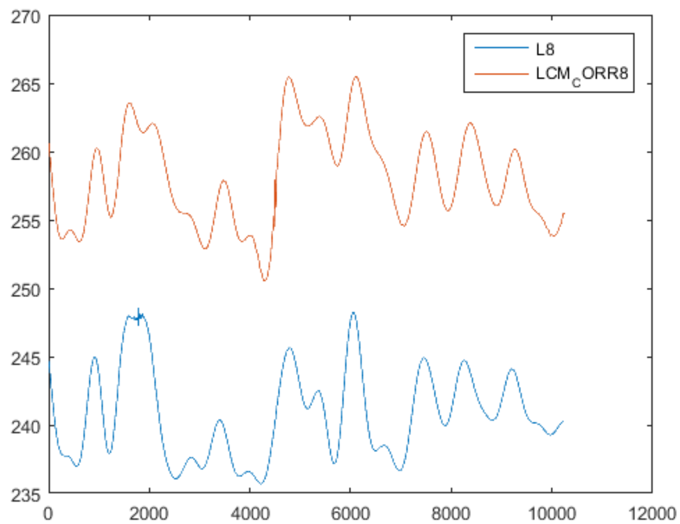

Figure 60. Slab 8 mass original versus corrected measurement

Slab 1, 2, 3, 4, 5, 6, 7, and 8 masses versus measured rain events are shown in Figures 61 through 68.

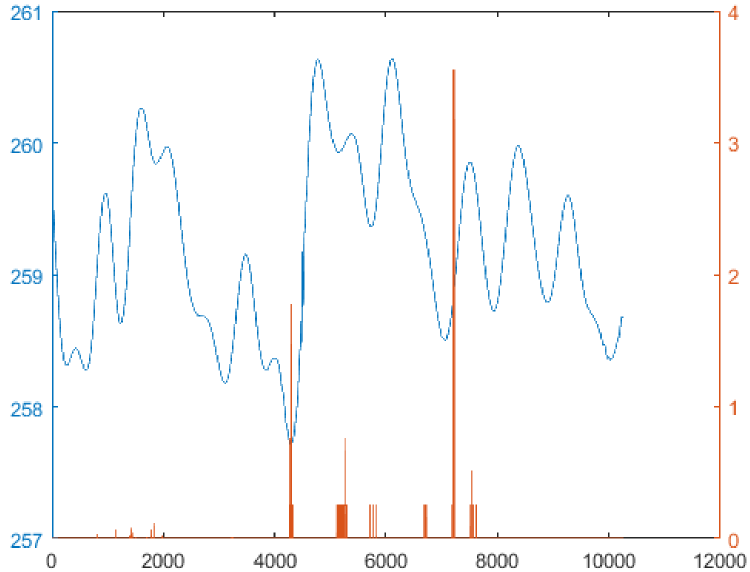

Figure 61. Slab 1 mass versus measured rain events.

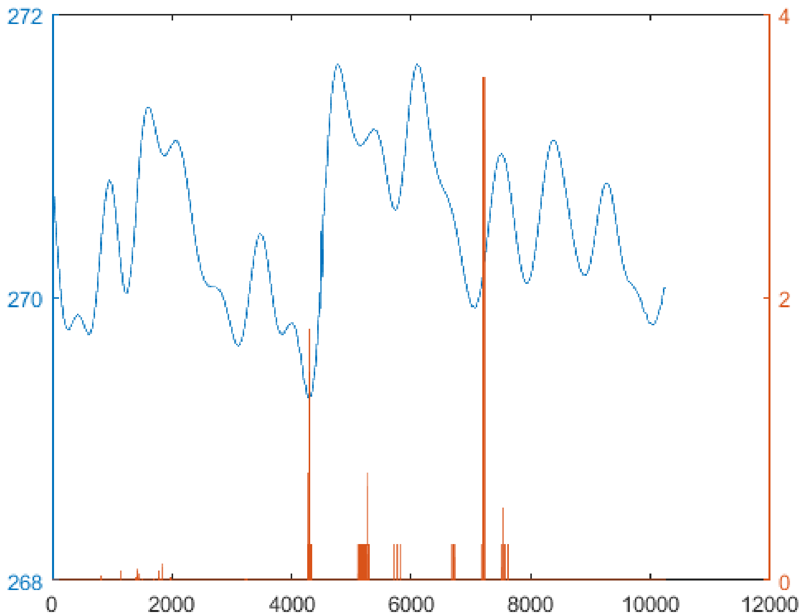

Figure 62. Slab 2 mass versus measured rain events.

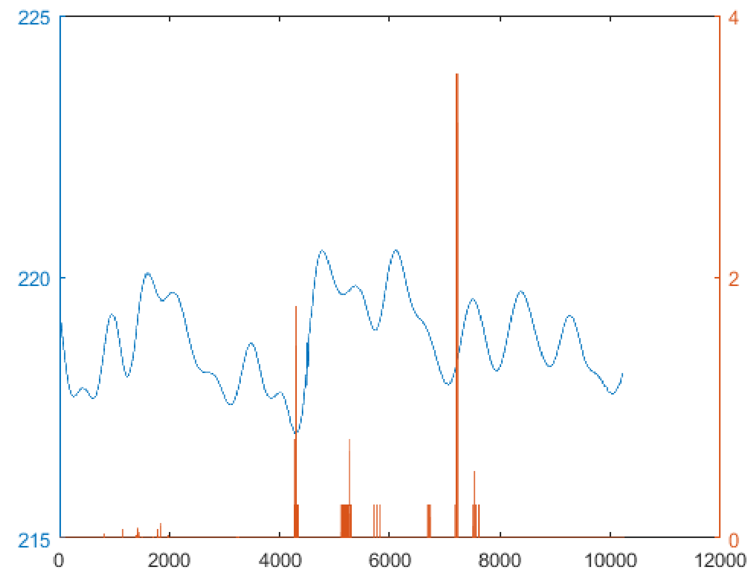

Figure 63. Slab 3 mass versus measured rain events.

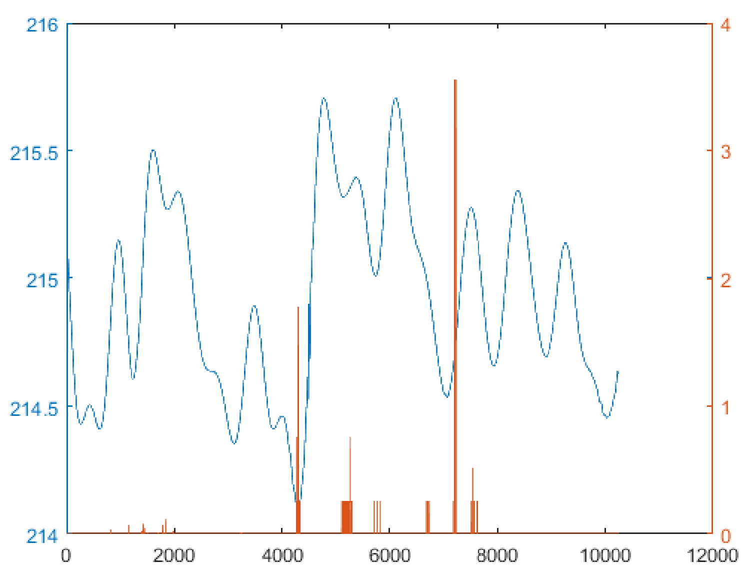

Figure 64. Slab 4 mass versus measured rain events.

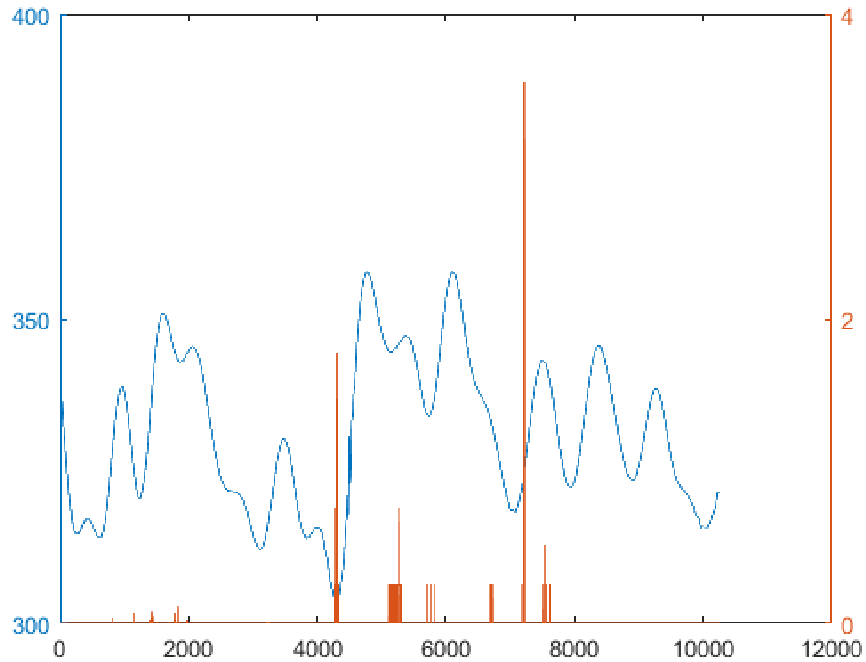

Figure 65. Slab 5 mass versus measured rain events.

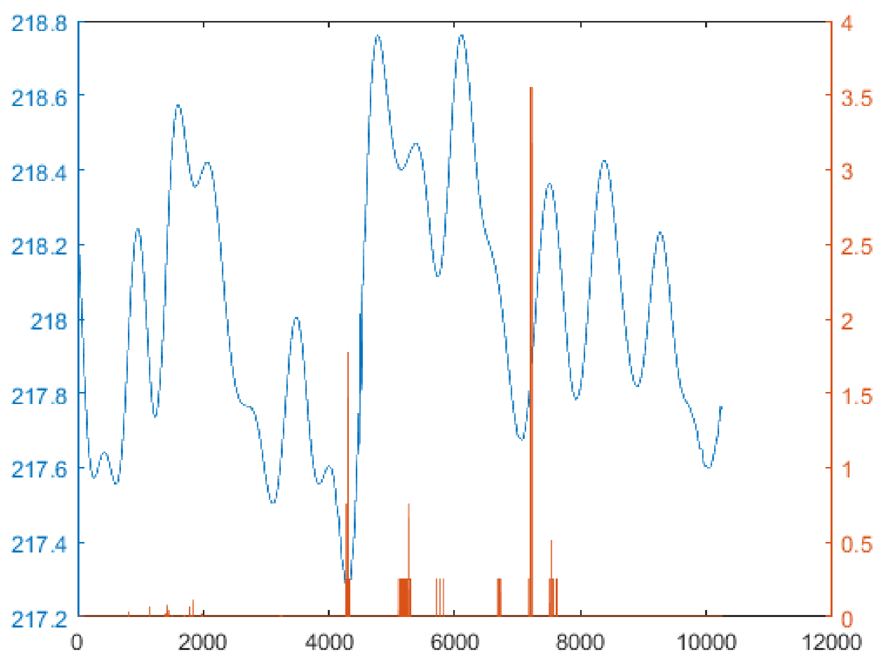

Figure 66. Slab 6 mass versus measured rain events.

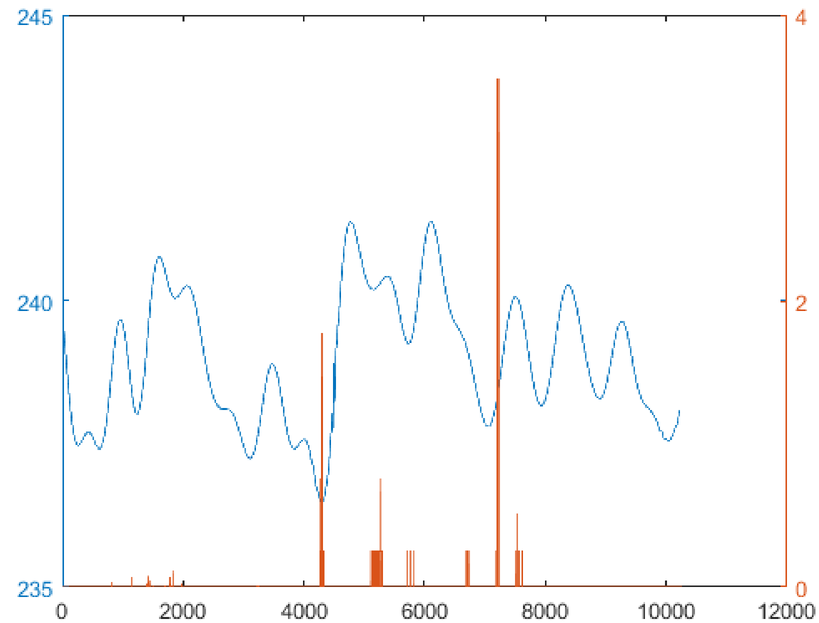

Figure 67. Slab 7 mass versus measured rain events.

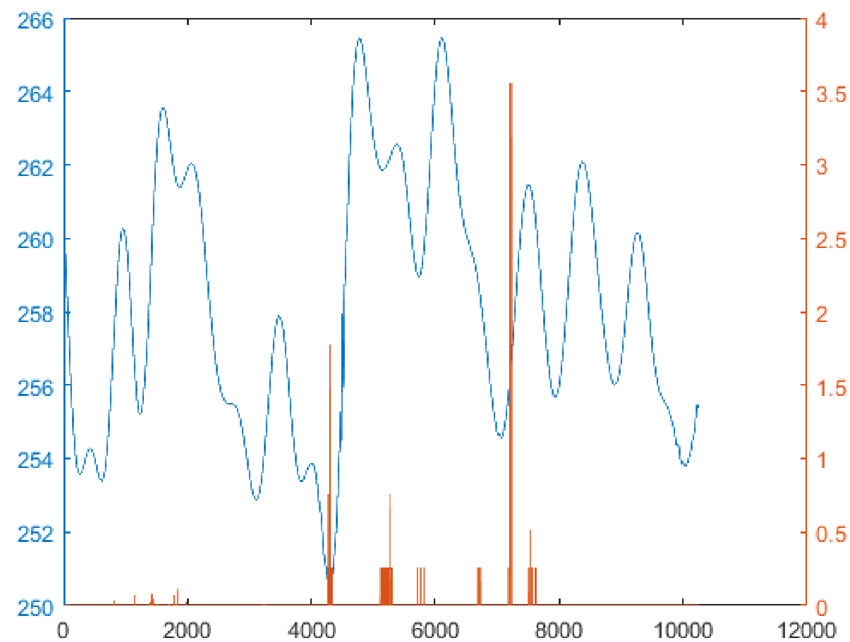

Figure 68. Slab 8 mass versus measured rain events.

Density Measurements

Bulk Density, Apparent Specific Gravity, and the Theoretical Maximum Specific Gravity of the pervious mixes was determined in the laboratory using a modified Air-Void Percentage method (Using Core-Lok Bag Density ASTM D6752, ACIXX) which first required the technician to follow the following procedure. First the technician ensured the samples were dry. Then the technician would record the dry mass of the sample in air. Then the technician recorded the mass of the Cor-Lok bag before vacuum sealing the bag to the sample. The technician would then record the mass of the sample in bag after vacuum sealing to verify the mass of bag plus sample. The vacuum sealed sample would then be placed in a water bath on a balance hanger for four minutes to ensure there were no leaks in the bag. At this point, the technician would record the sealed buoyant mass. After pulling the sample from the water, the technician would dry the bag, verify the mass, and then cut off the bag. Very often the bag would leak, which would result in false measurements. Those measurements were disregarded, the samples were required to dry again, then that portion of the test could be repeated by the technician. Once the vacuum bag bouyant mass was determined, the sample would then be placed in a pycnometer mounted on a vibrating plate. The sample was placed under water in the pycnometer and vacuum was applied at 25 in Hg (635.00 mm Hg) for four minutes. During the four minute period, the vibrating table would be applied for three minutes. After the saturation process was completed, the entire pycnometer would be placed in the water bath before transferring the sample entirely underwater to the balance hanger. After a four minute normalization period, the fully saturated mass would be recorded.

Bulk Specific Gravity was calculated using the following equation:

$$\text{Bulk specific gravity } (G_{mb}) = A\,[B - E - (B - A)/F_t\,]$$

Where:
A = mass of the dry sample in air before sealing
B = mass of the dry sealed sample
E = mass of the sealed sample in water
F_t = apparent specific gravity of the plastic sealing material at 25 °C, when sealed, (provided by the manufacturer) (0.7)

Apparent Specific Gravity was calculated using the following equation:

$$\text{Apparent specific gravity} = A\,[B - C - (B - A)/F_t1]$$

Where:
C = mass of the unsealed sample in water (total saturation)
F_t1 = apparent specific gravity of plastic sealing material at 25 °C, when opened underwater, (still need to get this number (assumed F_t for the time being)

The Bulk Specific Gravity and Apparent Specific gravity were corrected for water bath water density at various measurement temperatures based on the following equation:

$$\rho H_2O = 2E\text{-}5x3\text{-} 6.3E\text{-}3x2+2.69E\text{-}2x + 1000$$

The Theoretical Maximum Specific Gravity was calculated using the following equation:

$$\text{Theoretical maximum specific gravity} = G_{mm} = A\ (A - C)$$

This was then utilized to determine the Effective AV percentage based on the following equation:

$$\textit{Effective Air-Void Content (\%)} = 100 * (1 - G_{mb}/G_{mm})$$

Once the Apparent Specific Gravity, Bulk Specific Gravity, and Maximum Specific Gravity was determined, it was necessary to conduct a separate test to determine the Maximum Effective Moisture Content Since the air voids could only fill if the sample were overtopped, the Effective water content metric was designed to represent the maximum amount of water that the sample could hold in service, by following the follow procedure: Dry samples were fully submerged in the water bath for less than 1 minute. After that, the sample would be placed on an open-aired wire rack for four minutes, or effectively once the dripping stopped.

The mass was recorded at that point and the following equation was utilized to determine the Modified Saturated Surface Dry measurement or Maximum Effective Moisture Content:

Maximum Effective Water Content (%) = Mass of Stored water/Dry Mass of Sample.

Energy Budget: ΔQ

The total energy balance was determined by the following equation:

$$Q=RN-QH-QE- QG$$

Energy Budget: ΔJ

APPENDIX E: GUIDE DOCUMENT FOR USE OF PERVIOUS CONCRETE FOR SIDEWALKS

INTRODUCTION

Pervious concrete is a permeable material, often built with an underlying stone reservoir that temporarily stores surface runoff before it infiltrates into the subsoil. Unlike conventional concrete, pervious concrete allows stormwater to infiltrate directly into the soil. There are various types of pervious surfaces, including pervious asphalt, pervious concrete and grass or permeable interlocking pavers. The focus of this guide will be on the use of pervious concrete for sidewalks. Until more information is determined related to its field performance, maintainability, constructability, and improved benefit over other approved storm-water best management practices (BMPs), the inclusion of pervious concrete for sidewalks into NJDOT projects needs to be carefully considered. This document is intended to provide general guidance on the design and applicability of pervious concrete systems for NJDOT sidewalk projects. The intent was to have consistent guidelines and standards, if a pervious sidewalk installation was ultimately chosen. A major concern related to pervious concrete in sidewalks is maintainability. When considering pervious concrete for stormwater treatment, a project team should also evaluate the other approved BMPs and compare them to determine if pervious concrete would be considered the preferred BMP. Although, pervious concrete has seen growing use in the United States, there is still very limited practical experience with this measure. According to the U.S. EPA, pervious concrete sites have had a high failure rate – approximately 75 percent. Failure has been attributed to poor design, inadequate construction techniques, and soils with low permeability, heavy vehicular traffic and poor maintenance. When using pervious concrete for sidewalks as BMP measure, its performance should be carefully monitored over the life of the development. With proper design and installation, pervious concrete for sidewalks can provide a cost-effective solution for stormwater management in an environmentally friendly way. As a result, they are recognized as a best practice by the U.S. Environmental Protection Agency (34) and many state agencies (71).

BENEFITS AND LIMITATIONS

There are several benefits for using pervious concrete in sidewalks. One of the most important benefits is its effectiveness for stormwater management, improving water runoff quality, reducing stormwater runoff, and restoring groundwater supplies. It can also filter contaminants thus improving water quality. Several studies have quantified high removal rates of total suspended solids (TSS), metals, oil and grease, as well as moderate removal rates for phosphorous, from using pervious concrete (27,85). They also can minimize the use of deicing chemicals and while they do not remove chlorides, the reduction of deicing chemicals use is an effective method for reducing chloride pollution [85]. However, pervious concrete has shown to clog with time without the proper periodic vacuuming, cleaning and maintenance. Pervious concrete can also ravel and fail if used in unstabilized areas and not properly designed, constructed, and maintained. Pervious concrete construction also requires skilled labor and has higher initial costs. While pervious sidewalks have become popular in the area of stormwater management, the true applicability in specific applications still needs further evaluation especially if there is potential for ground water contamination. A site investigation is critical to evaluate whether pervious sidewalks are an appropriate BMP for a site. The site investigation should be conducted with appropriate staff to be able to consider hydrology and hydraulic design, soil permeability, pervious concrete thickness design, and environmental considerations and regulations.

Applicable Sites and Requirements

The first step in considering pervious sidewalks for a project is to confirm that the location is appropriate and will be able to provide infiltration for the life of the sidewalk. Because the primary means of storm-water treatment will be by infiltrating water, pervious concrete will act in a manner similar to other infiltration BMP's. Hydrologic Soil Groups A and/or B would be considered as the desired areas for considering infiltration BMPs. However, other soil types can be considered with the understanding that the design will still be driven by the determination of the infiltration rate, adhering to drawdown time requirements and meeting the minimum separation to groundwater. According to the NJDEP [71], pervious concrete systems are not suitable on sites with hydrologic group D or most group C soils, or soils with a high (>30%) clay content. Table 33 show USDA hydraulic soil group designations.

Table 33. USDA Hydrologic Soil Group Designations

Group	Infiltration in./hr.	Curve Number (CN)		
		Pavement	Bare Soil	Grass (good condition)
A	> 0.3	98	72	39
B	0.15 to 0.3	98	82	61
C	0.05 to 0.15	98	87	74
D	0 to 0.05	98	89	80

In general, the use pervious concrete systems are not recommended where certain conditions exist [27,71]. Table 34 summarizes the conditions were the use of pervious concrete systems is not recommended.

Table 34. Conditions were the use of pervious concrete systems is not recommended.

Landscaped and other pervious areas drain to the proposed pervious sidewalk. Debris and sediment from these areas could lead to clogging.	Not Recommended
Systems designed to infiltrate into the subsoil may not be used where their installation would create a significant risk of adverse hydraulic impacts. These impacts may include exacerbating a naturally or seasonally high water table that results in surficial ponding, flooding of basements, or interference with the proper operation of a subsurface sewage disposal system or other subsurface structure, or where their construction will compact the subsoil. **(NJDEP)**	Not Recommended
Locations regularly receive winter sanding. Seal coating or repaving are not appropriate for pervious sidewalks.	Not Recommended
Sidewalk placement will be in close proximity to structural foundations. Consult with your Storm Water Coordinator, Structures representative, or Geotechnical staff. It is not feasible to perform routine and long term maintenance, such as vacuuming to maintain the hydraulic function.	Not Recommended
Locations with potential for ground water contamination and areas with heavy use of pesticides**(NJDEP)**	Not Recommended
Karst topography, which is characterized by highly soluble bedrock, is susceptible to infiltration of runoff that may lead to subsidence and sinkholes. Only use pervious sidewalks with underdrains in these areas **(NJDEP)**	Not Recommended

DESIGN CRITERIA

Site Considerations (NJDEP Chapter 9.7)

When planning a pervious paving system, consideration should be given to a number of factors, including soil characteristics, depth to the groundwater table, site location and shading, sensitivity of the region, and inflow water quality. It is also important to note that the use of pervious paving designed to infiltrate into the subsoil is recommended in this manual only for the Water Quality Design Storm or smaller storm events. Use of these systems to infiltrate larger volumes, should only be considered when another applicable rule or regulation requires the infiltration of a larger storm event. In such a case, the pervious paving system should be designed to infiltrate the minimum storm event required to address that rule or regulation.

In general, County Soil Surveys may be used to obtain necessary soil data for the planning and preliminary design of pervious paving systems; however, for final design and construction, soil tests are required at the exact location of a proposed system. The results of this soil testing should be compared with the County Soil Survey data used to calculate runoff rates and volumes and to design BMPs on-site to ensure reasonable data consistency. If significant differences exist between the soil test results and the County Soil Survey data, additional soil tests are recommended to determine whether there is a need for revised site runoff and BMP design computations. All significant inconsistencies should be discussed with the local Soil Conservation District prior to proceeding with such redesign to help ensure that the final site soil data is accurate. The placement of pervious paving systems must comply with all applicable laws and rules adopted by Federal, State, and local government entities. Additionally pervious paving systems designed to infiltrate into the subsoil could negatively impact other facilities. Therefore, consideration should be given to the siting of these systems in areas where such facilities exist. These facilities include subsurface sewage disposal systems, water supply wells, groundwater recharge areas protected under the Ground Water Quality Standards rules at N.J.A.C 7:9C, streams under antidegradation protection by the Surface Water Quality Standards rules at N.J.A.C. 7:9B, or similar facilities or areas geologically and ecologically sensitive to pollutants or hydrological changes.

The presence or absence of Karst topography, which is characterized by highly soluble bedrock, is an important consideration when planning a pervious paving system designed to infiltrate into the subsoil. If Karst topography is present, infiltration of runoff may lead to subsidence and sinkholes; therefore, only pervious paving systems designed with underdrains should be used in these areas.

Soil Characteristics (NJDEP Chapter 9.7)

For pervious paving systems designed to infiltrate into the subsoil, soils are perhaps the most important consideration for site suitability.

- The bottom of the storage bed must be as level as possible in order to allow runoff to uniformly infiltrate into the subsoil.

- The seasonal high water table (SHWT) or bedrock must be at least 2 feet below the bottom of the storage bed.
- The permeability of the subsoil must be sufficient to allow the system to drain within 72 hours.
- Soil tests are required at the exact location of the proposed system in order to confirm its ability to function as designed. Take note that permits may be required for soil testing in regulated areas, such as areas regulated under the Flood Hazard Area Control Act Rules (N.J.A.C. 7:13), the Freshwater Wetlands Protection Act Rules (N.J.A.C. 7:7A), the Coastal Zone Management Rules (N.J.A.C. 7:7), and the Highlands Water Protection and Planning Rules (N.J.A.C. 7:38).
- The testing of all permeability rates must be consistent with Appendix E: Soil Testing Criteria in this manual, including the required information to be included in the soil logs, which can be found in section 3.b Soil Logs. In accordance with Appendix E: Soil Testing Criteria, the slowest tested permeability must be used for design purposes.
- Since the actual permeability rate may vary from soil testing results and may decrease over time, a factor of safety of 2 must be applied to the slowest tested permeability rate to determine the design permeability rate. The design rate would then be used to compute the system’s drain time for the maximum design volume. The drain time is defined as the time it takes to fully infiltrate the maximum design storm runoff volume through the most hydraulically restrictive layer.
- The maximum design permeability rate is 10 inches/hour for any tested permeability rate of 20 inches/hour or more.
- The minimum design permeability rate of the subsoil is 0.5 inches/hour, which equates to a minimum tested permeability rate of 1.0 inch/hour.
- Filter fabric is required along the sides of the storage bed to prevent the migration of fine particles from the surrounding soil. However, unlike systems with underdrains, filter fabric may not be used along the bottom of the storage bed because it may result in a loss of permeability.
- An outlet at the elevation of the Water Quality Design Storm is required to prevent the infiltration of larger storm events; however, additional storage above this elevation may be included to address quantity control requirements.
- At least one inspection port, with a removable cap, must be provided in the storage bed with its location denoted in the maintenance plan. The inspection port must be placed at least 3 feet from any edge. Additionally, each inspection port must be flush with the surface of the surface layer and extend down 4 – 6 inches into the subsoil, and the depth of runoff for the Water Quality Design Storm must be marked on each structure and its level included in the design report and maintenance plan. The size of the inspection port must be large enough to allow for maintenance activities.
- As with any infiltration BMP, groundwater mounding impacts must be assessed, as required by N.J.A.C. 7:8-5.4(a)2.iv. This includes an analysis of the reduction in permeability rate when groundwater mounding is present. Where the mounding analysis identifies adverse impacts, the pervious paving system must be redesigned or relocated, as appropriate. The mounding analysis must provide details and supporting documentation on the methods used and assumptions made, including values used in calculations.

- Testing must be performed on the subsoil below the storage bed after excavation but prior to placement of the stone in accordance with the Construction and Post-Construction Oversight and Soil Permeability Testing section in Appendix E: Soil Testing Criteria of this manual. Whereas-built testing shows a longer drain time than designed, corrective action must be taken. The drain time is defined as the time it takes to fully infiltrate the maximum design storm runoff volume through the most hydraulically restrictive layer. The illustration below shows one possible configuration and flow path of a pervious paving system designed to infiltrate into the subsoil and is not intended to limit the design. Note that the surface of the system is sloped and the choker course varies in depth. This example provides additional storage for runoff generated by storm events larger than the Water Quality Design Storm and the perforated inspection ports are tied in to the laterals for distribution of excess runoff at the surface.
- Pervious concrete systems should not be used on slopes greater than 5% with slopes of no greater than 2% recommended. For slopes greater than 1% barriers perpendicular to the direction of drainage should be installed in sub-grade material to keep it from washing away, or filter fabric should be placed at the bottom and sides of the aggregate to keep soil from migrating into the aggregate and reducing porosity.
- A minimum of four feet of clearance is recommended (may be reduced to two feet in coastal areas) between the bottom of the gravel base course and underlying bedrock or the seasonally high groundwater table.
- Pervious concrete systems should be sited at least 10 feet down-gradient from buildings and 100 feet away from drinking water wells.
- To protect groundwater from potential contamination, runoff from designated hotspot land uses or activities must not be infiltrated. Pervious concrete should not be used for manufacturing and industrial sites, where there is a potential for high concentrations of soluble pollutants and heavy metals. In addition, pervious concrete should not be considered for areas with a high pesticide concentration. Pervious concrete is also not suitable in areas with karst geology without adequate geotechnical testing by qualified individuals and in accordance with local requirements.
- Frost depth should be considered. UNH [(88)] recommends the bottom of the stone reservoir be 60% of the frost depth. However, many projects in cold regions have been constructed at lesser depths with no problems from freezing noticed.
- The aggregate reservoir can sometimes be avoided or minimized if the sub-grade is sandy and there is adequate time to infiltrate the necessary runoff volume into the sandy soil without by-passing the water quality volume.

HYDROLOGICAL DESIGN

Hydrological design determines what storage layer thicknesses are required to sufficiently infiltrate, store, and release the expected inflow of water, which includes both rainfall and may include excess stormwater runoff from adjacent impervious surfaces. This requires information regarding the layer thicknesses and subgrade permeability along with precipitation intensity levels. The hydrologic design of pervious concrete should be performed by a licensed engineer. The two most common methods for modeling stormwater runoff are the SCS/NCRS Curve Number method and the Rational method. The Rational method is not recommended for evaluation of pervious systems.

Pervious sidewalks are often not designed to store and infiltrate the maximum precipitation at the site. Therefore overflow should be included in the design to prevent stored stormwater from reaching the surface layers. This typically will involve perforated pipes in the stone reservoir that are connected to discharge pipe. It is also recommended that an alternate path for stormwater to enter the stone reservoir be provided in case the surface should become clogged.

NJDEP Requirements for Hydrological Design (NJDEP Chapter 9.7)

- Pervious concrete systems can be used where the underlying in-situ subsoils have an
  infiltration rate greater than 0.5 inches per hour. Therefore, pervious concrete systems are not suitable on sites with hydrologic group D or most group C soils, or soils with a high (>30%) clay content. During construction and preparation of the subgrade, special care must be taken to avoid compaction of the soils.
- Pervious concrete systems should typically be used in applications where the sidewalk receives tributary runoff only from impervious areas. Actual pervious surface area sizing will depend on achieving a 24 hour minimum and 48 hour maximum draw down time for the design storm volume.
- If runoff is coming from adjacent pervious areas, it is important that those areas be fully stabilized to reduce sediment loads and prevent clogging of the pervious concrete surface. Pretreatment using filter strips or vegetated swales for removal of course sediments are recommended. (see sections 3.3.1 and 3.3.2)
- Nonstructural stormwater management strategies design standard in the SWM rules must be addressed for all major development, pursuant to NJAC 7:8-5.3(a).
- Must be designed to meet the soil erosion and sediment control standards in NJ
- May be designed to meet Groundwater Recharge (See Ch. 6)
- Must not be used where their installation would result in adverse hydraulic impacts such as exacerbating a naturally or seasonally high water table (resulting in surface ponding).
- Pretreatment only applies for vehicular surfaces. However, must minimize sediment and particulates in runoff by installing gutter guards, sumps and traps with maintenance access points in the conduits of the storage beds (where underdrain is planned)
- The minimum tested infiltration rate of any of these surfaces to be considered pervious is 6.4 inches/hour. A system designed for quantity control must have a minimum infiltration rate of the surface course of 20 inches per hour.
- The BMP requires the treatment of the entire Water Quality Design Storm volume without overflow; Total Suspended Solid (TSS) removal rate of 80%.

- For stormwater quantity control, storage times in excess of 72 hours are not allowed.
- For systems designed for stormwater quantity control, emergency overflow catchments must be provided to direct surface runoff in excess of that generated by the maximum design storm.
- Where an outlet structure is included in the pervious sidewalk system, the effective opening of the outlet must be calculated as if it is partially obstructed by the rock screen and stone of the storage bed.
- Effects of tailwater must be analyzed for instances where the lowest outlet in the system is flooded by design flood or tide elevation.

STRUCTURAL DESIGN

While limited field performance information is available, pervious concrete slabs should have good durability if constructed and maintained properly. For pervious sidewalks carrying light traffic only, the structural demands do not control its design and the material thicknesses are determined by the hydrological design and minimum thicknesses required for incidental bending stresses. Typical thickness of pervious concrete for sidewalks is 4 inches. Typical cross section consists of a pervious concrete later, filter layer(s), aggregate storage layer, and filter fabric as shown in Fig. 1.

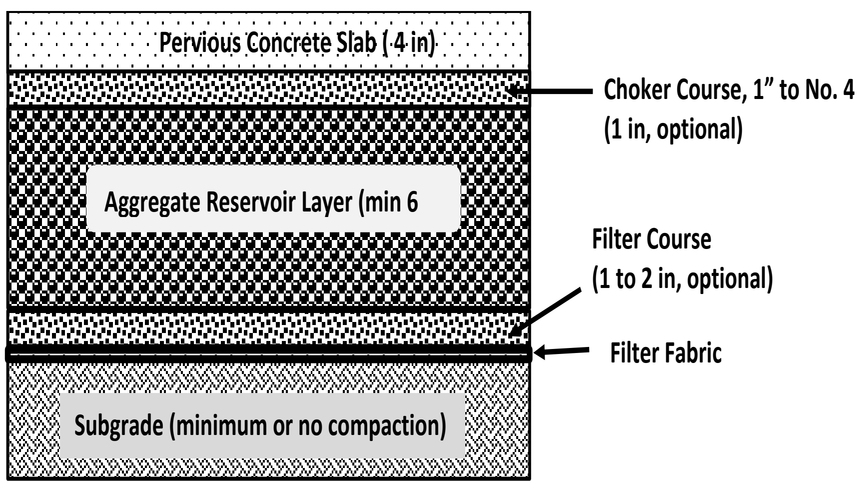

Figure. 69. Typical Cross Section of Pervious Concrete for Sidewalks

<u>*Pervious Concrete Layer*</u> – The pervious concrete layer consists of an open-graded concrete mixture usually 4 inches thick depending on required bearing strength and the sidewalk design requirements. *Pervious concrete can be assumed to contain 18 percent voids (porosity = 0.18) for design purposes*.
<u>*Choker Layer*</u> – Consists of 1/2 inch diameter crushed stone to a depth of 1 to 2 inches on top of the aggregate reservoir. *This layer is optional as NJDEP does not require a choker layer for pervious systems designed to infiltrate into the subsoil.* This layer

serves to stabilize the pervious concrete layer. Can be combined with reservoir layer using suitable stone.

Aggregate Reservoir Layer – The reservoir gravel base course consists of washed, clean gravel, 1 1/2 to 2 1/2 inches in diameter with a void space of about 40% (No. 2 and No. 57 per ASTM C33). *The depth of this layer depends on the desired storage volume, which is a function of the soil infiltration rate and void spaces, but typically ranges from a minimum of 6 inches to three feet. The layer should be designed to drain completely in 48 hours. This layer should be designed to store at a minimum the water quality volume. Aggregate contaminated with soil shall not be used. A porosity value of 0.32 can be used in calculations unless voids specific data exist.*

Filter Layer – Covers the subgrade and can be 6 inch layer of sand (ASTM C33 concrete sand) or 1 to 2 inch thick layer of 1/2 inch crushed stone, and be completely flat to have infiltration across the entire surface. This layer serves to stabilize the reservoir layer, to protect the underlying soil from compaction, and act as the interface between the reservoir layer and the filter fabric covering the underlying soil.

Filter Fabric – Should cover the entire trench area, including the sides, with filter fabric prior to placement of the aggregate. The filter fabric serves a very important function by inhibiting soil from migrating into the reservoir layer and reducing storage capacity.

Underlying Soil or Subgrade – The underlying soil should have an infiltration capacity of at least 0.5 in/hr, but preferably greater than 0.50 in/hr. as initially determined from NRCS soil textural classification, and subsequently confirmed by field geotechnical tests. The subgrade is minimally compacted.

PROPERTIES AND SPECIFICATIONS

Properties

Typical properties of pervious concrete are summarized in Table 2. These values are based on criteria provided by several departments, agencies, field experience and others [References]

Table 35. Typical properties of pervious concrete.

Property	Range
Density	105 lb/ft3 to 130 lb/ft3 (ASTM C29)
W/Cementitious Ratio	0.27 – 0.34
Void Ratio	15% to 25% (ASTM C138)[1]
Permeability	300 in/hr to 1000 in/hr
Compressive Strength	2000 psi to 3000 psi
Bending Strength	250 psi to 350 psi

[1] *NJDEP Chapter 9.7*

NJDOT Material Specifications

- Type I or II Portland Cement with minimum cementitious content equal to 550 lb/cu.yd
- Aggregates (pervious concrete): Use No. 8 (3/8 in to No. 16) per ASTM C33 or No. 89 coarse aggregate (3/8 to No. 50) per ASTM D448.
- Aggregate content: The volume of aggregate shall be equal to approximately 27 cu. ft. per cu. yd. when calculated as a function of the unit weight determined in accordance with ASTM C29(6) jigging procedure
- Aggregate (reservoir layer): No. 2 (2 ½ to 1 ½) and No. 57 (1" to No. 4) per ASTM C33(7).
- Admixtures Type A, B, D (Water reducing/Retarding).
- Hydration stabilizing admixtures meeting requirements of ASTM C 494. Type B Retarding or Type D Water Reducing/Retarding admixtures can be utilized and are recommended. The stabilizer suspends cement hydration by forming a protective barrier around the cementitious particles, delaying the initial set as the pervious concrete heats up in the truck.
- Air Entrainment: has been shown to increase freeze thaw durability of pervious concrete.
- Subgrade compaction 92% ± 2% of the max dry density
- Non-woven Geotextile filter fabric to be placed on top of the subgrade per ASTM D6767-02.
- Mixture Water: Water shall be potable and comply with ASTM 1602.
- Fine aggregate can be used but its volume should not exceed 3 cu. ft. and should also be included in the total aggregate volume. Final aggregate content will depend upon the specific gravity of the aggregate to be used and the desired void content to be obtained in the hardened pervious concrete. If required for added strength, the percentage and type of synthetic fibers or quantity of fine sand required in the mix must be specified and testing must be in accordance with current pervious concrete industry standards **(NJDEP Section 9.7)**
- Fly Ash shall conform to ASTM C 618. Fly ash conforming to ASTM C618 may be used in amounts not exceeding twenty percent (20%) by weight of the total cementitious material.
- Ground Granulated Blast Furnace Slag shall conform to ASTM C 989. Ground Granulated Blast Furnace Slag conforming to ASTM C 989 may be used in amounts not exceeding 50 percent by weight of the total cementitious material.

NJDOT Construction Specifications

1. Subgrade Preparation. Construct subgrade to ensure that the required sidewalk thickness is obtained at all locations. Ensure the subgrade is compacted by a mechanical vibratory compactor to a maximum density of 92% ± 2% of a maximum dry

density as established by ASTM D1557. Ensure the prepared subgrade is not disturbed prior to construction. Scarify, regrade and minimally recompact disturbed subgrade prior to concrete placement.

2. Aggregate Base Course. Prior to placing the aggregate base course, place the non-woven geotextile on top of the prepared subgrade. Ensure the geotextile is wrapped around the side and over the top of the aggregate base course extending a minimum of 6-inches from the edge of the top. Place the aggregate base course to a thickness as shown in the Plans. Ensure that required sidewalk thickness is achieved at all locations.

3. Forms. Ensure that the forms are thoroughly cleaned and treated with a material that will prevent adherence of the concrete to the forms without discoloring the concrete prior to each use of the forms.

4. Expansion Joints. Construct ½-inch wide expansion joints, placed at intervals of approximately 20 feet, with preformed joint filler. Ensure that the expansion joint material extends to the full depth of the concrete.

5. Mixing. Use pervious concrete within one (1) hour from introducing water in the mix unless otherwise approved by the RE. The time can be increased to ninety (90) minutes when using set control admixtures.

6. Admixtures. Admixtures shall be used in accordance with the manufacturers' instructions and recommendations.

7. Placing Concrete and Finishing. Obtain RE approval of formwork and joint placement before placing concrete. Place concrete according to the limitations specified in 504.03.02.C. Ensure the placement of pervious concrete also is in accordance with ACI 522.1. Do not use steel trowels or power finishing equipment. Finish the sidewalk to the elevation and thickness specified in Plans.

8. Curing. Place polyethylene sheeting on the finished surface within 20 minutes of concrete discharge. Completely cover the sidewalk surface with polyethylene sheeting. Cut sheeting to a minimum of full placement width. Secure polyethylene sheeting without using dirt. Cure sidewalk for a minimum of 7 uninterrupted days.

9. Skilled Personnel and Test Strip. Care should be taken in hiring and training all contractors and subcontractors, inspectors and other personnel to ensure proper methods and sequences are followed. Construction of a test strip prior to installation of the proposed pervious paving system is recommended to nail down site specific issues. Additionally, until any adjacent landscaping is complete, it is strongly recommended that the surface course be covered with plastic film and held in place with timber to discourage vehicular access and storage of landscaping materials on the surface course ***(NJDEP Chapter 9.7)***

Control and Acceptance Testing

1. Mix Design. Contractor shall furnish a proposed mix design with proportions of materials prior to commencement of work. Design at least one (1) mix to equal or exceed required strength and other required properties. At least 20 days prior to start of pervious concrete placement, submit each mix design for approval.
2. Fresh Density. Measure density using 0.25 ft3 cylindrical metal apparatus per ASTM C1688. Fresh density shall be within $\pm$ 5% of the design density.
3. In-Place Infiltration. Measure in-place infiltration in accordance with ASTM C1701.
4. Post-construction Testing of the pervious concrete surface course is required and must conform to the methods of ASTM C1701: Standard Test Method for Infiltration Rate of InPlace Pervious Concrete, on the day the plastic sheeting is removed. At least three locations must be used for the test, and they should be spaced evenly across the pervious paving system. Failure to achieve the minimum design infiltration rate of the surface course at one or more location indicates the system cannot be put in service until the system is corrected to yield all passing values. Unlike the test methodology outlined in the ASTM standards, the test results must not be averaged. The maintenance plan must include a log for recording each location and its test result for future reference. **(NJDEP Chapter 9.7).**
5. Contractor shall place, joint and cure two test panels, each to be a minimum of 225 sq. ft. at the required project thickness to demonstrate to the Project Manager's satisfaction that sidewalk compaction and finish can be installed at the site location.
6. Test panels may be placed at any of the specified Portland cement pervious locations. Test panels shall be evaluated for thickness, compaction, and porosity. If the test panels are found to be insufficiently pervious or insufficiently compacted, the test panel shall be removed at the Contractor's expense and disposed of in an approved landfill.
7. If test panels are satisfactory, they can be left in place and included in the completed work.
8. For each day of paving, core 3 samples for each 10,000 sq. ft or fraction thereof. The Engineer determines coring locations.

CONSTRUCTION

One of the most important concerns during the construction of pervious concrete is the clogging of the surface or filling of the voids in the stone reservoir. As a result, protecting the stone reservoir during construction from uncontrolled runoff from adjacent areas and the surrounding soil is critical. This includes having temporary stormwater controls in place until the site is stabilized with clear specific guidance for construction.

Concrete Placement and Restrictions (NJDEP Chapter 9.7)

- Construction may not take place during rain or snow, or when the subsoil is frozen. Frozen aggregate materials may not be installed.
- If required for added strength, the percentage and type of synthetic fibers or quantity of fine sand required in the mix must be specified and testing must be in accordance with current pervious concrete industry standards.
- The air temperature must be above 32 degrees Fahrenheit on the day of placement and for seven calendar days prior.

- Finishing techniques, such as floating or troweling must not be used, because this would close the surface voids of the concrete.
- Covering pervious concrete with plastic sheeting during curing is required, as it prohibits moisture loss in the concrete mix. Plastic sheeting placement must conform to industry standards for timing and duration. While the plastic sheeting is in place, the pervious concrete must be blocked off from pedestrian or vehicular traffic.
- Pervious concrete shall not place when the ambient temperature is predicted by the National Weather Service Point Forecast for the jobsite to be 40°F (4.4ºC) or lower or if it rises above 90°F (32.2ºC) during the seven days following placement during the seven days following placement, unless otherwise permitted in writing by the Architect/Engineer **(CRMCA)**

Construction Requirements

- The proposed area of the pervious sidewalk system must be kept free from sediment during the entire construction process. Construction materials contaminated by sediments must be removed and replaced with clean materials **(NJDEP Chapter 9.7)**
- The excavation to the final design elevation of the storage bed may only occur after all construction within its drainage area is completed and the drainage area is stabilized. This prevents soil migration into pervious sidewalk system during its construction. If construction of the pervious paving system cannot be delayed, during all phases of construction all flows must be diverted away from the pervious paving system. The diversions may not be removed until all construction within the drainage area is completed and the area is stabilized **(NJDEP)**
- The location of the proposed pervious paving system should not be used to provide sediment control during construction; however, when unavoidable, the bottom of the sediment control basin should be at least 2 feet above the final design elevation of the bottom of the storage bed in the pervious paving system **(NJDEP Chapter 9.7)**
- The contributing drainage area must be completely stabilized prior to pervious paving system use **(NJDEP Chapter 9.7)**
- The pit excavation should be limited to the width and depth specified in the design. Excavated material should be placed away from the open trench as not to jeopardize the stability of the trench sidewalls. The bottom of the excavated trench should not be loaded so as to cause compaction, and should be scarified prior to placement of sand. The sides of the trench shall be trimmed of all large roots. The sidewalls shall be uniform with no voids and scarified prior to backfilling. All infiltration trench facilities should be protected during site construction, and should be constructed after upstream areas have been stabilized.
- Plan to construct the pervious sidewalk as late as possible in the construction schedule.
- Protect site area from excessive heavy equipment running on the subgrade, compacting soil, and reducing permeability.
- Excavate the subgrade soil using equipment with oversized tires or tracks to minimize compaction

- As soon as the bed has been excavated to the final grade, the fabric filter should be placed with an overlap of a minimum of 16 inches. Use the excess fabric (at least 4 feet) to fold over the stone bed to temporarily protect it from sediment.
- Install drainage pipes, if required.
- Place the aggregate stone recharge bed carefully to avoid damaging the fabric. The aggregate should be dumped at the edge of the bed and placed in layers of 8 to 12 inches using tracked equipment and compacted with a single pass of a light roller or vibratory plate compactor.
- When using a stabilizer course, it is important that the aggregate be sized properly to interlock with the aggregate in the recharge bed. The stabilizer course should be placed at a thickness of about 1 inch. Some larger stones from the stone reservoir should be visible at the surface.

Adjacent Landscaping (NJDEP Chapter 9.7)

- Runoff from pervious areas should be directed away from the pervious system, where possible.
- Where it is not possible to direct runoff from adjacent landscaping away from a pervious paving system, a gravel strip or swale should be provided to filter and reduce the intrusion of sediment, with additional monitoring and corrective measures added to the maintenance plan. Care should be taken in the selection of top dressing for nearby vegetated areas; particulates transported by wind or during rainfall or snowmelt could result in the clogging of the surface course. Preventative measures should be included in the maintenance plan and should be re-evaluated as necessary to ensure long-term functionality of the system.

MAINTENANCE

According to the NJDEP (2016), pervious paving systems must have a maintenance plan and must be protected by easement, deed restriction, ordinance, or other legal measures that prevent its neglect, adverse alteration and removal. It's often in the best interest of local governments or agencies to care for the facility via a Maintenance Agreement if proposed sidewalk will require specialized care or equipment. Early communication between NJDOT and local partners can help define respective needs, abilities, and limitations. The primary goal of pervious sidewalk maintenance is to prevent the sidewalk surface, reservoir, and/or underlying soil (infiltration bed) from being clogged with sediments. To keep the system clean throughout the year and prolong the pervious sidewalk life span, the sidewalk surface should be inspected, tested as, and vacuumed.

General Maintenance (NJDEP Chapter 9.7)

Regular and effective maintenance is crucial to ensure effective pervious paving system performance; in addition, maintenance plans are required for all stormwater management facilities on a major development. In addition to the manufacturer's maintenance requirements, there are a number of required elements in all maintenance plans, pursuant to N.J.A.C. 7:8-5.8; these are discussed in more detail in Chapter 8: Maintenance of Stormwater Management Measures. Furthermore, maintenance activities are required through various regulations, including the New Jersey Pollutant Discharge Elimination System (NJPDES) rules, N.J.A.C. 7:14A. Specific maintenance requirements for pervious paving systems are presented below; these requirements must be included in the maintenance plan for pervious paving systems. Table 3 summarizes maintenance activities and frequencies.

Table 36. Maintenance activities and schedule

Activity	**Schedule**
Proper training of personnel to perform inspection and use of equipment	By Arrangement
First annual maintenance in the spring after pervious concrete construction	First annual maintenance
Fall maintenance after fallen leaves are collected and removed	*
Inspect surface for deterioration, spalling, cracking, subsidence, erosion, vegetation	Annually
Vacuum sweep pervious concrete surface followed by air blowing or high pressure power washing	Four (4) times per year
Test infiltration rate after last snow or ice event (ASTM C1701 or ASTM C1781)	Each spring
Ensure pervious layer is free of sediments	After major rain events

General Maintenance

- Failure to correctly maintain a pervious paving system will shorten its lifespan or result in system failure; therefore, the maintenance plan must ensure proper training of personnel and include the special equipment necessary in accordance with the industry's or manufacturer's requirements.
- The surface course must be inspected, at least once annually, for cracking, subsidence, spalling, erosion, deterioration and unwanted vegetation. Remedial measures must be taken as soon as possible. Herbicides must not be applied.
- The surface course of a pervious paving system must be vacuum swept, not power swept, at least four times per year. Vacuum sweeping must be followed by either air blowing or high pressure power washing performed in accordance with the specifications recommended for the particular type of system. All dislodged material must be promptly removed. The first annual maintenance must be performed in the spring. Maintenance must additionally be performed in the autumn, after the fallen leaves are collected and removed.
- Each spring, after the last snow or ice event, the infiltration rate of the surface course must be tested in accordance with the methods of either ASTM C1701 or C1781, as corresponds to the post-construction test performed for the system. At least 3 locations must be tested. One of the locations must be in an area where sediment is most likely to be deposited, such as, but not limited to, a parking lot entrance. The other test locations must be evenly spaced across the system surface. The locations and results obtained must be recorded in the maintenance plan for future reference

and compared to the as-built testing results as a metric for determining if a system requires corrective action. The chart provided below shows the approximate infiltration rate based upon the time it takes to infiltrate either 8 or 40 pounds of water specified in the above-cited tests. This chart should be included in the maintenance plan for future reference.

Cold Weather Maintenance (NJDEP Chapter 9.7)

- Care must be taken when removing snow from the surface course; pervious paving surface courses may be damaged by snowplows or loader buckets set too low to the ground or not equipped with a rubber blade guard. Sand, grit or cinders may not be used on surface courses for snow/ice control.
- De-icing chemicals may not be used on pervious concrete less than one year old.
- De-icers containing magnesium chloride, calcium magnesium acetate or potassium acetate may never be used on pervious concrete.
- Snow and ice, especially from areas treated with sand, cinders or de-icing materials, may not be stockpiled on a pervious paving system.
- A grade-separated area must be designated on the plan for stockpiling snow and ice separate from the pervious paving system.
- Although pervious sidewalk may have less need for de-icers, de-icing may still be necessary, and some de-icing compounds may react chemically with one or more components in a pervious paving system resulting in deterioration; therefore, care should be taken when selecting these compounds. Take into consideration that some of the volume of commercially available products may contain magnesium or other damaging compounds without being declared on the product packaging; therefore, any compound selected should be used on a test area prior to applying to the whole system. Take further note that that de-icing compounds used on adjacent, traditional sidewalk may be tracked onto a pervious paving system, and consideration should also be given to the selection of those compounds. The application of a penetrating silane based sealant to a pervious concrete or concrete paver surface course is strongly recommended as additional protection against chemical degradation by de-icing compounds, as long as the chosen sealant does not impair the rate of infiltration of the surface course. During design, frost penetration and the ability of each layer to fully drain should also be taken into account when calculating layer thicknesses to ensure that each component is thick enough to prevent frost heave. Finally, because stored runoff may expand during freezing, provisions, such as a lateral drainpipe or an increased depth of the storage bed below the frost line, should be included in the design to reduce the likelihood of frost heave.

Signage (NJDEP Chapter 9.7)

Because pervious paving systems look like traditional sidewalk, signage may be necessary to eliminate improper application of de-icing compounds, to prevent dumping of hazardous materials and to eliminate the intrusion of vehicles exceeding the design-loading rate of the system, which could compact and deform the surface course.

Trees (NJDEP Chapter 9.7)
Trees may be planted near a pervious parking lot, provided ample clearance and sufficient soil volume for maturation are included, as it is essential to prevent tree roots from penetrating into the stone bed of a pervious sidewalk installation; however, consideration must also be given to the location of the arboreal dripline and the potential for fallen leaves, icicles and snow to cover the surface of the pervious sidewalk after a wind event.

Corrective Actions (NJDEP Chapter 9.7)
Corrective action must be immediately taken to restore the infiltration capacity of the pervious paving system under the following scenarios:

- Standing water is observed on the surface course
- The testing methods above show an infiltration rate of 20 inches per hour or less for a system designed for quantity control or 6.4 or less for a system designed for water quality control only.
- If mud or sediment is tracked onto the surface course, it must be removed as soon as possible. Removal should take place when all runoff has drained from the surface course.
- Disposal of debris, trash, sediment and other waste material must be done at suitable disposal/recycling sites and in compliance with all applicable local, state and federal waste regulations.
- Under no circumstances may any sealants or coatings be applied to pervious paving systems, except for those approved by the manufacturer to improve surface course resistance to de-icing chemicals or refresh traffic striping.
- Over the lifetime of the surface course, no more than 10% of its surface area may be patched with impervious material such as bituminous asphalt or concrete. All patching must be recorded in the maintenance manual for future reference to prevent exceedance of this maximum.
- The approximate drain time for the maximum design storm runoff volume below the top of the surface course must be indicated in the maintenance manual.
- If the actual drain time is significantly different from the design drain time, the components and groundwater levels must be evaluated and appropriate measures taken to return the pervious paving system to minimum and maximum drain time requirements.
- If the system fails to drain the maximum design storm volume within 72 hours, corrective action must be taken.