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Implementation of Porous Concrete in Sidewalks in New Jersey

Final Report
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16. Abstract
Pervious (or porous) concrete has been gaining popularity as a potential solution to reduce the amount of impermeable surfaces associated with sidewalks, reduce puddling, and potentially slow storm water surface runoff. As important as these benefits are to surface runoff mitigation, there are concerns with the ability of pervious concrete to provide sufficient structural support and longevity for the expected service life of the sidewalks as well as its 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 in sidewalks is relevant to its geographical location, subsurface conditions, and intended application. There is a need to collect information on construction practices and performance data of porous sidewalks. To collect data, a porous concrete sidewalk was constructed and monitored. The sidewalk is part of the Skillman Road Pathway project in Montgomery Township. The Skillman Road Pathway project was a good candidate because of its location, ease of access, intended use, and timeline. The sidewalk was 4 in thick constructed on top of 10 in storage (reservoir) layer made of No. 57 stone with 40% voids. The sidewalk is about 200 ft long and 6 ft wide (approximately 1,200 ft^2). Monitoring the sidewalk included visual inspection of surface texture for raveling or clogging; periodic infiltration tests to measure variation of infiltration rates over time. The research team prepared several mix designs in the lab with and without sand and worked with the supplier to adjust these mixes and select two mixes for field application. Observation from this project showed the supplier, contractor and the field crew need to have prior experience in placement and finishing of porous concrete, as well as the operator of the ready mix truck and supervising field personnel. Constructing a near test slab nearby the site prior constructing the sidewalk can be beneficial for placement and finishing and is recommended. It also can be used to take cores and select the desired water pressure for pressure washing when needed. Visual inspection showed air blowers can keep the sidewalk free of debris if done frequently but vacuuming with suction twice per year is more effective and can keep the porous concrete sidewalk free of debris and minimize clogging. If clogging occurs, pressure washing should be used to clean the sidewalk. Water pressure of 2000 psi is sufficient to clean minor clogging and 3000 psi to 3500 psi is sufficient to clean moderately to severely clogged locations. Higher water pressure could damage the surface and cause raveling. A LCCA tool was developed based on MS Excel platform consisting of multiple excel worksheets including main input, secondary input, calculations, and results. The worksheets provide a friendly interactive interface for users and also maintain the flexibilities for advanced users to alter embedded functions and update secondary inputs. The LCCA tool combines hydrologic design and the life cycle cost analysis of porous concrete pavements.

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EXECUTIVE SUMMARY

Pervious (or porous) concrete has been gaining popularity as a potential solution to reduce the amount of impermeable surfaces associated with sidewalks, reduce puddling, and potentially slow storm water surface runoff. As important as these benefits are to surface runoff mitigation, there are concerns with the ability of pervious concrete to provide sufficient structural support and longevity for the expected service life of the sidewalks as well as its 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 in sidewalks is relevant to its geographical location, subsurface conditions, and intended application. There is a need to collect information on construction practices and performance data of porous sidewalks. To collect data, a porous concrete sidewalk was constructed and monitored. The sidewalk is part of the Skillman Road Pathway project in Montgomery Township. The Skillman Road Pathway project was a good candidate because of its location, ease of access, intended use, and timeline. The sidewalk was 4 in thick constructed on top of 10 in storage (reservoir) layer made of No. 57 stone with 40% voids. The sidewalk is about 200 ft long and 6 ft wide (approximately 1,200 ft^2). Monitoring the sidewalk included visual inspection of surface texture for raveling or clogging; periodic infiltration tests to measure variation of infiltration rates over time. The research team prepared several mix designs in the lab with and without sand and worked with the supplier to adjust these mixes and select two mixes for field application. Observation from this project showed the supplier, contractor and the field crew need to have prior experience in placement and finishing of porous concrete, as well as the operator of the ready mix truck and supervising field personnel. Constructing a near test slab nearby the site prior constructing the sidewalk can be beneficial for placement and finishing and is recommended. It also can be used to take cores and select the desired water pressure for pressure washing when needed. Visual inspection showed air blowers can keep the sidewalk free of debris if done frequently but vacuuming with suction twice per year is more effective and can keep the porous concrete sidewalk free of debris and minimize clogging. If clogging occurs, pressure washing should be used to clean the sidewalk. Water pressure of 2000 psi is sufficient to clean minor clogging and 3000 psi to 3500 psi is sufficient to clean moderately to severely clogged locations. Higher water pressure could damage the surface and cause raveling. A LCCA tool was developed based on MS Excel platform consisting of multiple excel worksheets including main input, secondary input, calculations, and results. The worksheets provide a friendly interactive interface for users and also maintain the flexibilities for advanced users to alter embedded functions and update secondary inputs. The LCCA tool combines hydrologic design and the life cycle cost analysis of porous concrete pavements.

BACKGROUND

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 be designed to 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 [1,2]. It can also reduce 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[3]. However, pervious concrete has shown to clog with time if periodic vacuuming, cleaning, and maintenance protocols are not followed. Pervious concrete can also ravel and fail if used in unstabilized areas and not properly designed, constructed, and maintained. Pervious concrete construction also requires experience and skilled labor. Despite the increased use of pervious concrete in the area of storm water management, the true applicability in specific applications still needs further evaluation. According to the U.S. EPA [4], 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 supervision, 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 implementation project is intended to provide information on the design, construction, and monitoring of porous concrete in sidewalk in New Jersey. A structural and hydrological design will be conducted, and mix designs will be selected for field application. The implementation will also include refined life cycle cost analysis for porous concrete sidewalks. 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 the preferred BMP for a sidewalk[5]. Although, pervious concrete has seen growing use in the United States, there is still limited construction and performance data and practical experience with its use. This implementation will provide needed information for its application in sidewalks.

OBJECTIVES

The primary objective of this study is to implement porous concrete in sidewalks and monitor its performance over time. This study addresses construction and maintenance issues regarding porous sidewalk including a cost benefit analysis based on the life cycle of conventional sidewalks versus porous sidewalks.

The following tasks will be performed to achieve these objectives:

1. Conduct survey of NJ counties, municipalities, developers, NJTPA, SJTPA, DVTPA to collect information from stake holders to learn about their experience with porous sidewalks and their interest in implementing a porous concrete sidewalk and monitor its performance overtime.

2. Evaluate the performance of existing porous concrete sidewalks in New Jersey.

3. Study and evaluate the various factors that influence the performance of porous concrete in sidewalks and identify the project site where the porous concrete sidewalk will be built.

4. Select viable mix designs based on results from previous study and narrow them down through observing mechanical properties and durability and using survey results from several state DOT from a previous study. And work with supplier on modifying and adjusting selected mixes for filed application.

5. Construct porous concrete sidewalk and evaluate construction practices, placement and finishing.

6. Monitor the constructed sidewalk by ding periodic visual inspection, infiltration tests, power vacuuming, and pressure washing if needed.

7. Refine life-cycle cost analysis using results from previous study and using refined cost data based on field projects and refined expected life of porous concrete depending on its application.

8. Provided refined guidelines for the design, construction, and maintenance of porous concrete sidewalks based on the results of previous tasks refinements of guidelines for the design, construction, and maintenance of porous concrete sidewalks in NJ.

INTRODUCTION

The purpose of this research is the implementation of porous concrete in sidewalks in New Jersey. Earlier research performed by the research team on the properties of porous concrete identified several mix designs and evaluated mechanical properties as well as durability. The implementation used this information to select the mix design that is appropriate for field application. The research team worked with the supplier to adjust the mixes for proper transit and application in the field. The research team surveyed several stakeholders and identified a site for the construction of the sidewalk.

The Skillman Road Pathway project was identified as a good candidate because of its location, ease of access, intended use, and timeline. A structural design as well a hydrological design was performed to design the sidewalk. During construction the research team worked with the supplier, the contractor and Township supervisor to successfully implement the sidewalk in the field. The research team prepared a plan to monitor the sidewalk using visual inspection, infiltration measurements and methods to for cleaning of debris and removal of clogging if it happens. The sidewalk was 4 in thick constructed on top of 10 in storage (reservoir) layer made of No. 57 stone with 40% voids. The sidewalk is about 200 ft long and 6 ft wide (approximately 1,200 ft^2). The construction included two segments with different mix design with and without sand. Monitoring the sidewalk will include visual inspection of surface texture for raveling or clogging; periodic infiltration tests to measure variation of infiltration rates over time. Observation from this implementation and monitoring with provide needed information that will be useful for stakeholders when using porous concrete as BMP measure.

LITERATURE REVIEW

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 be designed to 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 (1,2). 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 (3). However, pervious concrete has shown to clog with time if periodic vacuuming, cleaning, and maintenance protocols are not followed. 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. According to the U.S. EPA (4), 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. When considering pervious sidewalks for a project, it is important to confirm that the location is appropriate and will be able to provide the required 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 (5), 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 1 show USDA hydraulic soil group designations and curve numbers (CN) for selected surfaces.

Table 1- USDA Hydrologic Soil Groups and curve numbers (CN) for selected surfaces (6)

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 unfavorable soil conditions exist [5]. Table 2 summarizes the conditions where the use of pervious concrete systems is not recommended.

Table 2- Conditions where 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)[5]	**Not Recommended**
Locations regularly receive winter sanding. Seal coating or repaving are not appropriate for pervious sidewalks (Caltrans)[7]	**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 [7]	**Not Recommended**
Locations with potential for ground water contamination and areas with heavy use of pesticides [5]	**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 [5]	**Not Recommended**

Site Consideration

According to the NJDEP[5] (Chapter 9.7), when planning a pervious 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 anti-degradation 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.

Table 3- Typical permeability of each layer in the porous pavement system

Layer	Description	Permeability (in/hr)	References
Porous Concrete Surface	19 mixture designs	50 - 300	Testing Samples from Rutgers Research Team
Choker Course	(AASHTO No. 57 – NJDOT Specification 901.03)	10000	Cedergren et al.[8] (1973)

Reservoir bed	(AASHTO No. 2 – NJDOT Specification 901.03)	60000	Cedergren et al. [8] (1973)
Geotextile	Non-woven AASHTO M288 Class 2 (NJDOT Specification 919.01)	k(fabric)>= k(Soil)	Huang [9] (2004)
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 [10] (1982)

Porous Pavement Maintenance Requirements

According to the County of San Diego (2014) [11], it is essential that the porous pavement surface and/or the underlying infiltration bed are prevented from being clogged with fine sediments. They recommend that the pavement surface be vacuumed biannually with a commercial cleaning unit.

For pavements that has become significantly clogged where routine vacuuming does not restore required infiltration, then a more intensive level of treatment may be required such as pressure washing (Country of San Diego, 2014) [11]. Recent studies have revealed the usefulness of washing porous pavements with clean, low-pressure water, followed by immediate vacuuming. Combinations of washing and vacuuming techniques have proved effective in cleaning both organic clogging as well as sandy clogging. Research in Florida found that a “power head cone nozzle” that “concentrated the water in a narrowly rotating cone” worked best. If the pressure is too high, the water jet can drive debris and contaminants into the pavement.

The State of Wisconsin DNR [12] 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. The Wisconsin DNR [12] report also requires effective cleaning of the porous pavement when the infiltration rate is less than 10 in/hr. For repair, they allow repairs of the defective locations with conventional concrete if the repair area is less than 10% of the total area.

Based on review of the specs and the requirements of several agencies, DOT’s authorities, cities, and counties, the following requirements for porous concrete mix proportions, performance properties, construction requirements, hydraulic requirements, and structural design are identified:

Recommended Mix Proportions for Porous Concrete (per cubic yard) (13)
500 – 620 lbs. of cement Type I/II
2500-2800 lbs. of 3/8 in aggregates
Fine aggregates (maximum 7% 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 (13)
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 100” to 300” of rain per hour)**

Recommended Construction Requirements for Porous Concrete (14)
Construct test pad or test slab 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 (14)
Subgrade compacted to 92%+/- 2%
Avoid subgrade compaction
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 (14)
4” for sidewalks/pathways
6” parking lots
6” residential driveways
8” residential streets
8” commercial driveways

***** *Coring is recommended for compressive strength information. 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

EVALUTION OF EXISTING POROUS SIDEWALKS IN CAMDEN COUNTY

Three existing porous concrete sidewalks were evaluated in Camden County in South Jersey. The evaluation included visual inspection as well as infiltration tests.

Location A (Built 2015)
Porous concrete sidewalk, Brimm medical arts high school, 1626 Copewood st, Camden, NJ 08103
Area = $\underline{1200\ ft^2}$

At this location the visual inspection showed no signs of raveling and it looked like the sidewalk was well maintained. The average infiltration rate of three tests on the site was approximately 300 in/hr. Fig. 1 shows the infiltration test and Figs 2 and 3 show the sidewalk surface.

Location B (Built 2015)
Porous Concrete Sidewalk, Vietnamese Community Center, N 29th St & Cramer St, Camden, NJ 08105,
Area = $\underline{1525\ ft^2}$

At this location the visual inspection showed no signs of raveling, but the sidewalk did look like it was well maintained as debris and dirt was visible on the surface and some grass has appeared very close of the sides of the sidewalk. The average infiltration rate of three tests on the site was approximately 200 in/hr. Fig. 4 shows show the sidewalk surface at this location. A crack was also observed at this site as shown in Fig. 5.

Location C (Built 2014)
Porous Concrete Sidewalk, 278 Kaighn Avenue. Camden 08104
Area = $\underline{1725\ ft^2}$

At this location the visual inspection showed severe raveling and clogging in several location of the sidewalk as can be seen in Figs 6 and 7. A lot of sand and debris has accumulated between the voids over the years. Lack of periodic maintenance leads to the severe clogging. The average infiltration rate of three tests on the site was less than 60 in/hr.

<u>Porous concrete infiltration tests</u>

The infiltration tests are carried in accordance with ASTM C 1701[(15)]. The test requires 12 in diameter PVC pipe – at least 2 in high. The PVC pipe will be placed tight on top of the porous concrete surface and sealed using a sealant to prevent water from seeping from the sides. A total of 40 lbs of water poured into the PVC at a rate such that the water height inside the PVC pipe does not exceed 0.5 in to

0.6 in. Determine the time for the the 40 lbs of water to infiltrate the porous concrete

Infiltration Rate (in/hr) is calculated as follows:

$$I = \frac{KM}{D^2 * t} = \frac{126{,}870\ M}{D^2 * t}$$

Where

K = constant = 126, 870

M = the weight of the water = 40 lbs

D = Diameter of the PVC pipe (in)

t = time of infiltration (seconds)

Figure1. Infiltration Test setup

Figure 2. Porous concrete surface of well-maintained porous concrete sidewalk (Location A)

Figure 3. Porous concrete surface of well-maintained porous concrete sidewalk (Location A)

Figure 4. Porous concrete surface of well-maintained porous concrete sidewalk (Location B)

Figure 5. Porous concrete surface showing a crack initiating from the corner of the utility manhole (Location B)


Figure 6. Medium to severe raveling and clogging (Location C)


Figure 7. Severe clogging and severe raveling (Location C)

HYDROLOGICAL AND STRUCTURAL DESIGN

The hydrological design includes the design of drainage system and the depth of storage (reservoir) layer underneath porous pavement surface. This design depends on the void ratio of the aggregates in the storage layer, the different storm events and the infiltration rate of soil underneath which is the most hydraulically restrictive layer in the porous system. The structural design includes the design of porous concrete mix(es) with sufficient compressive strength, the required porosity to allow rainwater through the voids without any surface runoff and provide good durability to maximize the service life of the sidewalk.

The design thickness of the sidewalk is determined based on the traffic demand and the flexural strength (modulus of rupture) and fatigue resistance of the pervious concrete. In this sidewalk, there will be no traffic on the sidewalk. The minimum design thickness of the pavement (sidewalk) is 4.0 inches (16,17). The thickness of the storage layer (reservoir) depends on the hydrological properties such as void ratio of the aggregates, permeability and infiltration rate of the subgrade, and storm intensity. The design thickness of a sidewalk should be sufficient to support light vehicles. *The geotechnical report prepared for the Skillman Road sidewalk showed silty clay loam at the location of the pervious concrete segment of the sidewalk.* Hydrological design determines what storage layer thicknesses are required to sufficiently 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 two most common methods for modeling stormwater runoff are the SCS/NCRS Curve Number (17) method and the Rational method. The Rational method is not recommended for evaluation of pervious systems.

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 system. The USDA (6) designations of the Hydrologic Soil Groups (HSG) is given in Table 5. The typical permeability of each layer in the porous pavement system is shown in Table 6. The ideal practice of porous pavement should retain 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.

One of the design methods is the runoff curve number method developed by USDA Natural Resources Conservation Service (NRCS) (18). This method 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 (5) Stormwater Management Rules, the quality design storm should be 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 design steps follow the NJDEP Stormwater Management Rules.

Table 4- USDA Hydrologic Soil Groups (HSG) and infiltration rates (SCS, 1986)[6]

Hydrologic Soil Group (HSG)	**Infiltration in./hr.**	**Curve Number (CN)**		
		Pavement (Impermeable)	**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

Table 5- Typical permeability of each layer in the porous system

Layer	Description	Permeability (in./hr)		References
Porous Concrete Surface	12 mixture designs	50 - 300		Rutgers Porous Mixes [14]
Choker Course	AASHTO No. 57 (NJDOT Spec 901.03)	10000		Cedergren et al. [8]
Reservoir bed	AASHTO No. 2 (NJDOT Spec 901.03)	60000		Cedergren et al., [8]
Non-woven Geotextile Fabric	AASHTO M288 Class 2 (NJDOT Spec 919.01)	k(fabric)>= k(Soil)		Huang [9]
Hydrologic Soil Group (HSG) (Min Infiltration Rate)	A B C D	0.3 0.15 0.05 0	0.45 0.3 0.15 0.05	McCuen [10]

<u>Runoff calculations for quality design storm</u>

Although the porous concrete pavement system retains and infiltrates 100% of captured runoff, *it is assumed that the surface has less than 50% grass in order to estimate the volume of rainfall collected by the system*. So, a CN of 89 will be assigned to the porous concrete surface. A 10-year Return period event was used for the design. Using the NRCS methodology described in the PCA publication (Leming et al, 2007) [18], the water quality design storm runoff volumes were calculated as shown below:

NRCS Method:

$$Q^* = \frac{(P-0.2S)^2}{P+0.8S} \quad \text{(inches)}$$

S = (1000 / CN) – 10 (inches)

P = Runoff volume (inches) [from NOAA Hydrological Studies Center)
S = area (basin) retention (inches)
CN = curve number of the site (CN = 89)

Design Quality Event = 10 Year Return Period (24 hr rainfall frequency)
P = 5.12 inches in New Brunswick, NJ

S = 1000 / CN – 10 = 1000 / 89 – 10 = 1.236 in

$$Q^* = \frac{(5.12-0.2*1.236)^2}{5.12+0.8*1.236)} = 3.88 \text{ inches}$$

Determine the depth (T) of the storage layer
The storage bed under porous concrete surface is filled with AASHTO No.2 coarse aggregate with *40 percent air void*. The geotechnical report prepared for the Skillman Road sidewalk showed silty clay loam at the location of the pervious concrete segment of the sidewalk. From the HSG group date it was assumed Soil Group D with an estimated infiltration rate of approximately ~ *0.01 in/hr.* The 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 storage layer depth corresponding for 1-year storm to 100-year storm events in 24 hours period is determined. Table 7 shows the storage layer depths T at different storm events. For example, the reservoir depth T is equal to 1.53 inches for the 2-hr quality design storm and about 18 inches for 100 year storm event respectively.

The design event chosen for the Skillman Road pervious sidewalk was 10 year storm event (P = 5.12 in)

Quality Design Storm, P = 5.12 in, S = 1.236, Q* = 3.88 inches

With 40% voids in the storage layer, the 0.4* T = Q* - *kavg* * 2 hr
Where T is the depth of the storage layer (in) and *kavg* is the subgrade infiltration rate per hr

Therefore, for Soil Group D (*kavg* = 0.01 in/hr), then

$$T = \frac{Q^* - k_{avg} * 2\ hrs}{0.4} = \frac{3.88\ in - 0.01 * 2}{0.4} = \mathbf{9.67\ inches}$$

Therefore, use the thickness of the storage layer equal to 10 in. A typical cross section of porous sidewalk is shown in Fig. XXX. The sidewalk consists of 4 inch pervious concrete slab, 10 inch aggregate storage layer, and filter fabric. The *aggregate Reservoir Layer* 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 <u>filter Fabric</u>* should be long lasting with high infiltration rate and covers 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. The underlying soil or the subgrade is minimally compacted. Table 6 shows similar calculations for the storage layer depth for various Return Events from NOAA for Middlesex County[19]

Table 6- Storage Layer depth for various storm events in Middlesex County, NJ[19]

Storm Events	Return Period (yrs)	Duration (hr)	Rainfall Depth P (in)	Runoff Volume Q* (in)	Storage Layer Depth, T (in)
Design Storm	-	2	1.50	0.63	1.53
Middlesex County 24 hr. Rainfall Frequency Data	1	24	2.76	1.68	4.16
	2	24	3.33	2.20	5.45
	5	24	4.26	3.07	7.62
	10	**24**	**5.12**	**3.88**	**9.67**
	25	24	6.24	4.97	12.37
	50	24	7.26	5.96	14.86
	100	24	8.40	7.08	17.65

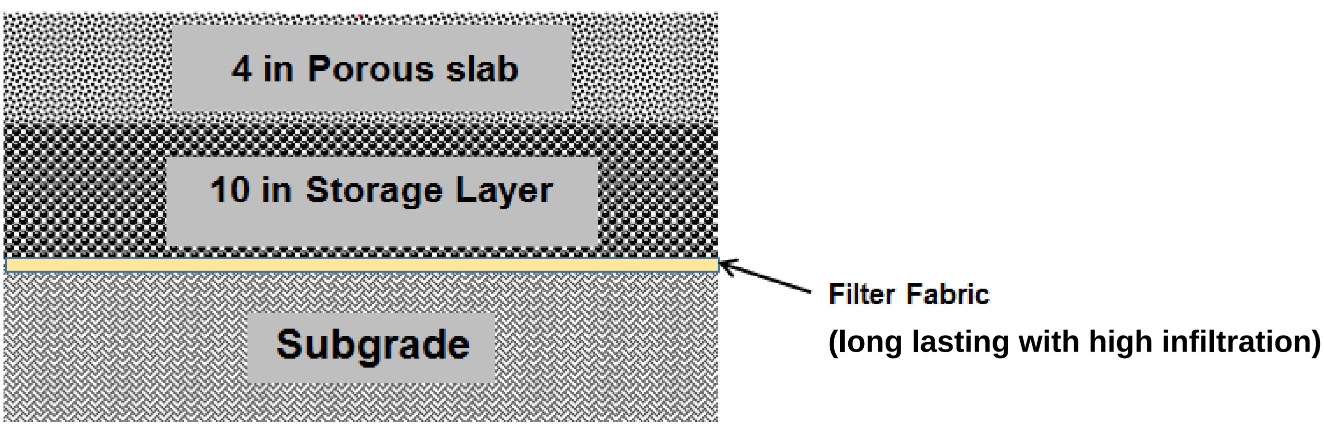

Figure 8. Cross section of the porous concrete sidewalk

Selection of Porous Concrete Mix Design

Several mix designs using New Jersey aggregates, 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. These mix designs were chosen from a previous study done by the research team in 2018 [14] and were slightly modified for filed applications. In that study 12 mixes were investigated as shown in Table 5. 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. These mix designs are listed in Table 8. 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. 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. Two sizes of aggregates were used: 1 /4 in and 3/8 in stones, including crushed stones and river gravels were used in the mixes listed in Table 8. 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. The results of the compressive strength of these mixes at 7 and 28 days are shown in Table 9 and the void ratios of these mixes are shown in Table 10.

Table 7- Mix design proportions of selected porous concrete mixes [14]

Mix	Cem (lbs)	3/8 agg (lbs)	1/4 agg (lbs)	Sand	FA (lb	Slag (lbs)	Wat (lbs)	w/c ratio	MR WR (lb)	HS (lb)	V M A	AE (lb)
PRC-1	**635**	**2430**	**---**	**224**	**---**	**---**	**209**	**0.33**	**1.9**	**1.9**	**-**	**0.8**
PRC-2 (Weld.)	864	2430	---	---	---	---	236	0.27	1.9	1.9	-	0.8
PRC-3 (Clay.)	**600**	**2835**		**-**	**-**	**-**	**162**	**0.27**	**1.9**	**1.9**	**-**	**0.8**
PRC-4	**620**	**2700**	**-**	**-**			**168**	**0.27**	**1.9**	**1.9**	**-**	**0.8**
PRC-5	620	2700	-	-			168	0.27	1.9	1.9	2	0.8
PRC-6	620	1380	1380	-	-	-	168	0.27	1.9	1.9	-	0.8
PRC-7 (FA)	525	2500			95		168	0.27	1.9	1.9	-	0.8
PRC-8 (Slag)	465	2500				155	168	0.27	1.9	1.9		0.8
PRC-9 (Silvi)	500		2700				165	0.33	1.9	1.9	- -	0.8
PRC-10 (gravel)	600	2700					180	0.30	1.9	1.9	- -	0.8
PRC-11 (gravel)	600		2700				180	0.30	1.9	1.9	- -	0.8

Table 8- Summay of compressive strength results at 7 and 28 days[14]

Mix	f'c (psi)		C.O.V (%)	
	7-Day	28-Day	7-Day	28-Day
PRC-1	**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

Table 9- Voids ratios from ASTM D7063 and the falling head method [14]

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

For the implementation sidewalk on Skillman Road, Mixes PRC-1, PRC-3 and PRC-4 were selected for further improvement. These mixes were slightly modified to be more applicable to field implementation and ready mix transportation. The final mixes that were used for construction were the two mixes shown below. Mix 1 was used in the first 100 ft and last 50 ft of the sidewalk. The remaining 50 ft were Mix 2, which included 7% sand.

Mix 1 (Silvi Mix #8601), 150 ft long x 6 ft wide, Segments I (100 ft) and III (50ft)

cement = 600 lb/yd^3; Aggregates =2850 lbs, (no sand),
agg/cement ratio = 4.75, w/c ratio = 0.3,
admixtures: Sikatard 440 (Hydration Control) = 0.2% of cement, Air = 0.15%
Void Ratio = 21% (No Rodding); 17% (Rodded)
Compressive strength ~ 2080 psi at 28 days (average of 6 cylinders-No rodding)

Mix 2 (Silvi Mix #8613), 50 ft long x 6 ft wide, Segment II

cement = 620 lb/yd^3; Aggregates =2420 lbs, Sand = 185 lbs, (7% sand),
agg/cement ratio = 4.20, w/c ratio = 0.32, admixtures
admixtures: Sikatard 440 (Hydration Control) = 0.2% of cement, Air = 0.15%
Void Ratio = 16.5% (No Rodding); 13% (Rodded)
Compressive strength = 2590 psi at 28 days (Not rodding)

The correlation between the compressive strength and void ratio is shown in Fig. 9. The data includes testing several mixes with and without sand and with and without rodding to vary the void ratio. The correlation also includes data from a study performed by Amde and Rogge for MDOT[20].

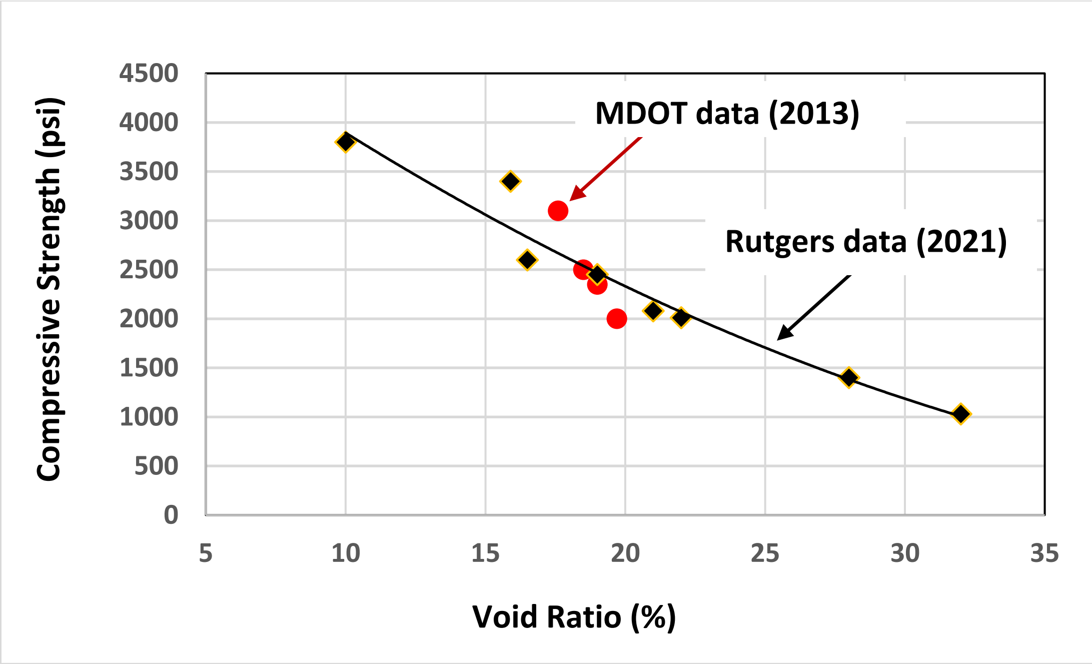

Figure 9. Correlation between compressive strength and void ratio (including data from MDOT Report MD-13-SP009B4F by Amade and Rogge, 2013[20])

Flexural Strength

Since the sidewalk was not designed for traffic and no vehicles are allowed on the sidewalk except for light vehicle for seasonal cleaning, the flexural strength was not investigated in this study. Effects of scaling, abrasion, and fatigue were beyond the scope of tis implementation and will be needed for implementations that require medium to heavy traffic on the pavements such as driveways and parking lots.

CONSTRUCTION OF POROUS SIDEWALK AND OBSERVATIONS

The porous concrete sidewalk location is shown in Fig. 10. The porous section of the Skillman Pathway is 200 ft long and 6 ft wide. A plan and section of the sidewalk are shown in Figs. 11 and 12 respectively. The research team worked closely with the contractor and the concrete supplier during all phases on the project. This coordination was very important for the success of this implementation project. The concrete supplier made few adjustments to the proposed mixes for field applications- mostly by modifying and adjusting the types of admixtures. This was necessary for keeping the required workability and consistency of the porous concrete during transportation of ready mix porous concrete to the construction site.

The mix design and aggregate type and size followed NJDOT Specs[21] section 903.11 for pervious concrete; section 901.03 for aggregate size and type, and section 919.01 for the non-woven geotextile filter fabric[21]. The construction followed NJDOT specification[22] section 606.03.04 for pervious concrete in sidewalks, driveways, and islands.

The contractor excavated about 18 in of the soil to reach the required subgrade surface. The excavation was followed by placement of the non-woven geotextile membrane. Fig. 13 shows excavation for the sidewalk and placement of the non-woven geotextile fabric. Fig. 14 shows the installation of the aggregate storage layer.

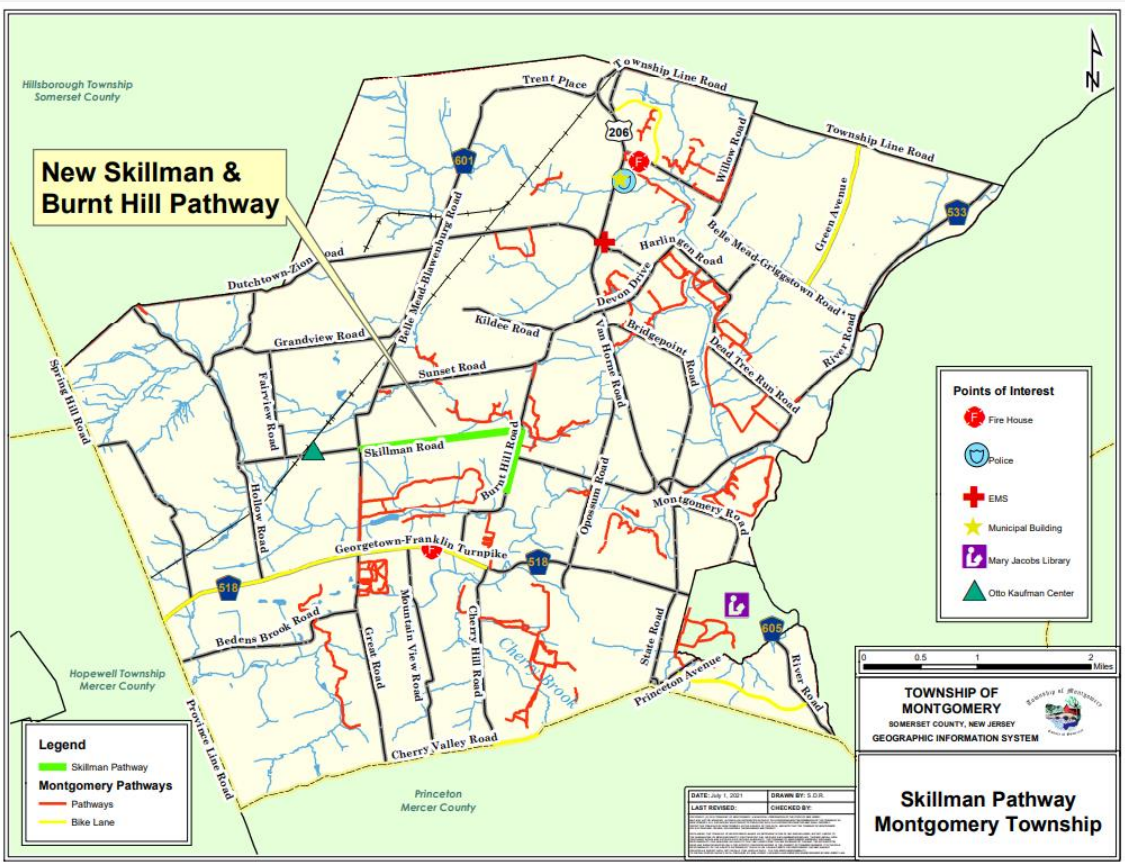

Figure 10.Location of the New Skillman Pathway where the porous sidewalk is located.

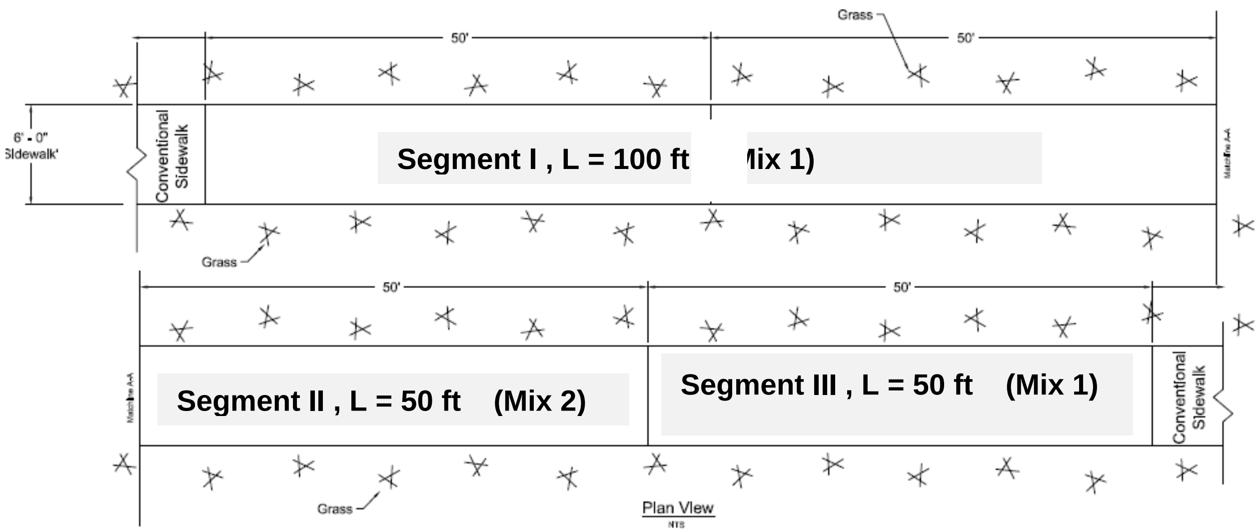

Figure 11. Plan of the sidewalk showing Segments I, II, and III

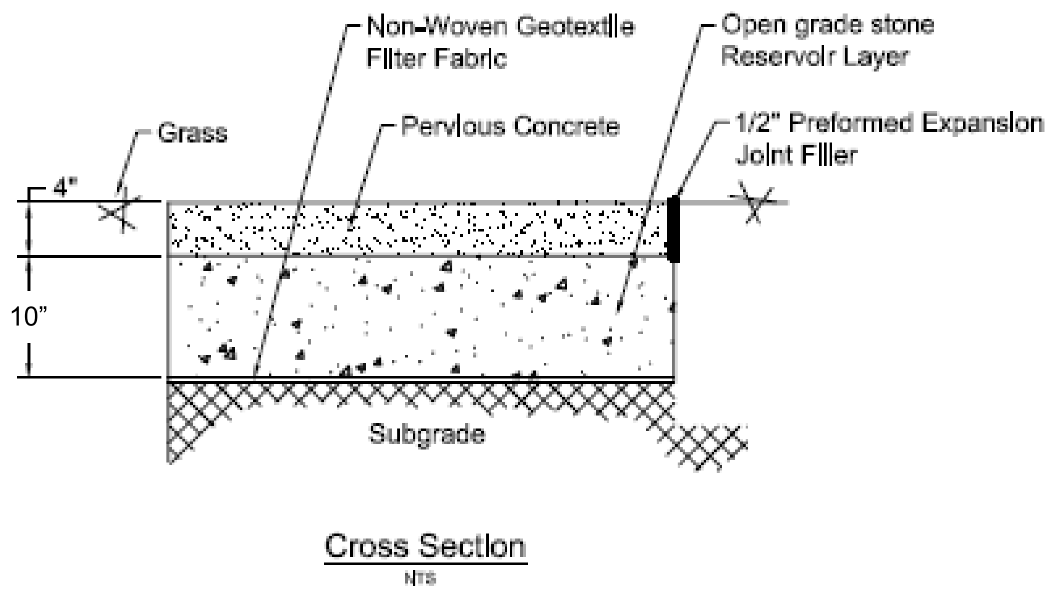

Figure 12. Cross section of the sidewalk

Figure 13. Excavation and placement of geotextile membrane

Figure 14. Placement of aggregate layer (storage layer)

Expansion joints were placed every 20 ft per NJDOT specifications Section 606 as shown in Fig. 15. The porous concrete was discharged from the ready mix truck as shown in Fig. 16. Initially, the porous concrete seemed to be stiff and was not flowing under its own weight on the belt. Later when more quantities were discharged and with the workers pushing the concrete down the belt the porous concrete started to flow continuously into the formwork. Because no vibration is allowed, the workers had to spread the concrete horizontally while the truck was moving and discharging concrete to next location.

Some of the field crew will spread the concrete and other members of the crew will use a 2x4 lumber piece to do the finishing as shown in Fig. 17. The finished surface of the porous concrete sidewalk is shown in Fig 18. A close-up photo of the finished surface of the porous sidewalk is shown in Fig. 19. Once the placement and finishing operations were completed, the filed crew used polyethylene sheets to cover and cure the finished surface as shown in Fig. 20.

Figure 15. Location of expansion joint (every 15 ft)

Figure 16. Discharging porous concrete from ready mix truck

Figure 17. Porous concrete placement

Figure 18. Finished porous concrete surface

Figure 19. Closeup of finished porous concrete surface

Figure 20. Curing of porous sidewalk using polyethylene sheets

Observations from the Field Activities

During construction, placement, finishing, and curing, we identified several important quality control and construction practices that are essential for a successful implementation of porous concrete in sidewalks.

Quality Control and Construction Practices

- Certified suppliers who have experience with porous concrete mix design and transportation to construction sites are required
- Pre-construction: it is important to for the designer to work closely with the supplier to make any adjustment to the filed mix. In this project, we worked closely with the supplier (Silvi Concrete) to make adjustments to mixes to make them easy to work with in the field and remain workable and consistent during transit to the site.
- It is important the contractor be certified and has workers on site who are skilled in placement and finishing of porous concrete.
- It is important to have a field supervisor who is also skilled and experienced with porous concrete placement and finishing
- Need to collect samples to do lab tests for strength and porosity tests and compare with field data.
- Coring is also recommended quality control but should be discussed with the owner to make sure they allow it (poor coring and poor filling or core locations can have adverse effects on durability)
- It is recommended to build a nearby test pad or test slab prior to construction of the sidewalk. This will help train in experienced the filed crew with this type of concrete, avoid unforeseen issues with mixes after arriving on site, practice placement, and finishing of porous concrete and application of construction joints. The test pad can also be used to get cores and run infiltration tests and other field tests in the future as long as it is kept on site.

PERIODIC TESTING AND MONITORING

Monitoring and Field Tests

Monitoring and testing of the sidewalk started about a month after the construction is completed. The monitoring and testing included visual inspection and infiltration tests to establish a baseline for future comparisons. Visual inspection will provide information on clogging and raveling. Infiltration rate will provide information on clogging. A sample baseline photo is shown in Fig. 21.

Figure 21. Baseline photo of finished sidewalk surface

Infiltration tests were conducted on the newly completed sidewalks following ASTM 1701[1]. Three tests were performed for each of the two mixes used. Mix 1 does not include sand and Mix 2 includes 7% sand. Figs. 22 and 23 show a plan for the locations of the infiltration tests. Summary of the infiltration test results are shown in Table 10. Th infiltration tests vary between locations as expected. ASTM 1701[15] uses the average infiltration from three locations. With the exceptions of a couple of locations (location 2) in Segment Mix 2 56 ft, all infiltration rates were well above 100 in/hr. The average infiltration rate of Mix 1 from all measurements was 258 in/hr. The average infiltration rate of Mix 2(with sand)from all measurements was 175 in/hr. Both of these infiltration rates are much higher than the minimum required by the NJDEP (NJDEP BMP Manual, 2016) and the minimum required by Wisconsin's Department of Natural Resources Standards [95] for permeable pavements. Looking at the values in Table 10, it is difficult to see a trend or a pattern of the change of infiltration rate with time. More time is needed to monitor the infiltration rate to be able to find a trend. Cores were planned to be taken but the Township was concerned about introducing discontinuities in the pavement that could result in cracks and also was concerned about the change of color.

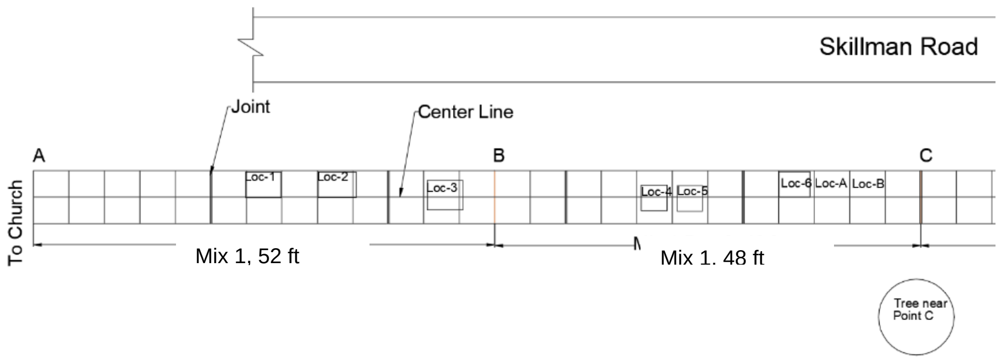

Figure 22. Location of infiltration tests for Mix 1 52 ft and 48 ft segments.

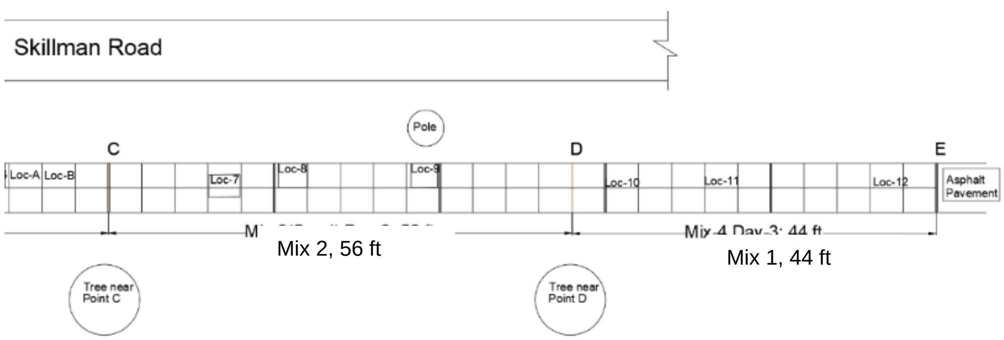

Figure 23. Location of infiltration tests for Mix 2 56 ft segment and Mix 1 44 ft segment.

Table 10. Summary of infiltration rates 6/21 to 1/22 (in/hr)

Mix	Location	July 7 2021	July 13 2021	July 21 2021	Nov 19 2021	Dec 6 2021	Dec 7 2021	Dec 15 2021	Jan 6 2022
Mix 1, 52 ft	1	254.9	123.3	273.1	296.3		238.9	224.9	254.9
	2	173.8	305.8	460.6	281.1		166.2	382.9	177.8
	3	354.9	238.9	273.1	490.1		---	424.8	176.2
Mix 1, 48 ft	1					217.2			
	2					265.5			
	3					212.4			
Mix 2, 56 ft	1			263.6	224.9			218.4	
	2			147.0	82.2			81.3	
	3			283.2	139.5			123.3	
Mix 1, 44 ft	1						273.1		275.0
	2						238.9		231.7
	3						172.2		119.5

Periodic Maintenance Requirements

Periodic visual inspection and infiltration were performed periodically to look for any signs of clogging and any signs of raveling. Clogging can be observed from visual inspection but also can be confirmed from infiltration tests and comparing infiltration rates with baseline rates. Six months after the construction, the sidewalk looks very good with no signs of clogging or raveling. There is no consensus on how much reduction in infiltration rate would indicate certain levels of clogging. Chen at al (2020) [23] reported that pervious pavements tend to clog more at the corners and at the edges more than at the center. Fig. 24 shows the variation of infiltration rate with age of pervious asphalt pavements in Sweden (Winston, at al, 2016) [24]. A combination of visual inspection showing significant clogging and very low infiltration rates would likely signal significant clogging that requires vacuum cleaning followed by pressure washing.

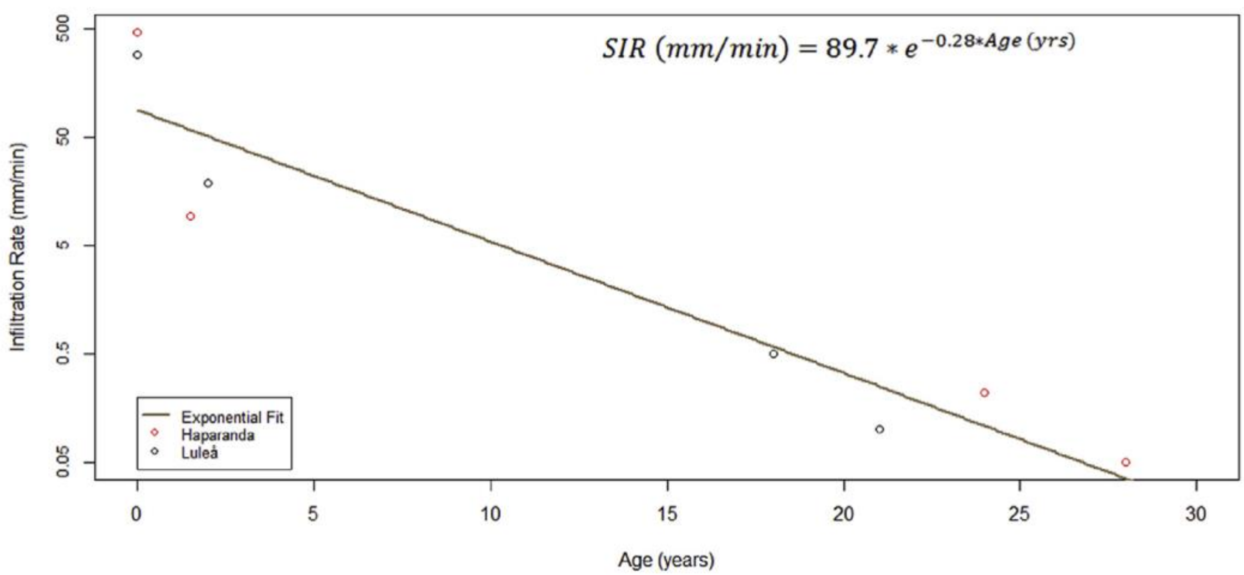

Figure 24. Variation of infiltration rate with age of pavement for pervious asphalt pavements in Sweden (Reported in a paper by Winston, et al, 2016) [24]

A study by Kumar et al (2016) [25] evaluated the variation of infiltration rate and its relationship to clogging in permeable pavements in a parking lot over a 4-year period. Their results for three different types of permeable pavements are shown in Fig. 25.

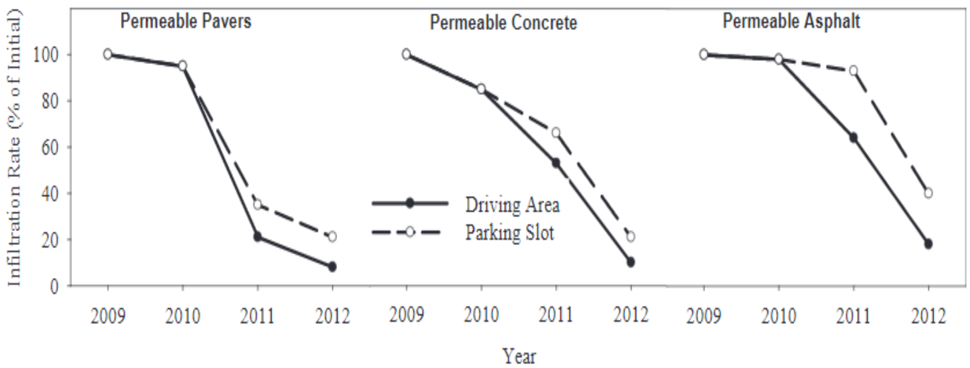

Figure 25. Percent decline in infiltration rates of permeable pavements during the four years of use at the Stickney Water Reclamation Plant (Kumar et al, 2016) [25]

The figure shows a reduction of about 50% in infiltration rate after two years and about 80% reduction after 3 years. They do not mention whether periodic maintenance was carried out on these pavements during this study. In their observation of the pervious concrete section, they report some minor raveling and small cracks after year one. Year two showed major raveling near the joints and two major cracks near the center of pavement. By the end of year three, more raveling was observed in the driving lanes compared to previous year but only minor raveling between the parking slots (Kumar et al, 2016)[25]

Our project is relatively new and less than 1 year old. It is also a sidewalk compared to the parking lot investigated in the mentioned study. Furthermore, as part of this research we conducted sidewalk cleaning using air blower, vacuuming with suction, and pressure washing. While the porous sidewalk did not show any signs of clogging or the need for cleaning, the air blower, vacuum cleaning, and pressure washing was conducted to evaluate their effectiveness in removing dirt and debris from the sidewalk.

The cleaning activities performed by the research team showed that periodic cleaning using vacuuming with suction should be sufficient to keep the porous sidewalk free of debris and sediments for several months. While air blowers can be used sometimes, the cleaning done in the field showed that 'walk behind' vacuuming with suction is much more effective. Our observations were similar to those reported in report by the San Diego County Facilities Department on porous pavement maintenance needs. In their report on porous pavement operations and maintenance control they observed that *'Superficial dirt does not necessarily clog the pavement voids, however, dirt that is ground in repeatedly by tires can lead to clogging.'* (County of San Diego, 2014) [11]. <u>The report recommends vacuuming large areas of porous asphalt and porous concrete pavement with a vacuum sweeper on biannual basis.</u> They also mention that handheld air sweepers (air blowers) can be used but are less effective. For small pavements like sidewalks and smaller parking areas, they recommend 'walk behind' vacuuming as it is the most effective for locations like sidewalks. Similar recommendations for biannual vacuum cleaning are given in the Wisconsin's Department of Natural Resources Standards [12] for permeable pavements.

They recommend cleaning the pavement surface at least twice a year using the regenerative air or vacuum sweeping. Fig. 26 shows cleaning using an air blower and Fig. 27 shows cleaning using ‘walk behind’ vacuuming machines.

Figure 26. Cleaning the porous sidewalk using handheld air blower

Figure 27. Cleaning the porous sidewalk using ‘walk behind’ vacuuming machines.

Pressure washing Requirements

Pressure washing should be used when there is significant clogging in the sidewalk or the pavement. As mentioned earlier in this section, this sidewalk looks very good and did not show any signs of clogging but we wanted to evaluate pressure washing for future needs if necessary. Initially we tried low pressure in the range of 2000 psi and it seems that it can be effective in removing low to medium clogging. Fig. 28 shows pressure washing using water pressure in the range of 2000 psi. We also did pressure washing using water pressure levels between 3000 psi to 3500 psi. The field observations showed that this pressure level (3000 psi to 3500 psi) is sufficient to remove significant clogging. Fig. 29 and 30 shows pressure washing with pressures between 3000 psi to 3500 psi. While higher pressures were not used in pressure washing in the field, it seems that higher pressures could cause raveling and separation of aggregates from the surface. The positioning of high pressure nozzle from surface of the porous surface has an effect on the pressure level and therefore, the operator has to be experienced in how close the nozzle should be close to the surface to maintain the required pressure level.

Figure 28. Pressure washing with water pressure of about 2000 psi

Figure 29. Pressure washing with water pressure ranging from 3000 psi to 3500 psi

Figure 30. Pressure washing with water pressure ranging from 3000 psi to 3500 psi

Fig. 31 shows the porous sidewalk surface after pressure washing. Visual inspection showed the sidewalk surface texture is very similar to the surface after the sidewalk was cured 6 months earlier. Infiltration tests carried out few days after the pressure washing showed similar infiltration rates similar to the base line readings (about 330 in/hr for Mix 1 and about 220 in/hr for Mix 2)

Figure 31. Finished porous concrete sidewalk after pressure washing

REFINED LIFE-CYCLE COST ANALYSIS AND TOOL DEVELOPMENT

Principle and Methodology

Life-cycle cost analysis (LCCA)

Life-cycle cost analysis (LCCA) as an engineering economic analysis tool 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 by FHWA [(26)] 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 the pavement design alternatives and timing 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 (Walls and Smith, 1998; U.S. DOT, 2002) [(27)]. The principal equation of life cycle cost estimation equation is shown as below:

$$NPV = \text{Initial Cost} + \sum_{k=1}^{N} \text{Rehab Cost}_k \left[\frac{1}{(1+i)^{n_k}} \right]$$

where: i = discount rate, n = year of expenditure.

The primary data source is from New Jersey Department of Transportation Capital Contracts Bid Price History from 2013 to 2019. The Bid Price reports include three pervious concrete sidewalk projects in 2013, 2014 and 2015[(28,29,30)]. The average bid price is $146 per square yard after escalated to 2019 price. Cost data from literature covers practices from 10 cities and 7 states including Florida, Philadelphia, Oregon, WA, California, Wisconsin, New York City, and Virginia. Cost data includes the applications of pervious concrete on highway shoulder, light traffic residential street, sidewalk, bicycle lanes, and driveway. The construction costs range from $90 to $140 / 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/ square yard.

The analysis period is another critical factor in LCCA analysis. FHWA suggests an analysis period of minimum 35 years for all pavement projects, while 30 to 40 years would be considered as a reasonable range (FHWA, 2002)[(26)]. The analysis period should cover at least one major rehabilitation activity for each alternative, while the number of maintenances is not required to be the same.

Real discount rate accounting for fluctuations in both investment interest rates and the rate of inflation. Report of Life-Cycle Cost Analysis in Pavement Design of FHWA 1998 [27] indicates that the average real discount rate based on data released by United States Office of Management and Budget (OMB) [31] from 1992 to 1998 is approximately 4% (Walls and Smith, 1998) [27]. A study conducted by ACPA in 2013 showed that 42% of states still used 4% as the real discount rate in transportation related project (Wathne, 2016) [32]. This study presented the updated real discount rate based on a 10-year average from 2009 to 2019 of OMB released 3-year to 30-year discount rates.

The salvage value of a pavement represents its economic value at the end of the analysis period. It is used to make equitable comparisons between alternative pavement designs with different service lives. Federal Highway Administration (FHWA) [26] characterizes the salvage value as the following equation:

$$Salvage\,Value = cost\ of\ the\ last\ rehabilitatio * \frac{\text{years until the end of the analysis period}}{\text{years until the next activity}}$$

Hydrologic Design of Porous Pavement

The design of drainage system and the depth of the reservoir layer underneath porous pavement surface depend on different storm events and the infiltration rate of the soil which is the most hydraulically restrictive layer in the porous paving system. The ideal practice of porous pavement should retain and infiltrate 100% of captured runoff, which means the runoff volume is 0 inch without accumulated water on the surface. However, extreme heavy storm events or low infiltration rates of the soil underneath might lead to a spilling effect since it is beyond the water process capacity of the designed porous system. We will use the runoff curve number method developed by USDA Natural Resources Conservation Service (NRCS) [18] 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. NJDEP [5] Stormwater Management Rules used Stormwater Quality Design Storm to analyze and design BMPs or structural stormwater quality measures. The NJDEP stormwater quality design storm has 1.25 inches rainfall depth in 2 hours and in a nonlinear accumulative rain fall pattern.

The design procedures follow steps in “Designing Pervious Paving Systems” of NJDEP Stormwater Management Rule. The first step is to calculate the runoff volume. Although the porous concrete pavement system retains and infiltrates 100% of captured runoff, to estimate the volume of rainfall collected by the system, we need to assume the surface is impermeable.

The second step is to calculate the storage volume and reservoir depth. The storage bed under the porous concrete surface is filled with AASHTO No.2 coarse aggregate with 40 percent air void. Assuming the sub-grade soil is extremely impermeable, we need to determine the maximum allowable reservoir depth to manage the total runoff volume caused by the storm event for the area calculated from the first step. 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. However, except extreme clayey soil, the sub-grade soil has different infiltration rate 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) as shown in Table 4. The minimum infiltration rate (inch/hour) for type A soil ranges from 0.3 to 0.45, type B soil ranges from 0.15 to 0.3, type C soil ranges from 0.05 to 0.15, and type D soil ranges from 0 to 0.05. Comparing to the maximum reservoir depth which depends on runoff volume, percent of air void in reservoir layer, and storage bed area, in addition, the minimum reservoir depth also considers soil permeability and storm duration.

The third step is to determine the drain time and if under drain system will be needed. The sub-grade soil is the most hydraulically restrictive layer in the permeable pavement system, which determines the drainage time of different storm evens. According to NJ-SWBMP[5] manual, the maximum drain time of permeable paving system is 72 hours, failing to meet the requirement may render the system infective. Since 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 extreme clay type soil, the drain time is estimated to exceed 72 hours, thus a drainage piping system as the corrective action is necessary.

LCCA Tool Description

Framework of the Hydrologic Design and LCCA Tool

The proposed pervious concrete Hydrologic Design and LCCA tool was developed based on Microsoft Excel platform consisting of multiple excel worksheets including main input, secondary input, calculations, and results. The worksheets not only provide interactive interface primarily designed for non-technical users but also maintain the flexibilities for advanced users to alter embedded functions and to update the secondary inputs. It is noted that the inputs are at a project level. The tool combined the hydrologic design of the reservoir layer and the life cycle cost analysis. The figure below shows the system architecture of the developed tool.

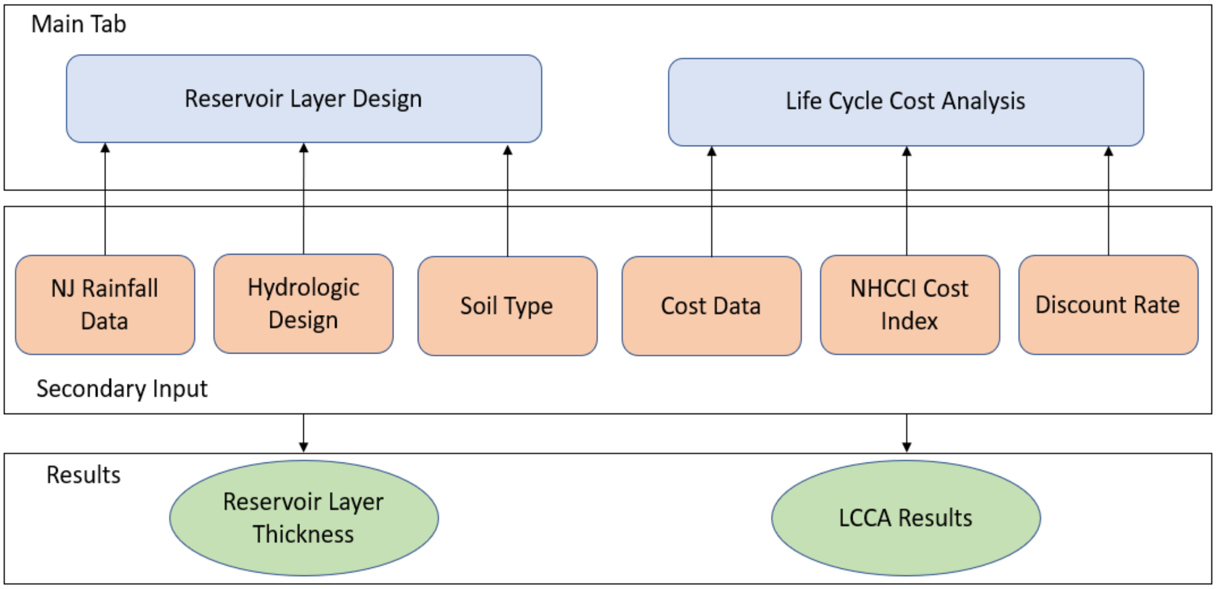

Figure 32. LCCA tool architecture

2.1 Worksheet Categories

Main Tab

In this worksheet, users can enter the basic input. There are three major components in the main tab: reservoir layer design input, pervious concrete structure design inputs, and life cycle cost analysis and results. The inputs of reservoir layer design include county, pervious concrete area, adjacent impervious area with runoff, the storm water event, and the subgrade soil type and permeability. The user then inputs the pervious concrete structure design with thickness of each layer.

For the life cycle cost analysis, the primary inputs are cost data (based on NJ Bid Price Report or literature review data and the user defined unit price), pervious concrete life, analysis period, and discount rate.

Reservoir Layer Design				
County	Passaic			
Pervious Concrete Area	21120	sf		
Adjacent Impervious Area with Runoff	0	sf		
Storm Event	100 year			
Subgrade Soil Type	Permeability (in./hr)	Recommended	Total Drain Time (hours)	Drainage System
C: Sandy clay loam	0.05 - 0.15	12 - 18	56 - 168	Yes
User Defined Soil Permeability	0.15	12	56	No
Pervious Concrete Structure Design				
Structure	Material	Thickness (inch	Quantity	Unit
Surface Course	Pervious Concrete	4	261	Cubic Yard
Choker Course	AASHTO No. 57	5	326	Cubic Yard
Reservoir Layer	AASHTO No.2	13	847	Cubic Yard
Geotextile	Non-woven AASHTO M288 Class	No	2347	Square Yard
Subgrade	Un-compacted Subgrade			

Life Cyle Cost Analysis				
	NJ Bid Price Report	Unit	User Defined Unit Price	Unit
Construction Cost (Lump Sum)	146.12	Square Yard	90	Square Yard
Material Cost				
Suface Cost	N/A	Cubic Yard	150.00	Cubic Yard
Choker Course	60.74	Cubic Yard	61.00	Cubic Yard
Reservoir Layer	51.02	Cubic Yard	51.00	Cubic Yard
Geotextile	5.67	Square Yard	5.70	Square Yard
Construction Cost	N/A	Square Yard	30.00	Square Yard
Total-Initial Construction Cost (Lump Sum)	342,902		211,200	
Total-Initial Construction Cost (material+constructic	#VALUE!		172,610	
	Literature Cost Data			
Maintenance Cost	2.19	Square Yard	12	Square Yard
Total-Maintenance/year	5129.83		28160.00	
Pervious Concrete Life	17	year		
Analysis Period	30	year		
Discount Rate	4.00%			
30-year average OMB Discount Rate	1.44%			
Results Summary (NPV)	NJ Bid Price Report	User Defined Unit Price		
Construction	$518,938	$319,624		
Maintenance	$88,705	$486,944		
Salvage Value	($80,847)	($49,795)		
Total	$ 526,796	$ 756,773		

Figure 33. Screenshot of Main Tab

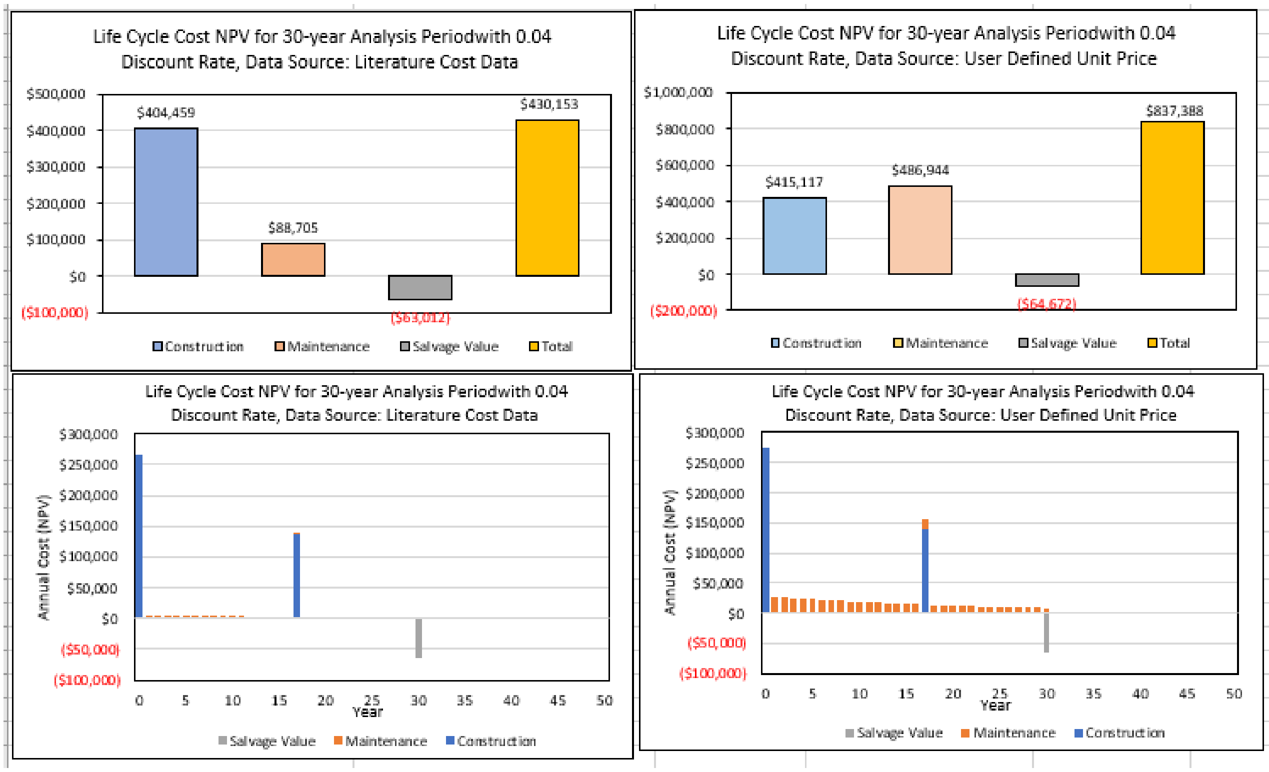

Figure 34. Screenshot of analysis results

The results of the LCCA include two types of figures: 1) total NPV and 2) the cost flow within the analysis period. Both figures show LCCA result for both referenced cost data and user defined cost data.

OMB discount rate worksheet

This worksheet shows the 3-year to 30-year real discount rates from 2009 to 2019 of OMB[31] released documents. The discount rates could be updated and maintain with new released data every year.

Table 11- OMB discount rates from 2009 – 2019 (data from OMB, 2020) [31]

Real Interest Rates	3-Year	5-Year	7-Year	10-Year	20-Year	30-Year
2008						
2009	2.1	2.3	2.4	2.6	2.8	2.8
2010	0.9	1.6	1.9	2.4	2.9	d
2011	0	0.4	0.8	1.3	2.1	2.3
2012	0.4	0.7	1.1	1.7	2	
2013	-1.4	-0.8	-0.4	0.1	0.8	1.1
2014	0.1	0.4	0.7	0.9	1.2	1.4
2015	0.1	0.4	0.7	0.9	1.2	1.4
2016	-0.5	-0.3	0.0	0.1	0.5	0.7
2017	-0.8	-0.6	-0.3	-0.1	0.2	0.6
2018	1.3	1.3	1.3	1.4	1.5	1.5
2019	-0.4	-0.3	-0.2	0	0.3	0.4
average	0.23	0.54	0.8	1.12	1.5	1.4375
%	0.23%	0.54%	0.80%	1.12%	1.50%	1.44%

Cost database worksheet

This worksheet summarized two set of cost data: NJ bid price report and literature review data. Escalation factors were used to convert the construction price to 2019 value.

NJ BID PRICE REPORT					
ITEM	UNITS	YEAR	AVERAGE WEIGHTED PRICE	Escalation factor	2019 Value
COARSE AGGREGATE, SIZE NO. 57	CUBIC YARD	2019	48.68	100.00%	48.68
COARSE AGGREGATE, SIZE NO. 57	CUBIC YARD	2018	30.40	110.42%	33.57
COARSE AGGREGATE, SIZE NO. 57	CUBIC YARD	2017	45.46	114.34%	51.98
COARSE AGGREGATE, SIZE NO. 57	CUBIC YARD	2016	69.38	113.37%	78.65
COARSE AGGREGATE, SIZE NO. 57	CUBIC YARD	2015	93.57	107.53%	100.61
COARSE AGGREGATE, SIZE NO. 57	CUBIC YARD	2014	51.83	113.60%	58.88
COARSE AGGREGATE, SIZE NO. 57	CUBIC YARD	2013	45.40	116.24%	52.77
Average					60.74
ITEM	UNITS	YEAR	AVERAGE WEIGHTED PRICE	Escalation factor	2019 Value
COARSE AGGREGATE STORAGE BEE	CUBIC YARD	2016	45	113.37%	51.02
ITEM	UNITS	YEAR	AVERAGE WEIGHTED PRICE	Escalation factor	2019 Value
GEOTEXTILE, PAVING FABRIC	SQUARE YAR	2019	5.00	100.00%	5.00
GEOTEXTILE, ROADWAY STABILIZAT	SQUARE YAR	2019	4.69	100.00%	4.69
ROADWAY STABILIZATION	SQUARE YAR	2018	2.21	110.42%	2.44
GEOTEXTILE	SQUARE YAR	2017	4.00	114.34%	4.57
GEOTEXTILE, ROADWAY STABILIZAT	SQUARE YAR	2017	2.01	114.34%	2.30
GEOTEXTILE	SQUARE YAR	2016	1.20	113.37%	1.36
GEOTEXTILE, ROADWAY STABILIZAT	SQUARE YAR	2016	2.80	113.37%	3.17
SEPARATION AND FILTRATION GEC	SQUARE YAR	2016	5.00	113.37%	5.67
GEOTEXTILE	SQUARE YAR	2015	2.35	107.53%	2.53
GEOTEXTILE, ROADWAY STABILIZAT	SQUARE YAR	2015	2.20	107.53%	2.37
GEOTEXTILE	SQUARE YAR	2014	4.15	113.60%	4.71
GEOTEXTILE, ROADWAY STABILIZAT	SQUARE YAR	2014	3.59	113.60%	4.08
GEOTEXTILE	SQUARE YAR	2013	5.58	116.24%	6.49
GEOTEXTILE, ROADWAY STABILIZAT	SQUARE YAR	2013	2.99	116.24%	3.48
ITEM	UNITS	YEAR	AVERAGE WEIGHTED PRICE	Escalation factor	2019 Value
PERVIOUS CONCRETE SIDEWALK	SQUARE YAR	2015	180.00	107.53%	193.55
PERVIOUS CONCRETE SIDEWALK	SQUARE YAR	2014	105.00	113.60%	119.28
PERVIOUS CONCRETE SIDEWALK	SQUARE YAR	2013	108.00	116.24%	125.54
Average					146.12

Figure 35. Screenshot of the cost database worksheet

Literature Cost Data						
ITEM	UNITS	YEAR	UNIT PRICE	Escalation factor	2019 Value	Reference
Pervious concrete lane	SQUARE YAR	2006	140	127.65%	178.71	Olympia, WAR
Pervious Concrete Sidewalk	SQUARE YAR	2006	92.25	127.65%	117.76	Olympia, WAR
Porous Concrete	SQUARE YAR	2016	83.25	113.37%	94.38	http://www.3
Permeable Pavement - Porous Cor	SQUARE YAR	2005	49.5	149.02%	73.77	https://green
Permeable Pavement - Porous Cor	SQUARE YAR	2007	54	118.26%	63.86	https://green
Permeable Pavement - Porous Cor	SQUARE YAR	2009	104.4	123.28%	128.71	https://green
Porous Concrete	SQUARE YAR	2009	71.21	123.28%	87.79	https://exten
Porous Concrete	SQUARE YAR	2009	60.75	123.28%	74.89	https://exten
Porous Concrete	SQUARE YAR	2005	18	149.02%	26.82	Virginia DCR S
Porous Concrete	SQUARE YAR	2005	58.5	149.02%	87.18	Virginia DCR S
Average					93.39	
ITEM	UNITS	YEAR	UNIT PRICE	Escalation factor	2019 Value	Reference
Filter Fabric	SQUARE YAR	2012	0.72	117.27%	0.84	Puget Sound S
Filter Fabric	SQUARE YAR	2012	4.95	117.27%	5.80	Puget Sound S
Filter Fabric	SQUARE YAR	2012	10.35	117.27%	12.14	Puget Sound S
Filter Fabric	SQUARE YAR	2005	6.3	149.02%	9.39	Virginia DCR S
Filter Fabric	SQUARE YAR	2005	9	149.02%	13.41	Virginia DCR S
Average					8.32	
ITEM	UNITS	YEAR	UNIT PRICE	Escalation factor	2019 Value	Reference
reservoir course	CUBIC YARD	2012	25.92	117.27%	30.40	Puget Sound S
reservoir course	CUBIC YARD	2012	44.01	117.27%	51.61	Puget Sound S
Average					41.00	
ITEM	UNITS	YEAR	UNIT PRICE	Escalation factor	2019 Value	Reference
O&M	SQUARE YAR	2016	3.69	113.37%	4.18	http://www.3
O&M	SQUARE YAR	2003	0.81	184.92%	1.50	https://green
O&M	SQUARE YAR	2009	1.44	123.28%	1.78	https://green
O&M	SQUARE YAR	2005	2.07	149.02%	3.08	https://green
O&M	SQUARE YAR	2005	0.261	149.02%	0.39	City of Oxnard, C
Average					2.19	

Figure 35 (cont'd) Screenshot of the cost database worksheet (cont'd)

National Highway Construction Cost Index Worksheet

The National Highway Construction Cost Index was used to determine the escalation factor for the construction cost to reflect the current year dollars.

National Highway Construction Cost Index		
year	Quarter	index
2003	Q1	1
2003	Q2	1.009624
2003	Q3	1.02399
2003	Q4	1.021636
2004	Q1	1.045945
2004	Q2	1.100941
2004	Q3	1.143055
2004	Q4	1.149222
2005	Q1	1.240895
2005	Q2	1.281448
2005	Q3	1.371839

Figure 36. Screenshot of the NHCCI Index Worksheet

NJ Rainfall Data Worksheet

The Natural Resources Conservation Service (NRCS) has provided revised rainfall frequency data for counties in New Jersey. This worksheet is used to support the calculation of hydrologic design.

Table 12- NJ 24 hr rainfall frequency data used in the analysis (NOAA, 2020)[19]

County	1 year	2 year	5 year	10 year	25 year	50 year	100 year
Atlantic	2.72	3.31	4.30	5.16	6.46	7.61	8.90
Bergen	2.75	3.34	4.27	5.07	6.28	7.32	8.47
Burlington	2.77	3.36	4.34	5.18	6.45	7.56	8.81
Camden	2.73	3.31	4.25	5.06	6.28	7.34	8.52
Cape May	2.67	3.25	4.22	5.07	6.34	7.47	8.73
Cumberland	2.69	3.27	4.25	5.09	6.37	7.49	8.76
Essex	2.85	3.44	4.40	5.22	6.44	7.49	8.66
Gloucester	2.71	3.29	4.24	5.05	6.29	7.36	8.55
Hudson	2.73	3.31	4.23	5.02	6.19	7.20	8.31
Hunterdon	2.80	3.38	4.26	5.00	6.09	7.02	8.03
Mercer	2.74	3.31	4.23	5.01	6.19	7.20	8.33
Middlesex	2.76	3.35	4.30	5.12	6.36	7.43	8.63
Monmouth	2.79	3.38	4.38	5.23	6.53	7.66	8.94
Morris	2.94	3.54	4.47	5.24	6.37	7.32	8.35
Ocean	2.81	3.42	4.45	5.33	6.68	7.87	9.20
Passaic	2.87	3.47	4.42	5.23	6.43	7.47	8.62
Salem	2.69	3.26	4.20	5.00	6.22	7.28	8.45
Somerset	2.76	3.34	4.25	5.01	6.15	7.13	8.21
Sussex	2.68	3.22	4.02	4.70	5.72	6.60	7.58
Union	2.80	3.39	4.35	5.17	6.42	7.49	8.69
Warren	2.78	3.34	4.18	4.89	5.93	6.83	7.82
Rainfall amounts in Inches							

Soil Type Worksheet

Soils are classified by the Natural Resource Conservation Service into four Hydrologic Soil Groups based on the soil's runoff potential. The four Hydrologic Soils Groups are A, B, C and D. Where A generally has the smallest runoff potential and D the greatest. This worksheet is used to support the calculation of hydrologic design.

Hydrologic Soil Groups	Permeability (in./hr)	
A: Sand, loamy sand, sandy loam	0.3	0.45
B: Silt loam or loam	0.15	0.3
C: Sandy clay loam	0.05	0.15
D: Clay loam, sandy clay, or clay	0	0.05
User Defined Soil Permeability	0.15	

Figure 37. Screenshot of the soil type worksheet

LCCA Worksheet

This worksheet is the embedded calculation of the LCCA based on user's inputs in the main tab.

Discount Rate		Year	Construction	Maintenance	Salvage Value		NPV-Construction	NPV-Maintenanc	NPV-Salvage Value		Total NPV-Constructio	Total NPV-Maintenanc	NPV-Salvage Value
4.00%		0	342901.6604		0		342901.6604	0	0		$518,938	$88,705	($80,847)
		1	0	5130	0		0	4933	0				
		2	0	5130	0		0	4743	0		#VALUE!		
		3	0	5130	0		0	4560	0				
		4	0	5130	0		0	4385	0				
		5	0	5130	0		0	4216	0				
		6	0	5130	0		0	4054	0				
		7	0	5130	0		0	3898	0				
		8	0	5130	0		0	3748	0				
		9	0	5130	0		0	3604	0				
		10	0	5130	0		0	3466	0				
		11	0	5130	0		0	3332	0				
		12	0	5130	0		0	3204	0				
		13	0	5130	0		0	3081	0				
		14	0	5130	0		0	2962	0				
		15	0	5130	0		0	2848	0				
		16	0	5130	0		0	2739	0				
		17	342901.6604	5130	0		176036.5384	2634	0				
		18	0	5130	0		0	2532	0				
		19	0	5130	0		0	2435	0				
		20	0	5130	0		0	2341	0				
		21	0	5130	0		0	2251	0				
		22	0	5130	0		0	2165	0				
		23	0	5130	0		0	2081	0				
		24	0	5130	0		0	2001	0				
		25	0	5130	0		0	1924	0				
		26	0	5130	0		0	1850	0				
		27	0	5130	0		0	1779	0				
		28	0	5130	0		0	1711	0				
		29	0	5130	0		0	1645	0				
		30	0	5130	-262219		0	1582	-80847				
		31	0	0	0		0	0	0				
		32	0	0	0		0	0	0				
		33	0	0	0		0	0	0				
		34	0	0	0		0	0	0				
		35	0	0	0		0	0	0				

Figure 38. Screenshot of the LCCA Worksheet

Hydrologic Design Worksheet

This worksheet has the embedded calculation of the hydrologic design based on user's inputs in the main tab.

Total Runoff Area	=	21120	sf					
Pervious Concrete Area	=	21120	sf					
P (cumulative precipitation)	=	Water Quality D	=	1.25	inches			
Impervious CN	=	98						
Impervious area S	=	0.204081633	inches					
AASHTO No.2 coarse aggregate air void	=	40%						
Runoff Volume	1 year	2 year	5 year	10 year	25 year	50 year	100 year	NJ Water Quality Design Storm
Passaic	2.87	3.47	4.42	5.23	6.43	7.47	8.62	1.25
S Potential maximum retention	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Q Precipitation excess (runoff)	2.64	3.24	4.18	4.99	6.19	7.23	8.38	1.03
Runoff Volume (cf)	4644	5696	7364	8787	10897	12726	14749	1821
Storage Bed Depth (inches) If subgrade impermeable	7	8	10	12	15	18	21	3
Storage Bed Depth (inches) Depends on soil type (permeability Low)								
A: Sand, loamy sand, sandy loam	0	0	0	0	0	0	3	1
B: Silt loam or loam	0	0	1	3	6	9	12	2
C: Sandy clay loam	4	5	7	9	12	15	18	2
D: Clay loam, sandy clay, or clay	7	8	10	12	15	18	21	3
User Defined soil permeability	0	0	1	3	6	9	12	1.8
Storage Bed Depth (inches) Depends on soil type (permeability high)								
A: Sand, loamy sand, sandy loam	0	0	0	0	0	0	0	0
B: Silt loam or loam	0	0	0	0	0	0	3	1
C: Sandy clay loam	0	0	1	3	6	9	12	2
D: Clay loam, sandy clay, or clay	4	5	7	9	12	15	18	2
Drain Time Hydrologic Soil Groups (permeability Low)	1 year	2 year	5 year	10 year	25 year	50 year	100 year	NJ Water Quality Design Storm
A: Sand, loamy sand, sandy loam	9	11	14	17	21	24	28	3
B: Silt loam or loam	18	22	28	33	41	48	56	7
C: Sandy clay loam	53	65	84	100	124	145	168	21
D: Clay loam, sandy clay, or clay	9999	9999	9999	9999	9999	9999	9999	9999
User Defined soil permeability	18	22	28	33	41	48	56	7
Hydrologic Soil Groups (permeability High)								
A: Sand, loamy sand, sandy loam	6	7	9	11	14	16	19	2
B: Silt loam or loam	9	11	14	17	21	24	28	3
C: Sandy clay loam	18	22	28	33	41	48	56	7
D: Clay loam, sandy clay, or clay	53	65	84	100	124	145	168	21

Figure 39. Screenshot of the Hydrologic Design Worksheet

1. Example Case

This section will demonstrate an example case on how to use the developed LCCA Tool.

Step 1

Under "Reservoir Layer Design" section, enter the basic parameters in green boxes:

County	Passaic
Pervious Concrete Area	21120
Adjacent Impervious Area with Runoff	0
Storm Event	100 year

Subgrade Soil Type	Permeability (in./hr)
C: Sandy clay loam	0.05 - 0.15
User Defined Soil Permeability	0.15

Step 2

Under "Pervious Concrete Structure Design" section, enter the pavement structure thickness in green boxes and indicate whether geotextile will be applied:

Structure	Material	Thickness (inch)
Surface Course	Pervious Concrete	4
Choker Course	AASHTO No. 57	5
Reservoir Layer	AASHTO No.2	12
Geotextile	Non-woven AASHTO M288 Class 2	Yes

Step 3

Under "Life Cycle Cost Analysis" section, first select the reference cost data source of NJ Bid Price Report or Literature Cost Data. The reference cost data includes construction cost in lump sum and maintenance cost per square yard. User can define the unit construction cost and maintenance cost in green boxes.

It is noted that the construction cost is only available in lump sum; construction cost divided into materials, equipment, labor, and others is currently not available due to the lack of data. Future update could be made to include more detailed capital cost for construction.

	Literature Cost Data	Unit	User Defined Unit Price	Unit
Construction Cost (Lump Sum)	93.39	Square Yard	105	Square Yard
	Literature Cost Data			
Maintenance Cost	2.19	Square Yard	3	Square Yard
TotalMaintenance/year	5129.83		28160.00	

Step 4

Under "Life Cycle Cost Analysis" section, define the expected pervious concrete life in year, analysis period (Max limit=50 years), and discount rate. The tool also provides the 30-year average OMB discount rate as a reference.

Pervious Concrete Life	17	year
Analysis Period	30	year
Discount Rate	4.00%	

Step 5

Results in table and figures will be automatically generated based on the above inputs.

Results Summary (NPV)	Literature Cost Data	User Defined Unit Cost
Construction	$331,652	$372,895
Maintenance	$88,705	$121,736
Salvage Value	($51,669)	($58,094)
Total	$ 368,688	$ 436,537

The results from step 5 above are plotted in bar charts in Figs. 40 and 41. Fig. 40 shows a plot of the life cycle cost NPV for 30 year analysis period with 4% discount rate based on Literature Cost Data. Fig. 41 shows a plot of the life cycle cost NPV for 30 year analysis period with 4% discount rate based on User Defined Cost Data.

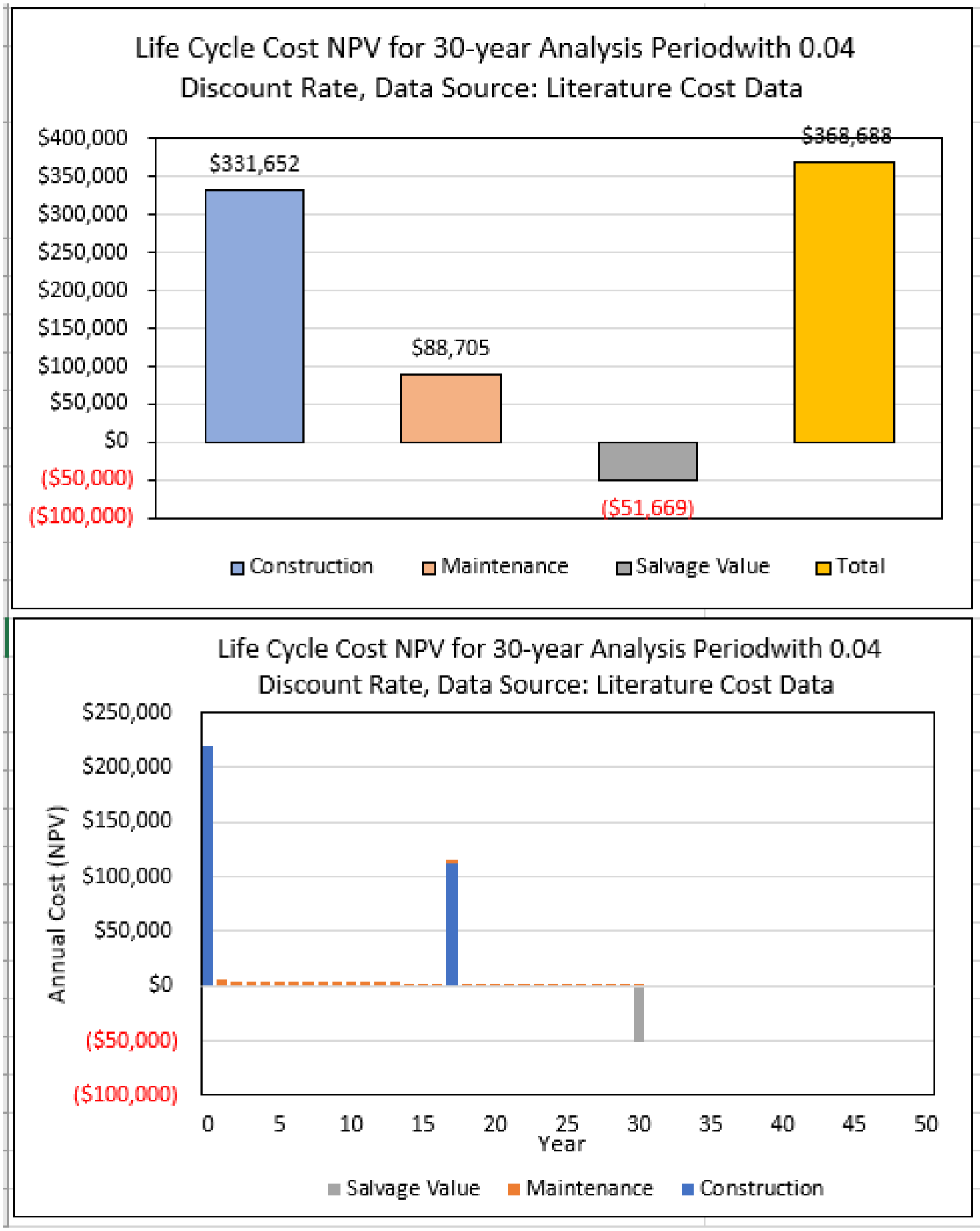

Figure 40. Screen shot of analysis results (Source: Literature Cost Data)

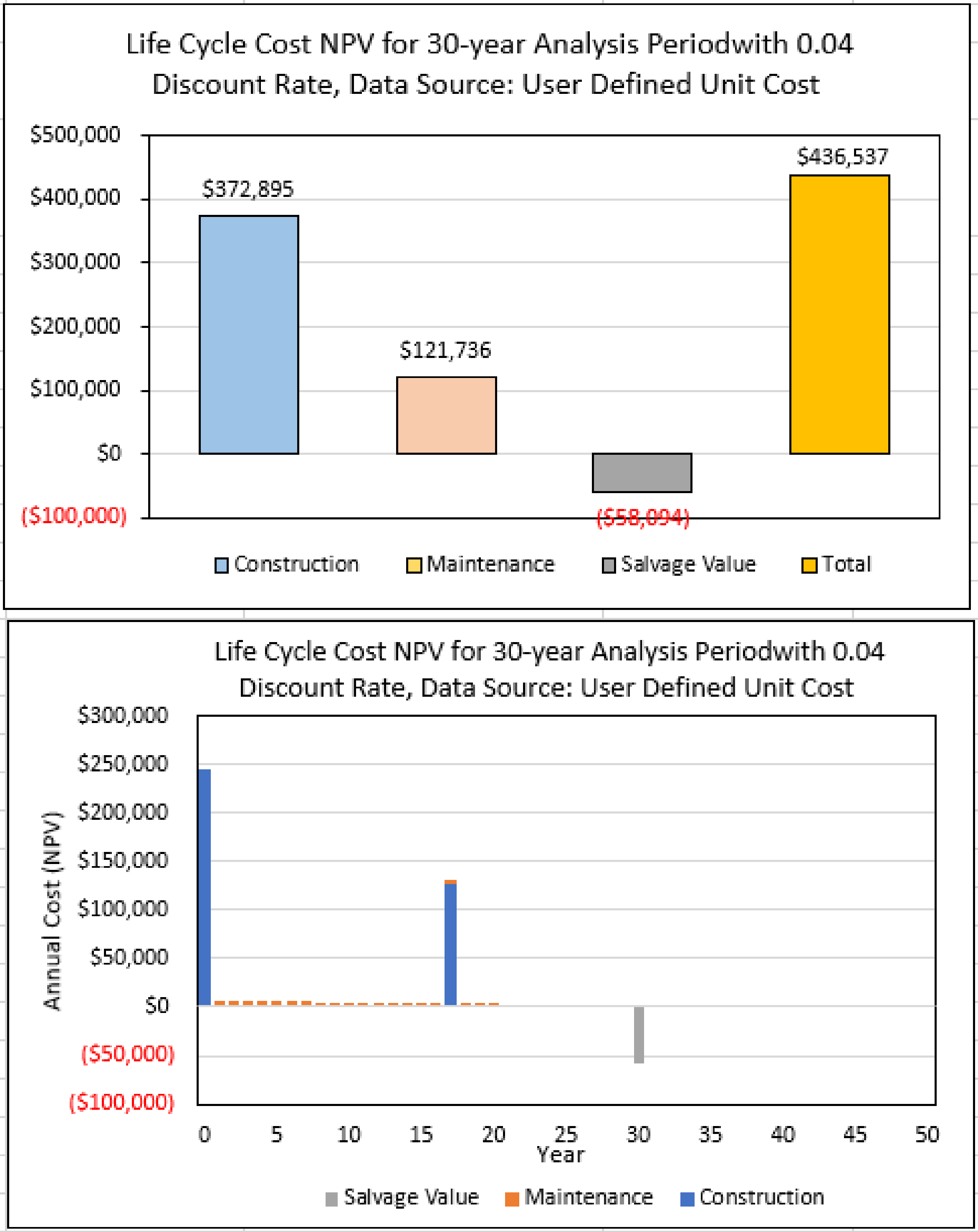

Figure 41. Screen shot of analysis results (Source: User Defined Unit Cost)

REFINED GUIDELINES FOR USE OF POROUS CONCRETE IN SIDEWALKS

The mix design and aggregate type and size followed NJDOT Specs section 903.11 for pervious concrete; section 901.03 for aggregate size and type, and section 919.01 for the non-woven geotextile filter fabric. The construction followed NJDOT specification section 606.03.04 for pervious concrete in sidewalks, driveways, and islands. These specs were found to be consistent with other specs from other DOT's agencies, counties and worked well for our implementation project. We only needed to make minor modifications to the mix design to make it applicable to filed implementation. The compressive strength and void ratio were consistent with previous research and were within the recommended values published by the NRMCA (2014)[(13)]and the ACPA (2012)[(17)]

Based on the observation from the implementation, the following guidelines are recommended:

- Certified suppliers who have experience with porous concrete mix design and transportation to construction sites are required
- Pre-construction: it is important to for the designer to work closely with the supplier to make any adjustment to the filed mix prior to construction. This will make the mixes easy to apply in the filed remain workable and consistent during transit to the site.
- It is important the contractor be certified and has workers on site who are skilled in placement and finishing of porous concrete.
- Field supervisors need to be also skilled and experienced with porous concrete delivery, placement and finishing.
- Field sample should be taken and tested in the lab for compressive strength and void ratio.
- Coring is also recommended to get as built strength and void ratio, but coring should be discussed with the owner to make sure they allow it (poor coring and poor filling or core locations can have adverse effects on durability)
- It is recommended to build a nearby test pad or test slab prior to construction of the sidewalk. This will help to practice discharging, placement and finishing of porous concrete to avoid unforeseen issues with mixes during real construction. It will also help train inexperienced field crew with this type of concrete ahead of time. The test pad can also be used to get cores and run infiltration tests and other field tests in the future as long as it is kept on site.
- The sidewalk should be visually inspected regularly for raveling, debris, sediments, and clogging. This can be done by routine inspection of Township and County bi-monthly or when needed.
- It is recommended to do bi-annual cleaning of the surface using ‘walk behind' vacuuming machines. Air blowers maybe used but should have sufficient power to clean well. Vacuum cleaning is much more effective than air blowers.
- If the sidewalk is severely clogged, it can be cleaned using power washing. Water pressure between 3000 to 3500 psi should be sufficient to remove moderate to

severe clogging. Periodic vacuuming, however, should prevent clogging and minimize the need for power washing.

- It is recommended to place a sign at the sidewalk to prevent heavy vehicles from going over the sidewalk.
- During winter season, salt can be used to melt snow, but the use of sand should be minimized to avoid clogging.
- For applications where moderate to heavy traffic is expected such as driveways and parking lots, the mix design should be tested for scaling and abrasion. The mix design should also have enough bending strength and fatigue resistance to resist flexural stresses from repeated loadings.
- If minor raveling and small cracks are detected from visual inspection, the sidewalk should be inspected more frequently to monitor these defects. When the raveling becomes severe and the cracks are wider, the locations that has severe raveling and cracking should be removed and replaced. These locations can be replaced by porous concrete. They can also be replaced by conventional concrete is the are to be removed is small and does not compromise permeability requirements.
- Porous concrete can resist freeze and thaw cycles as long as the pores are free from clogging. Previous studies have shown enough resistance for freeze and thaw and less demand for dicing salts due to the presence of pores.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A. Evaluation of Existing Sidewalks in Camden County

1. Three existing sidewalks in Camden County built in 2014 and 2015 were inspected and tested. One location was maintained and was in good condition. Visual inspection showed no signs of raveling or cracking and the average infiltration rate at that location was about 300 in/hr. The second location was somewhat maintained, and minor raveling was observed at that location with no clogging. The third location was poorly maintained, and severe raveling and clogging was observed with a lot of debris, sand and sediments clogging the voids. A study of an existing porous concrete parking lot in Chicago showed that 'marginal' decline in infiltration rate after one year and significant decline after 2 to 4 years with clogging of voids.

B. Selection of Field Mixes

1. Twelve porous concrete mixes were evaluated in an earlier study by the research team. These mixes were evaluated for strength, workability, and durability. Two mixes from these twelve mixes were selected and modified for field application. The research team worked with Silvi Concrete (supplier) to finalize the two mixes that were selected for flied applications based on workability during transit and workability in the field. The selected two mixes were the following:

   Mix 1(Silvi Mix #8601) has 600 lb of cement per cu yd, 3/8 in aggregates, water, and admixtures. The w/c ratio was 0.3 and the agg/cement ratio was 4.75. The void ratio was about 21% and the compressive strength about 2080 psi at 28 dy.

   Mix 2 (Silvi Mix #8613) has 620 lb of cement per cu yd, 3/8 in aggregates, sand water, and admixtures. The w/c ratio was 0.32 and the (agg+sand)/cement ratio was 4.2. The void ratio was about 16.5% and the compressive strength about 2590 psi at 28 days.

C. Construction Practices and Quality Control

1. Certified concrete suppliers who have experience with porous concrete mix design and transportation to construction sites are required
2. Pre-construction coordination: it is important to for the designer to work closely with the supplier to make any adjustment to the mix prior to filed application. In this project, we worked closely with the supplier (Silvi Concrete) to make adjustments to mixes to make them easy to work with in the field and remain workable and consistent during transit to the site. That was necessary.
3. It is important the contractor be certified for porous concrete placement and finishing. The crew on the construction site should be skilled in placement and finishing of porous concrete. If not skilled, they need to be trained.
4. Field supervisor who will supervise the construction activities should be skilled and experienced with porous concrete placement and finishing.

5. Need to collect samples to do lab tests for strength and porosity.
6. Coring is also recommended but should be discussed with the owner to make sure they allow cores to be taken from the site. (poor coring and poor filling of core locations can have adverse effects on durability)
7. It is recommended to build a nearby test pad or test slab prior to construction of the sidewalk. This will help train experienced the field crew with this type of concrete, avoid unforeseen issues with mixes after arriving on site, practice placement, and finishing of porous concrete and application of construction joints. The test pad or slab can also be used to get cores and run infiltration tests and other field tests in the future as long as the test pad is kept on site.

D. Periodic Testing and Monitoring

1. Monitoring and testing started about a month after the sidewalk was completed. Also should be conducted after summer and winter storms.
2. Visual inspection and photo taken were used to establish a baseline for future comparisons and evaluation of raveling, cracking, and accumulation of debris and sediments.
3. Infiltration rate baseline was established. For Mix 1 the baseline average infiltration rate was 260 in/hr and for Mix 2 was 102 in/hr. Both of these infiltration rates are much higher than the minimum required by the NJDEP (NJDEP BMP Manual, 2016).
4. Infiltration rate tests 3 months after the base line tests showed insignificant changes in the infiltration rates.
5. Cores were planned to be taken but the Township was concerned about introducing discontinuities in the pavement that could result in cracks and also was concerned about the change of color.

E. Maintenance Requirements

1. Periodic visual inspection and infiltration are needed to look for any signs of clogging and any signs of raveling. Clogging can be observed from visual inspection but also can be confirmed from infiltration tests and comparing infiltration rates with baseline rates. Based on our limited monitoring period, it seems an inspection every 4 months seems to be reasonable.
2. Six months after the construction, the sidewalk looks very good with no signs of clogging or raveling. There is no consensus on how much reduction in infiltration rate would indicate certain levels of clogging. Chen at al (2020) reported that pervious pavements tend to clog more at the corners and at the edges more than at the center. A combination of visual inspection showing significant clogging and very low infiltration rates would very likely signal significant clogging that requires vacuum cleaning followed by pressure washing.
3. A study by Kumar et al (2016) evaluated the variation of infiltration rate and its relationship to clogging in permeable pavements in a parking lot over a 4 year period. They reported a reduction of about 50% in infiltration rate after two years and about 80% reduction after 3 years. They do not mention whether periodic maintenance was carried out on these pavements during this study. In their

observation of the pervious concrete section, they reported minor raveling and small cracks after year one. Year two showed major raveling near the joints and two major cracks near the center of pavement. By the end of year three, more raveling was observed in the driving lanes compared to previous year but only minor raveling between the parking slots (Kumar et al, 2016)

4. The cleaning activities performed by the research team showed that periodic cleaning using ‘walk behind’ vacuuming with suction should be sufficient to keep the porous sidewalk free of debris and sediments for several months. While air blowers can be used sometimes, the cleaning done in the field showed that ‘walk behind’ vacuuming with suction is much more effective. Our observations were similar to those reported in report by the San Diego County Facilities Department on porous pavement maintenance needs. In their report on porous pavement operations and maintenance protocol, they observed that *‘Superficial dirt does not necessarily clog the pavement voids, however, dirt that is ground in repeatedly by tires can lead to clogging.’* (County of San Diego, 2014). The report recommends vacuuming large areas of porous asphalt and porous concrete pavement with a street vacuum sweeper on biannual basis. They also mention that air sweepers (air blowers) can be used but are less effective. For small pavements like sidewalks and smaller parking areas, they recommend ‘walk behind’ vacuuming as it is the most effective for locations like sidewalks.
5. Pressure washing should be used when there is significant clogging in the sidewalk or the pavement. The sidewalk looked very good after 6 months and did not show any signs of clogging but we wanted to evaluate pressure washing for future needs if necessary. The field observations showed that water pressure levels of 3000 psi to 3500 psi is sufficient to remove significant clogging. While higher pressures were not used in pressure washing in the field, it seems higher pressures could cause raveling and separation of aggregates from the surface. The positioning of high pressure nozzle from surface of the porous surface is important and has an effect on the pressure level. The pressure washing operator has to be experienced in how close the nozzle should be to the surface to maintain the required pressure level.

F. <u>Summary Refined Life Cycle Cost Analysis</u>

1. A LCCA tool was developed based on Microsoft Excel platform consisting of multiple excel worksheets including main input, secondary input, calculations, and results. The worksheets not only provide interactive interface primarily designed for non-technical users but also maintain the flexibilities for advanced users to alter embedded functions and to update the secondary inputs. The tool combines the hydrologic design of the reservoir layer and the life cycle cost analysis. The figure below shows the system architecture of the developed tool.
2. In this worksheet, users can enter the basic input. There are three major components in the main tab: reservoir layer design input, pervious concrete structure design inputs, and life cycle cost analysis and results. The inputs of reservoir layer design include county, pervious concrete area, adjacent impervious area with runoff, the storm water event, and the subgrade soil type

and permeability. The user then inputs the pervious concrete structure design with thickness of each layer. For the life cycle cost analysis, the primary inputs are cost data (based on NJ Bid Price Report or literature review data and the user defined unit price), pervious concrete life, analysis period, and discount rate.

G. Summary of Refined Guidelines for Use of Porous Concrete in Sidewalks

1. NJDOT specs were found to be consistent with other specs from other DOT's agencies, counties and worked well for our implementation project. We only needed to make minor modifications to the mix design to make it applicable to filed implementation. The compressive strength and void ratio were consistent with earlier research and were within the recommended values published by the NRMCA (2014) and the ACPA (2012)
2. Certified suppliers who have experience with porous concrete mix design and transportation to construction sites are required
3. Pre-construction: it is important to for the designer to work closely with the supplier to make any adjustment to the filed mix prior to construction. This will make the mixes easy to apply in the filed remain workable and consistent during transit to the site.
4. It is important the contractor be certified and has workers on site who are skilled in placement and finishing of porous concrete.
5. Field supervisors need to be also skilled and experienced with porous concrete delivery, placement and finishing.
6. Field sample should be taken and tested in the lab for compressive strength and void ratio.
7. Coring is also recommended to get as built strength and void ratio, but coring should be discussed with the owner to make sure they allow it (poor coring and poor filling or core locations can have adverse effects on durability)
8. It is recommended to build a nearby test pad or test slab prior to construction of the sidewalk. This will help to practice discharging, placement and finishing of porous concrete to avoid unforeseen issues with mixes during real construction. It will also help train inexperienced field crew with this type of concrete ahead of time. The test pad can also be used to get cores and run infiltration tests and other field tests in the future as long as it is kept on site.
9. The sidewalk should be visually inspected regularly for raveling, debris, sediments, and clogging. This can be done by routine inspection of Township and County bi-monthly or when needed.
10. It is recommended to do bi-annual cleaning of the surface using 'walk behind' vacuuming machines. Air blowers maybe used but should have sufficient power to clean well. Vacuum cleaning is much more effective than air blowers.
11. If the sidewalk is severely clogged, it can be cleaned using power washing. Water pressure between 3000 to 3500 psi should be sufficient to remove moderate to severe clogging. Periodic vacuuming, however, should prevent clogging and minimize the need for power washing.
12. It is recommended to place a sign at the sidewalk to prevent heavy vehicles from going over the sidewalk. During winter season, salt can be used to melt snow, but

the use of sand should be prohibited to avoid clogging. Tiny sand particles may clog, settle and fill in the voids. The level of roughness of sidewalk already provides sufficient the friction without spreading sand.

13. For applications where moderate to heavy traffic is expected such as driveways and parking lots, the mix design should be tested for scaling and abrasion. The mix design should also have enough bending strength and fatigue resistance to resist flexural stresses from repeated loadings.
14. If minor raveling and small cracks are detected from visual inspection, the sidewalk should be inspected more frequently to monitor these defects. When the raveling becomes severe and the cracks are wider, the locations that has severe raveling and cracking should be removed and replaced. These locations can be replaced by porous concrete. They can also be replaced by conventional concrete is the are to be removed is small and does not compromise permeability requirements.
15. Porous concrete can resist freeze and thaw cycles as long as the pores are free from clogging. Previous studies have shown enough resistance for freeze and thaw and less demand for dicing salts due to the presence of pores.

Recommendations

1. For locations where there is traffic that can do slow turns or where snowplows are used, the scaling and abrasion resistance is important. For the sidewalk it is not as critical. However, we will reach out to the asphalt lab at Rutgers and check if they have an abrasion test machine that we can use to test sample porous concrete for loss weight versus number of cycles (ASTM C944, *Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method)*
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. Establishing an optimum sand content for pervious concrete is worth investigation.
3. 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). The resistance to raveling is very important for the long-term performance of pervious concrete especially for parking lots where braking an turning can lead to raveling.
4. The sidewalk was monitored during winter 2021-2022 no adverse effects were observed from snow removal and application of deicing salts. However, this is a very short period to make any observations. We will continue monitoring the sidewalk to evaluate freeze thaw effects and deicing salts.

REFERENCES

1. Bury, M., Mawby , C., and Fisher, D., 'Making Pervious Concrete Placement Easy', *Concrete In Focus*, *Fall Issue,* 2006, pp. 55-59.
2. Report on Key Conclusions and Recommendations of the Expert Panel on Drainage Design and Flood Protection Measures. (2012), January, 52pp.
3. Roseen, R.M. and T.P. Ballestero, *Porous Asphalt Pavements for Stormwater Management in Cold Climates*, Hot Mix Asphalt Technology, May/June 2008.
4. EPA,' *Pervious Concrete Pavement.* EPA, Washington, DC., 2010. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=137&minmeasure=5
5. NJ DEP, *NJ Storm water Best Management Practices Manual.* New Jersey Department of Environmental Protection, 2016.
6. SCS, *Urban Hydrology for Small Watersheds,* 2nd ed., 210-VRTR-55, Technical Release 55, Conservation Engineering Division, Natural Resources Conservation Service, US Department of Agriculture, June, 1986, 160 pages.
7. Caltrans, '*Pervious Pavement Design Guide',* California Department of Transportation Division of Design , Office of Storm Water Management, Sacramento, California, 2014, http://www.dot.ca.gov/hq/oppd/stormwtr/
8. Cedergren, H. R., Arman, J. A., & O'Brien, K. H., *Development of guideline for the design of subsurface drainage systems for highway pavement structural sections*, FHWA-RD-73-1, Final Report, 1973.
9. Huang, Y. H., *Pavement design and analysis.* Pearson/Prentice Hall. 2004.
10. McCuen, R. H., *A guide to hydrologic analysis using SCS methods*. Prentice-Hall, Inc., 1982.ACI Committee 522, *Report on previous concrete, ACI 522R-10*, American Concrete Institute, Farmington Hills, Michigan, USA, 2010, pp. 1-38.
11. Porous Pavement Operation and Maintenance Protocol' (2014), San Diego County Facilities, County of San Diego, Department of General Services
12. Wisconsin Department of Natural Resources (DNR), *Permeable Pavements (1008)*, Report, 2016.
13. NRMCA, *PIP1, Guide to Specifying Porous Concrete*, 2009.
14. NJDOT Report FHWA-NJ-2018-001, *The Use of Porous Concrete for Sidewalks*, 2018.
15. ASTM Standard C1701, "Test Method for Infiltration Rate of In Place Pervious Concrete", ASTM International, 2010, West Conshohocken, PA.
16. PCA (Portland Cement Association). (1984). "Thickness Design for concrete highway and street pavement". *PCA*, Skokie, IL.
17. American Concrete Pavement Association (ACPA), *Stormwater Management with Pervious Concrete*. Publication IS334P. Skokie, IL., 2006
18. Leming, M. L., Malcom, H. R., and Tennis, P. D., (2007),' *Hydrologic Design of Pervious Concrete,* EB303, PCA and NRMCA Publication.
19. NOAA National Weather Server, Precipitation Data Server. https://hdsc.nws.noaa.gov/hdsc/pfds/
20. Amade, A. and Rogge S., (2013), "*Development of High Quality Pervious Concrete Specifications for Maryland Conditions'*, Report No. MD-13-SP009B4F.

21. NJDOT Pervious Concrete Specifications, Section 903.11: Sidewalks', 2016.
22. NJDOT Sitework Specifications, Section 606: Sidewalks', 2016.
23. Chen, L., Chen, J., Lecher, T., Chen,T., and Davidson P., (2020)'Assessment of clogging of permeable pavements by measuring change in permeability', Elsevier Journal of Science of Total Environment, (749)
24. Winston, R., Al-Rubaei, A., Blecken, G., Viklander, M., Hunt, W., (2016) 'Maintenance measures for preservation and recovery of permeable pavement surface infiltration rate The effects of street sweeping, vacuum cleaning, high pressure washing, and milling', Elsevier Journal of Environmental Management, 169 , pp 132-144.
25. Kumar, K., Kozak, J., Hundal, L., Cox, A., Zhang, H., and Granato, T., (2016) 'In-situ infiltration performance of different permeable pavements in aemployee used parking loteA four-year study', Elsevier Journal of Environmental Management, 167, pp. 2-14.
26. Federal Highway Administration (2002). *Life-Cycle cost analysis primer, office of asset management*, FHWA-IF-02-047, August.
27. Walls III, J., & Smith, M. R. (1998). *Life-cycle cost analysis in pavement design-interim technical bulletin* (No. FHWA-SA-98-079,).
28. New Jersey DOT, Capital Contracts Bid Price History, 2015
29. New Jersey DOT, Capital Contracts Bid Price History, 2014.
30. New Jersey DOT, Capital Contracts Bid Price History, 2013.
31. OMB, Circular A-94 Appendix C. Retrieved from Office of Management and Budget:, 2016. https://obamawhitehouse.archives.gov/omb/circulars_a094/a94_appx-c
32. Wathne, L. (2016). *Fundamentals of Life Cycle Cost Analysis.* Retrieved from American Concrete Pavement Association: http://www.wisconcrete.org/wp-content/uploads/2016/02/5b-Wathne-LCCA-Fundamentals.pdf

APPENDIX A

Stakeholders Survey

NJDOT Porous Concrete Implementation for Sidewalks

Thank you for your time to answer our questions and complete this survey. If you have any additional comments you would to add, please do so. Any information you can provide will be very helpful to this study.

Q1. Would your County like to participate in constructing a porous concrete sidewalk or bike path?

[ ] Yes [ ] No

If the answer is No, Please go to question **Q9**

Q2. What would be the expected length of the sidewalk or bike path?

[ ] ft

Q3. What would be the expected width of the sidewalk or bike path?

[ ] ft

Q4. Would the County be willing to share with NJDOT in construction costs of the sidewalk or bike path?

[ ] Yes [ ] No [ ] May be (depending on cost and budget)

Q5. Would the sidewalk be accessible to researchers to run tests and collect data over time?

[ ] Yes [ ] No [ ] Need coordination with the County Engineer

Q6. Does the County have a list of pre-qualified contractors to build sidewalks in the County?

[ ] Yes [ ] No

Q7. After and signing an agreement with the County to build a sidewalk. Approximately, how long it will take to select a contractor and to start the construction?

[ ] ----- weeks [ ] ----- months

Q8. Do you require the Approval from the Public in your County to build a porous concrete sidewalk?

[ ] Yes [ ] No

Q9. When do you normally perform initial inspection/maintenance on a conventional sidewalk?

[ ] after 1 week, [ ] after 3 weeks [ ] after 3 months, [ ] after 6 months

[ ] after one year [ ] after first major storm

Q10. What is the frequency of cleaning of conventional sidewalks?

[ ] once every year, [ ] 2 times a year, [ ] 3 times a year, [ ] varies

Q11. When building a conventional sidewalk, do you include a drainage system near the sidewalk?

[ ] Yes [ ] No

Q12. Do you require the subgrade to be compacted for sidewalk construction?

[ ] Yes [ ] No

Q13. Would you consider precast concrete slabs instead of cast-in-place for conventional sidewalks?

[ ] Yes [ ] No [ ] Not sure

Q14. Do you specifications require contractors build test slabs before getting approval to go ahead and build the sidewalk (some agencies require test slabs before building porous concrete)?

[ ] Yes [ ] No

Q15. If the answer to Q14 above is yes, the required minimum area of the test slab is?

[ ] 50 ft^2 [ ] 100 ft^2 [ ] 225 ft^2 [ ] 250 ft^2 [ ] depends on the project size

Additional Comments: Please provide any comments that you feel will be helpful to the researcher in the evaluation of pervious concrete pavements or provide a link to your specs or reports that you believe it can be helpful to us.