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# Clogging effects of portland cement pervious concrete

By

Bin Tong

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MASTER OF SCIENCE

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## GENERAL ABSTRACT

Portland Cement Pervious Concrete (PCPC) is a unique and effective mean to solve the important environmental issues and to support green, sustainable growth, by reducing stormwater and providing treatment of pollutants contained within. As a replacement for conventional impermeable pavement, PCPC has seen increasing used in recent year.

Clogging of PCPC leading to potential problems in serviceability has been regarded as one of the primary drawbacks of PCPC systems. The clogging potential of three void ratios of pervious concrete were examined using three different soil types: sand, clayey silt and clayey silty sand. Pervious concrete cylindrical specimens were exposed to sediments mixed in water to simulate runoff with small and large load of soil sediments. Pressure washing, vacuuming and a combination of these were used as rehabilitation methods to clean the clogged specimens. The clogging tests were conducted using falling head permeability apparatus by allowing the “dirty water” to flow through the specimen. A clogging cycle included both clogging and cleaning procedure. The permeability was determined during the clogging procedure and after the cleaning procedure in each clogging cycle. 20 clogging cycles were repeated on each sample to simulate the 20 years of pavement service life.

The results show that permeability reduction magnitude as well as rate and permeability recovery by rehabilitation are significantly affected by sediment types, void ratios of specimens, and selection of rehabilitation methods. The results provide a quantitative evaluation of the clogging effect of pervious concrete, and the comparison of tested rehabilitation methods in terms of permeability recovery.

# ACKNOWLEDGEMENTS

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# Chapter 1. INTRODUCTION

## 1.1 General

Portland Cement Pervious Concrete (PCPC) has been used in construction for over 100 years [32]. Its first recorded use in construction buildings was found in Europe. In the U.S., PCPC has becoming popular due to its great environmental benefits in stormwater management and sustainable development [10, 50]. Pervious concrete pavement is an "environmental friendly" concrete pavement, which can be used to carry the light traffic load volume in urban area, and meanwhile, to decrease the effect of impervious concrete pavement on environment [32]. More than just the drainage of surface water runoff, its advantages include pollution treatment of runoff water, reducing traffic noise, recharging of aquifers, increasing skid resistance, and minimizing the heat island effect in large cities [12].

The hydrological performance of PCPC is always the “driving force” to agencies to permit PCPC construction. In contrast with traditional impervious pavement, the properly designed and constructed PCPC is regarded as a structural infiltration system, which can collect the large runoff volume and allow the water to infiltrate into the ground with purification, and recharge the natural water sources [10]. Hence, the cost of hydraulic facilities applied with conventional pavement can be saved by using PCPC.

The structural and hydrological designs of PCPC have been widely discussed in the literatures. Although pervious concrete has been successfully constructed and function in numerous geographical locations, and many basic regulations, standards, properties of pervious concrete have been well discussed and established, there still exists a series of issues that have not been completely resolved. Those issues continue to impede the wide application of pervious concrete, and reduce its long term functionality in service. These concerns are including [12, 26, 32, 47]:

1) the blockage of pores by sediments (clogging materials), resulting in the decrease of permeability or infiltration and loss of storage of PCPC pavement, as well as the maintenance methodology for this case;
2) the laboratory permeability test results, which can be very different with the design infiltration rate values of the in-place pervious concrete;
3) Standards for the fabrication of specimens for testing and permeability and porosity measuring, although universal standards are currently in development;
4) In-place pervious concrete quality control;
5) Freeze-thaw durability

The freeze-thaw durability problem of PCPC has been discussed and tested in laboratory conditions [19]. Current studies show that adding approximately 7% of fine aggregates by weight as the replacement of coarse aggregates, air entraining agent and fibers in the mixtures can significantly increase the freeze-thaw durability of PCPC and also its mechanical properties [22, 27]. These important findings are presently being testing in the field in the numerous installations of pervious concrete placed in the past six years.

The sedimentation effect on the hydrological behaviors of PCPS (Pervious Concrete Pavement System) has been studied in the laboratory condition, and the results show that finer sedimentation materials could cause more significant permeability loss for the PCPS compared to coarser sedimentation materials. Being exposured to the same clogging condition, the samples mixed with smaller aggregates have the better clogging resistance than the samples mixed with larger aggregates. The traditional cleaning method is not effective when PCPC pavement was exposure to finer sedimentation materials [28, 41, 59]. The filter fabric and sub-base design should be carefully considered when pavement being exposure to clogging conditions. Applying the rehabilitation methods to in-place pervious concrete, the results show that traditional maintenance increase approximately 200% over the original infiltration rates of pervious concrete cores, and achieve the satisfied performance [35].

## 1.2 Problem Statements

According to the literature and the behaviors of in-place PCPC pavements, the ability of effectively draining stormwater runoff for in-place pervious concrete decreases gradually as the pavements get clogged due to the fine particles entering into its pore structure, and subsequently block the water flow channels.

This study is recommended [28] to quantitatively determine the clogging effect on hydraulic properties of PCPC pavement, including permeability and effective service life, as well as the residual permeability at end of service performance. Although various maintenance methods have been reported and applied in the field to clean the PCPC pavement, and also shown great efficiency, there exist few studies to quantify the recovery of hydraulic function of PCPC after being clogged. More importantly, current research rarely shows the decrease trend of hydraulic behaviors during the service life of PCPC being exposed to clogging condition. It is noted that the trend of hydraulic behaviors would be helpful to establish the economical maintenance schedule. Based on the findings and confirmations in this study, PCPC pavement could be better evaluated, developed and applied by design professionals. The key element of such a study is the development of a rational design methodology based on recognized and well established engineering principles.

## 1.3 Objectives

The clogging failure is regarded as one of the primary reasons that cause the decrease of functionality and even the thorough failures of pervious concrete pavement eventually [28]. Solving clogging relevant problems will make the contributions to the sustainable urbanization and environmental issues [13, 15, 36, 63]. One of the important reasons that impede the widespread acceptance of pervious concrete is its perceived maintenance. It is empirically understood that vacuum sweeping and pressure washing can improve the infiltration capacity of pervious concrete, and increase the effective service life of PCPC pavement, but rarely understood the quantitative relationship between the permeability reduction and recovery of PCPC, the properties of clogging materials, properties of PCPC and the several of rehabilitation methods. Since the variability of density and void ratios of in-placed pervious concrete is so great; the results of simulated sedimentation tests on cylindrical specimens may not be able to predict the actual case. However, this provides an idea of understanding the influence of void ratios and clogging material's properties on clogging effect of pervious concrete

This study primarily focuses on the clogging effect or sedimentation issues, including the following important objectives:

1. Identify and analyze the effects of various void ratios on the change in permeability coefficients of pervious concrete being exposed to clogging;
2. Determine the deposition patterns and severity of different sedimentation materials on clogging effect;
3. Determine the efficiency and working mechanisms of three rehabilitation methods under different clogging conditions and for various void ratios of PCPC specimens;

## 1.4 Approach

This study investigated the clogging effect of various pervious concrete specimens containing different void ratios and subjected to clogging that caused by three sedimentation materials so as to bring the influence of void ratios, gradation of sedimentation materials on the change in permeability, and the efficiency of tested cleaning methods in this study.

This study was divided into two stages. In Stage I, the testing specimens were carefully casted, compacted and finished in order to achieve the anticipated design void ratios. The testing specimens were trimmed into 4 inch diameter and 6 inch height cylinders, and were divided into three groups based on measured void ratios, which were 15%, 20% and 25%. In Stage II, the permeability coefficients of three groups of pervious concrete were examined with three different types of clogging materials: sand, clayey silt, and clayey silty sand. The clogging test in this experimental study on permeability reduction is conducted using a falling head permeability test equipment. Three cleaning methodologies pressure washing; vacuuming and the combination of pressure washing followed by vacuuming were also conducted on clogged specimens.

To simulate the in-situ clogging condition, three groups of specimens were subjected to a small sedimentation load or so-called “typical sedimentation load", and a relatively high sedimentation load or "worst case". The use of sedimentation loads in both small load and large load was estimated based on the 20 years' service life of pavement. The testing results were used to evaluate the clogging potential of various sedimentation materials, effects of void ratios of PCPC on clogging, and efficiencies of rehabilitation methods applied in this study. However, due to the great variability of infiltration rates and density of in-place pervious concrete pavements, the testing results in this study based simulated clogging test may not truly indicate the “real” case, but provide a guidance of considering and preventing the clogging effect of pervious concrete from occurring in terms of three perspectives, which would be helpful to establish the quantitative and accurate study on clogging effect of pervious concrete pavement.

## 1.5 Organization of This Thesis

This thesis organized into seven chapters. Chapter One presents the general introduction on PCPC and research and methodology outline as well as the anticipated findings. Chapter Two presents a brief summary of current developments and researches of PCPC based on literature review, and particularly focuses on clogging effects of pervious concrete. The development and design of laboratory testing methodologies and materials, equipments, principal theories are introduced in Chapter Three. The testing results, data analysis and any notes and observations obtained through testing work were addressed in Chapter Four. Chapter Five includes the conclusion and recommendations developed based on the findings from this research, as well as the recommended study and further improvements. Important cited references in this study are listed.

# Chapter 2. LITERATURE REVIEW

## 2.1 General

Portland Cement Pervious Concrete (PCPC) has been widely used in infrastructures especially in urban areas over the past 4 decades [37]. With the support of the United States Environmental Protection Agency (EPA), a pervious pavement program was developed, and was initially installed in parking lots [37]. Currently, the main application of PCPC in the U.S. includes parking lots, pathways, sidewalks, slope stabilization, swimming pool decks, green house floors, zoos, shoulders, noise barriers, permeable base under a normal concrete pavement, friction courses for highway pavements and other cases with the low traffic loadings [15, 57]. As cited in Ferguson [37], it is recommended that it is possible to select pervious concrete materials for approximately half of the built cover in most of urban land due to the low or moderate traffic. Pervious concrete is a special building material with environmental, economic and structural benefits.

### 2.1.1 Environmental Benefits

The recent interests in sustainable development and recognition of the PCPC system as a best tool for stormwater management have been become the driving force that makes PCPC “the most popular material to” use in U.S. [42]. The application of PCPC pavement improves the urban drainage systems, purifies the stormwater, supports the supplement of underground water, reduces the heat island effect and increases the skid resistance in freezing conditions [37].

Due to its highly porous structure, PCPC pavement allows air and water to reach the roots promoting healthier and more beautiful trees rather than cut off the by conventional pavement [37]. Properly designed and constructed PCPC system can store some or all of the precipitation in a site, and reduce the quantity of surface stormwater water runoff [44, 48]. Reducing heat island effect is another important issue, especially in large cities where most areas are paved with impervious construction materials; the heat island causes the significant energy consumption up to 12% and higher urban temperatures [44, 52]

Pervious concrete pavement systems act a filter, which can retain the pollutants in the first flush of rainfall, and prevents it from entering the streams, ponds, and rivers [15]. Up to 75% of the total urban contaminant loads can be reduced by using PCPC pavement [63, 65]. This provides a valuable stormwater management tool under the requirements of EPA Storm Waer Phase II Regulation.  A recent study [43] indicates the removal efficiency of pollutants by PCPC pavement, the results shown in Table 2-1.

**Table 2-1. Effectiveness of Pervious Pavement Pollutant Removal, % by Mass [43]**

| Study Locations | Total Suspended Solids (TSS) | Total Phosphorus (TP) | Total Nitrogen (TN) | Chemical Oxygen Demand (COD) | Metals |
|---|---|---|---|---|---|
| Prince William, VA | 82 | 65 | 80 | - | - |
| Rockville, MD | 95 | 65 | 85 | 82 | 98-99 |

### 2.1.2 Economic Benefits

For regular and pervious concrete, installation costs for both ranges from $2 to $6 per square foot. Therefore, there is no significant increase in initial cost for pervious concrete [13]. For pervious concrete acting as pavement and detention area or drainage facility as a part of stormwater management, this pavement technology creates more efficient land use by eliminating the need for retention ponds, other stormwater management devices or sewer system. Pervious pavement was properly counted as both a pavement structure and a part of the drainage system. By doing so, pervious concrete can save the overall project costs on a first-cost basis [37].

Moreover, pervious concrete pavement can save up to 12% of energy consumption by reducing the effect of heat island effect, especially in large cities that are paved with large area of impervious pavement [37]. The life-cycle cost of pervious concrete is also much lower than normal pavement, because it can be recycled at the end of life cycle. This has been widely recognized as the lowest life-cycle cost option available for paving [13, 37].

### 2.1.3 Structural Benefits

The unique surface texture of PCPC compared to conventional concrete pavement provides the enhanced friction for vehicles tires and skid resistance, prevent the driving hazards especially in severe weather such as snow or rainfall. The open surface of PCPC allows rapid infiltration and prevents water puddling, which can eliminate the spraying and skidding under freezing temperature. Experiences show that pervious concrete pavement allows rapid thawing due to the high open voids on the surface. Figure 2-1 below shows the comparison of post-snowstorm pavement surface of conventional asphalt pavement and pervious concrete pavement.

**Figure 2-1. Conventional Asphalt Concrete Pavement and Pervious Concrete Pavement after Snowstorm (Adopted from [24])**

Compared to conventional pavements, pervious concrete pavements have many other advantages as below, as detailed below [23, 34, 37, 43, 48]

1) The ability to drain surface water runoff faster and decrease the cost of drainage facilities, detention basins, and water supplies;
2) Increase groundwater storage in urban areas and protect pristine water resources;
3) Reduce the pollutants of storm water in urban areas and purify the ground water;
4) Decrease effect of heat-island, decrease the surface temperature, keep the free exchange of moisture and air in underground soil and benefit for the plants to grow;
5) Increase skid resistance and surface friction, which would provide the safe driving;

6) Decrease tire noise, and achieve a lower noise level than normal concrete and dense asphalt pavement;
7) Regarded as green and recyclable building materials;

### 2.1.4 Disadvantages

These great advantages related with environmental, economic and structural issues have been the driving force of the increasing application of PCPC all over the world. However, there are also disadvantages and problems that have not been completely solved, and those problems impede the use and application of PCPC. However, its wide spread application has been limited by inconsistent information and absence of uniform standards that address the freeze-thaw durability, clogging, strength and the appropriate use and design. The disadvantages for pervious concrete as listed below are mentioned in the literature, and more research is necessary to solve these problems [23, 34, 42, 43, 48]:

(1) PCPC does not handle the heavy traffic loadings and vehicles due to its low compressive and flexural strength;
(2) The cost of maintenance and cleaning is high. The clogging effects on pervious concrete pavement decrease the initial drainage ability significantly in the short period. The drainage function may lose thoroughly if without the effective and timely cleaning;
(3) The resistance to freeze-thaw cycles and deicing chemicals attack are more sensitive than normal concrete;

(4) There are installation problems. Proper sub-grade preparation is important. With the different sub-grade materials, the compaction levels also change. A subgrade with uniform and stable surface, proper moisture content and the sufficient permeability is the key to drain the water infiltrate through the pervious concrete pavement. Over compaction may also cause the swelling of the subgrade;

(5) Effects on the neighboring environment and developed area. The mobile sediments from the surroundings area or construction sites must be prevented from blocking the open pores. The necessary oversight must be taken into the account in design. Particularly, the runoff from developed area is likely to contain lower levels of sediments loading to cause the clogging effects;

(6) Initial protection is important for lasting service life of pervious concrete pavement. For example, the pervious concrete should be finished after the adjacent area is finished and no construction traffic should be allowed onto the pervious pavement. This is normally discussed during the pre-construction meeting;

Pervious concrete sites have had a relatively high failure rate in the past, which has been attributed to poor design, inadequate construction techniques, low permeability soil, heavy construction traffic and poor maintenance [60, 62, 63]. Great progresses have been made in the past few years in increasing the mechanical properties, free-thaw durability, concrete properties, and construction techniques developments.

## 2.2 PCPC Materials Properties

Pervious concrete, also known as porous, gap-graded, permeable or enhanced porosity concrete in the literatures, is concrete made by eliminating most or all of the fine aggregate (sand) in normal concrete mixtures. Lacking the fines particles creates empty space between the coarse aggregates as there is. Insufficient paste fills the remaining space. This leaves a highly porous structure and the porosity anywhere from 15% to 35% but most frequently about 20%. The interconnected pores allow the concrete to transmit water at the relatively higher rates without compromising the durability or integrity of the concrete [35, 41]. In this section, the aggregates, cementatious materials, chemical admixtures and typical mixtures commonly used for PCPC will be discussed. A brief summary on fresh and hardened PCPC properties including unit weight, porosity, permeability, F/T resistance, mechanical properties and compaction methods based on current literature review is presented.

### *Aggregates*

Coarse aggregate grading used in pervious concrete is typically gap-graded or single-sized coarse aggregates or narrowly-graded between ¾ and 3/8 in (19 mm to 9.5 mm). Aggregates used in pervious concrete meet the requirements of ASTM D488 “Specification for Crushed Stone, Crushed Slag and Gravel for Waterbound Base and Surface and Surface Courses of Pavements” and ASTM C33 “Standard Specification for Concrete Aggregates”. A narrow grading is an important characteristic and is the remarkable difference with conventional concrete. Use of coarser aggregates in the mixture increases skid resistance, void ratio, and permeability. Smaller aggregates produces higher mechanical strength but with tradeoff decreasing of permeability. Angular aggregates produce less density, higher voids, permeability and lower strength compared to rounded aggregates [22].

In pervious concrete produced to date, fine aggregates are generally non-exist or present in a very small amount. Current studies show that the additional fine aggregates up to 7% of replacement of coarse aggregates significantly increase the freeze-thaw durability, compressive strength and flexural strength of PCPC [22, 27]. It also should be pointed that the permeability coefficient or hydraulic function decreases with the addition of fines aggregates in mixture. The increase of aggregates size would increase permeability and decrease the acoustic absorption property for the samples with similar total porosity [18-20]. Good mixtures should achieve the balance between the hydraulic performance and mechanical properties.

### *Cementitious Materials*

Cementitious materials used in pervious concrete meet the relevant ASTM specifications. Portland cement and blended cement conform with ASTM C 595 "Standard Specification for Blended Hydraulic Cements" and ASTM C 1157 "Standard Performance Specification for Hydraulic Cement" may be used in pervious concrete [15]. Fly ash, slag, and silica fume as supplementary cementitious materials confirming with ASTM C 618 "Standard Specification for Coal Fly Ash and Raw or Calcined Nature Pozzolan for Use in Concrete", ASTM C 989 " Standard Specification for Slag Cement for Use in Concrete and Mortars", and ASTM C 1240 "Standard Specification for Silica Fume Used in Cementitious" respectively, also used in pervious concrete.

### *Chemical Admixtures*

Chemical admixtures frequently used in conventional concrete are also used in pervious concrete for the same reasons. Due to the low workability and water cement ratio, the high range water reducer is always used. Air entraining agent is also commonly used to increase the freeze-thaw durability of pervious concrete in severe environment [22, 27, 56]. Retarders or hydration stabilizers are always used to increase the setting time in field [15].

### *Mixtures*

A good mixture for pervious concrete always meets the requirements listed below [25]:

1. Sufficient strength for loadings;
2. Desired permeability for acceptable hydrological function;
3. Freeze-thaw resistance;
4. Clogging resistance, and minimize the maintenance cost;

The relationship between water to cement ratio (w/c) and mechanical strength for pervious concrete has not been well established as with conventional concrete. Water-cement ratio (w/c) and aggregate-binder ratio (a/b) are two important ratios that affect the mechanical and hydrological properties of PCPC [25]**.**

#### 1) Effects of Water to Cement Ratio

Low w/c ratio around 0.27-0.3 is preferred for pervious concrete [25]. The low w/c ratios can cause insufficient cohesion and constancy, thus reducing bonds between the particles (See Figure 2-2), which cause the low workability of PCPC. On the contrast, high w/c ratios may lead to the over-workable PCPC with excessive paste volume than actually needed, thus cause segregation (See Figure 2-3) and much lower permeability than anticipated values after hardened.

**Figure 2-2. Samples of Pervious Concrete with Different Water Contents, Formed into A Ball (a) too little water, (b) proper amount of water, and (c) too much water (Adopted from [24])**

**Figure 2-3. Excessive Water Leading to Segregation of PCPC Slab: Top View (Left) & Bottom View (Right)**

### 2) Effect of Binder to Aggregate Ratio

Proper values of binder to aggregate ratio (b/a) primarily depends on the application and mixture materials. Similar with the effect of w/c on properties of PCPC, the high (low) b/a ratios cause strong (weak) contact between particles, thick (thin) paste layer around aggregates and occupation of hydraulic channels and void spaces, respectively. Figure 2-4 shows the difference for these two cases. However, it should be noted that the aggregate distance may decrease with the increase of b/a ratios.

The influence of w/c and b/a ratio on properties and performance of PCPC is summarized in Table 2-2. A typical mixture for pervious concrete is shown below in Table 2-3. A summary of PCPC properties published in the literature is presented in Table 2-4.

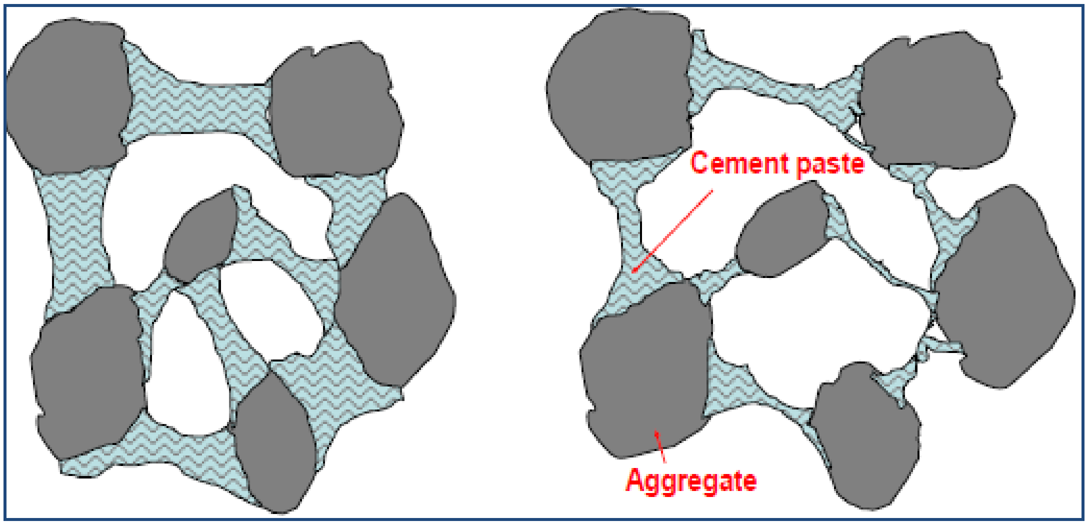


**Figure 2-4. Higher Binder/Aggregate Ratio (Left) and Lower Binder/Aggregates Ratio (Right) (Adopted from [15])**

### Table 2-2. Effects of w/c and b/a ratio on PCPC Properties

| Ratio | Proper Values | Low | High |
|---|---|---|---|
| w/c | 0.27-0.30 (by weight) | 1. Low workability<br>2. Low strength<br>3. Low flexural strength<br>4. Low elastic modulus<br>5. Low freeze-thaw-durability | 1. Low permeability<br>2. Low void ratios<br>3. Eliminate the anticipated hydraulic function<br>4. Eliminate the effective service life |
| b/a | 0.18-0.22 (by volume) | | |

### Table 2-3. Typical Mixtures of PCPC [15]

| Materials | Proportions | |
|---|---|---|
| Cementatious materials, lb/yd$^3$ (kg/m$^3$) | 0.18-0.24 | 450-700 (270-415) |
| Coarse Aggregates lb/yd$^3$ (kg/m$^3$) | - | 2000-2500 (1190-1480) |
| Fine: coarse aggregate (by mass) | 0-1:1 | - |
| W/C | 0.27-0.40 | - |
| Void Ratio | 15%-35% | - |
| Air Entraining Agent | - | 2 oz/cwt |
| Mid-Range Reducer Agent | - | 6 oz-cwt |
| Hydration Stabilizer | - | 6-12 oz/cwt |

**Table 2-4. PCPC Properties Presented from Literature**

| Void Ratio (%) | Density (lb/ft3) | Permeability (in/hr) | Compressive Strength (psi) | Flexural Strength (psi) | Reference |
|---|---|---|---|---|---|
| 15-25 | 100-125 | 288-756 | 800-3000 | 150-550 | Tennis et al.2004 |
| 15-35 | - | - | - | 363-566 | Olek st at.2003 |
| 15.6-24.4 | - | 91-687 | 2385-3260 | - | Delattee, 2009 |
| 18-31 | - | - | 1595-3626 | - | Park 2004 |
| 11-15 | - | 36-252 | - | 400-606 | Kajio 1998 |
| 20-30 | 118-130 | - | 2553-4650 | 561-825 | Beeldens 2001 |
| 18.3-33.6 | 104.1-130.9 | 142-694 | 1771-3661 | 205-421 | Wang et al. 2006 |
| 11.2-33.6 | 98.6-138 | 12-2120 | 784-4027 | 201-429 | Schaefer et al, 2008 |
| - | 109-125 | - | - | - | ASTM C 1688 |

### 2.2.1 Unit Weight

The fresh density of pervious concrete is an indicator of the mechanical and hydrological properties, and provides the best routine test for monitoring quality [15]. The fresh unit weight of pervious concrete is commonly between 105 lb/ft$^3$ to 120 lb/ft$^3$ (1680 to 1920 kg/m$^3$) depending on the mixtures, mixing materials and compaction levels and procedures [56]. By testing the sample prepared using gyratory compaction method [56], porosity was found to decrease linearly with unit weight increases (the blue line) as shown in Figure 2-5. The void ratio (porosity) of plastic and hardened pervious concrete can be determined from the unit weight, and furthermore, the compressive strength is predicted based on the direct relationship between voids and compressive strength [56]. Also, with increase of unit weight, the workability of fresh pervious concrete also decreases.

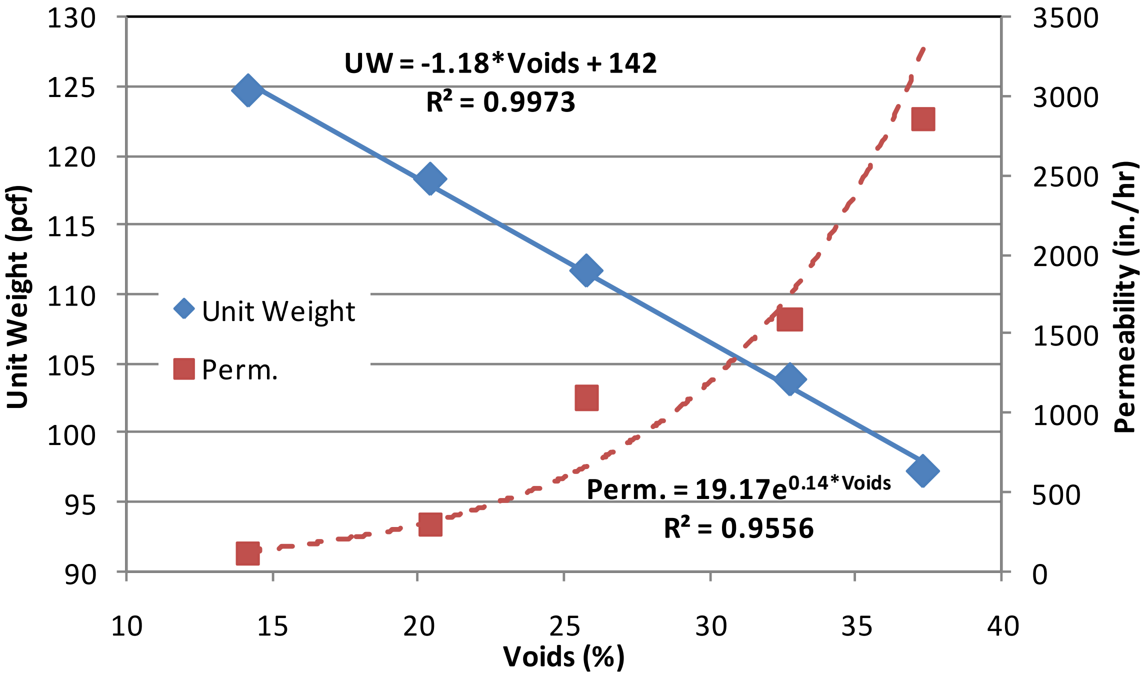


**Figure 2-5. The Linear Relationship between Unit Weight and Voids (Adopt from [56])**

### 2.2.2 Porosity

Porosity is a function of the mixtures, mixing materials and finishing and compaction procedures. The relationship and numerical functions between porosity and permeability of pervious concrete have been discussed by several studies [9, 20, 22, 27, 33, 35,]. Porosity affects the properties of pervious concrete including compressive strength, flexural strength, permeability and storage capacity, and is regarded an important parameter in many design calculations [33]. The typical range of total porosity is 15% to 30%. Insufficient hydraulic performance and weak mechanical properties may be caused if the porosity is lower than 15% and higher than 30%, respectively. 20% total porosity is considered as the reasonable range for hydrological and structural design of pervious concrete [15].

Unlike with conventional concrete, porosity or so-called total porosity in pervious concrete is the summation of open porosity or called “effective porosity or interconnected porosity” and closed porosity or so-called “dead-end porosity” [18, 19, 20, 33,]. The open porosity (interconnected porosity or effective porosity) allows fluids flowing through [20, 31], and in contrast, the dead-end or close porosity fairly make little contribution to transportation through the pavement. The closed porosity is randomly distributed within the paste and forms the isolated or open on one side and closed on the other side, which makes limited contribution on water infiltration. Studies show that the higher porosity may not be the indicator of the high permeability in pervious concrete. Also, the total porosity alone cannot provide the adequate information to predict the permeability since there was the high variability of permeability for the pervious concrete samples all with close total porosity. The open or effective porosity is more important to predict the permeability, acoustic absorption and mechanical properties [19, 20]. The effective porosity factor was defined as the ratio of the open porosity and total porosity. The higher the effective porosity factor, the greater the permeability with the similar total porosity would be [17, 67]. Effective porosity is normally measured in the laboratory using ASTM C 140 “Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units”, or ASTM D 7063 “Standard Test Method for Effective Porosity and Effective Air Void of Compacted Bituminous Paving Mixture Samples”.

The porosity measurements applied in this research were conducted by following the “Volume Method” or “Water-Displacement Method” [16, 33]. The Eqn. 2-1, 2-2 and 2-3 are used to determine the total, open and effective porosity, respectively. $W_1$ is regarded as the weight of the specimen measuring under surface saturated dry (SSD) condition; $W_2$ is the weight measurement under totally dry condition and $W_3$ is weight measurement under immersed condition.

$$P_{total}(\%) = (1 - \frac{W2 - W1}{\rho \times V}) \times 100\%$$ **Eqn. 2-1**

$$P_{open}(\%) = (1 - \frac{W3 - W1}{\rho \times V}) \times 100\%$$ **Eqn. 2-2**

$$P_{close(\%)} = P_{total(\%)} - P_{open(\%)}$$ **Eqn. 2-3**

Where

$P_{open}$ = Total porosity, %
$P_{close}$ = Closed porosity, %
$W_1$= Weight immersed, (lbs or kg)
$W_2$= Dry weight, (lbs or kg)
$W_3$= Surface saturated dry, (lbs or kg)
$V$= Normal sample volume based on dimensions of the sample, (ft3 or m3)
$\rho$ = Density of water, (pcf or kg/$m^3$)

### 2.2.3 Pore Structure

Recently, a number of studies [16, 18, 19, 20, 31] have been conducted on the pore structures of pervious concrete. The pore structure of pervious concrete included four factors which are pore volume, pore size, pore distribution and the connectivity of the pores [33, 34]. Studies on pore structure benefit the understanding the freeze-thaw damage occur in pervious concrete, permeability prediction and clogging phenomena and associated maintenance.

As cited in [33, 34], the results showed that a fairly linear vertical porosity distribution with lower porosity occurred in the top quarter of the specimen, with average porosities in the center half, and higher porosity near the bottom. This conclusion explains that larger clogging particles may be trapped on the top or near the surface within the pavement, which also explains that surface washing and vacuuming sweeping have a good efficiency in cleaning the clogged pavement subjected to larger sedimentation materials [31, 41].

The effect of pore size distribution has been studied [19, 20, 56]. The results showed that measured porosity is not the only factor that controls the hydraulic performance of pervious concrete. Increasing either the pore size or pore connectivity in terms of pore structure parameters would cause the increase of hydraulic conductivity in pervious concrete. The establishments of two-dimensional (2D) planar images of multiple cross-sections were applied to predict the three-dimensional (3D) pore structure, and the hydraulic conductivity of pervious concrete. The results showed a fairly good match between the predicted values and actual values, especially for the samples mixed with small aggregates (3/8 in) due to the more uniformly distributed pores [19, 20, 39].

#### 2.2.3.1 Tortuosity

The tortuosity of a porous medium is a fundamental property of the streamlines, or lines of flux, in the conducting capillaries [64]. The effects of porosity and pore characteristics on permeability can be captured through a single parameter called tortuosity, which is the property of a curve being tortuous, which describes the path taken by any species through porous medium, relative to direct route. It is the actual length of flow path, which is sinuous inform, divided by the straight distance between the ends of flow path or Le/L shown in Figure 2-6 [40, 67], where $L_e$ is the length of a flow channel for the fluid, and L is the straight line length between the ends of the flow path.

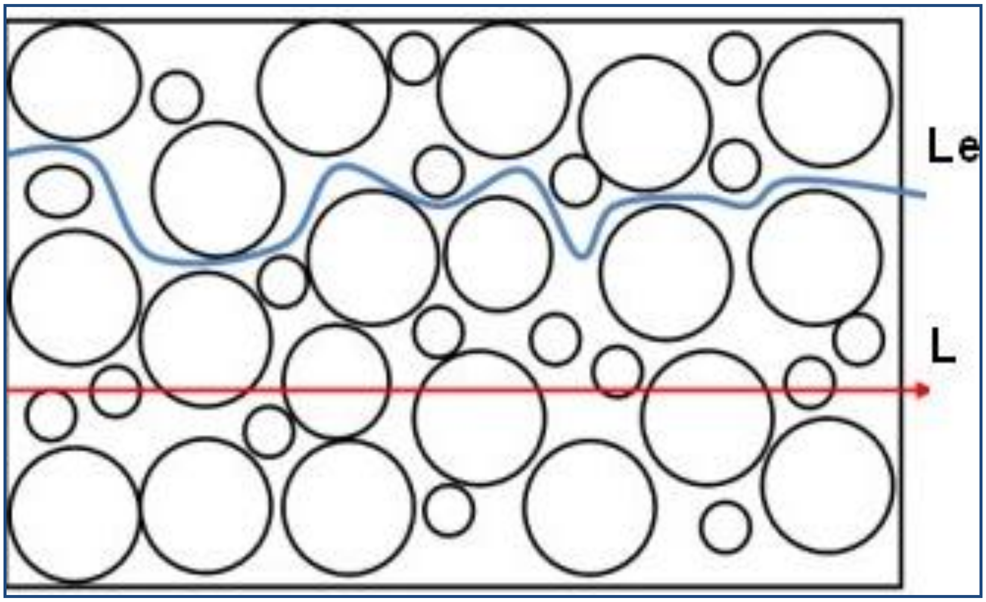


**Figure 2-6**. **The Indication of Tortuosity of Pervious Concrete (Adopted from [40])**

Tortuosity is viewed as an important indicator for pervious concrete infiltration rate. The high tortuosity indicated the more distance between the two points in concrete, which required more time for liquid to flow through. Tortuosity is also defined as structure factor and a purely geometrical independent of the solids or fluid densities factor [67]. A relationship between tortuosity and porosity has been found [68]

$$\alpha=1-r(1-1/\emptyset) \qquad \textbf{Eqn. 2-4}$$

Where α is regarded as tortuosity, and r = ½ for spheres and lies between 0 to 1 for other ellipsoids, and ∅ is regarded as measured porosity. As predicted from Eqn. 2-4, with the increase of porosity, the tortuosity decreases. A general relationship between porosity and tortuosity might be obtained. The minimum tortuosity is calculated equal to 0.5. The testing data is currently unavailable to verify the accuracy of this relationship.

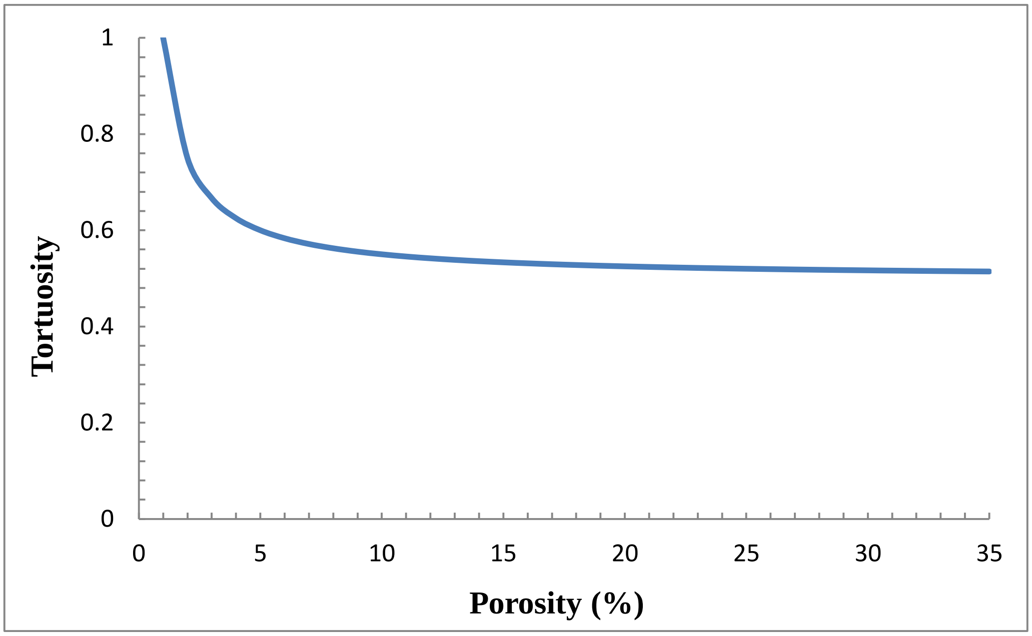


**Figure 2-7 General Relationship between Porosity and Tortuosity [68]**

Study results indicated that higher the tortuosity, the lower is the permeability [20, 67]. The permeability of concrete is the function of the porosity and pore size variation and distribution, orientation, and connectivity [19, 20]. As well known, permeability generally increases with an increase in porosity based**.** Further studies on pore structures in terms of tortuosity, pore size distribution and pores connectivity on permeability of pervious concrete may be important to investigate to better understand the relationship between hydraulic performance and pore structure of PCPC.

### 2.2.4 Permeability

Permeability or flow rate of water through PCPC is a property indicating the ease with which water will flow through the pore space or fractures of the PCPC layer, which depends on the materials, mixtures, compaction and placing operation. The permeability is the most important parameter used in hydrological design of PCPC. The typical range is from 3 gal/ft$^2$/min (288 in/hr, 120 L/m$^2$/min, or 0.2 cm/s) to 8 gal/ft$^2$/min (770 in/hr, 320 L/m$^2$/min, or 0.54cm/s), or up to 17 gal/ft$^2$/min (1650 in/hr, 700 L/m$^2$/min, 1.2cm/s) [17]. Under laboratory conditions, even higher rates could be achieved.

Nevertheless, for convenience, most permeability measurements are based on the theory of Darcy's Law and the assumption of laminar flow within the pervious concrete using falling head permeability test adopted from soil mechanics (Figure 2-8). The detailed procedures can be found in the literatures [18, 19, 20, 23, 26, 56]. The average coefficient of permeability (k) is calculated using Equation 2-4 established based on Darcy's law:

$$K = \frac{a \times L}{A \times t} \times Ln(\frac{h_1}{h_2}) \qquad \textbf{Eqn. 2-5}$$

Where

$K$ = coefficient of permeability, in/s or cm/s, (or L/T)
a = cross-sectional area of the pipe, in$^2$ or cm$^2$, (or L) etc
$L$ = length of the sample, (in or cm)
A = cross-section area of the sample specimens, in$^2$ or cm$^2$,
t = time for water to drop from $h_1$ to $h_2$, sec,
$h_1$ = initial water level, in or cm,
$h_2$ = final water level, in or cm,

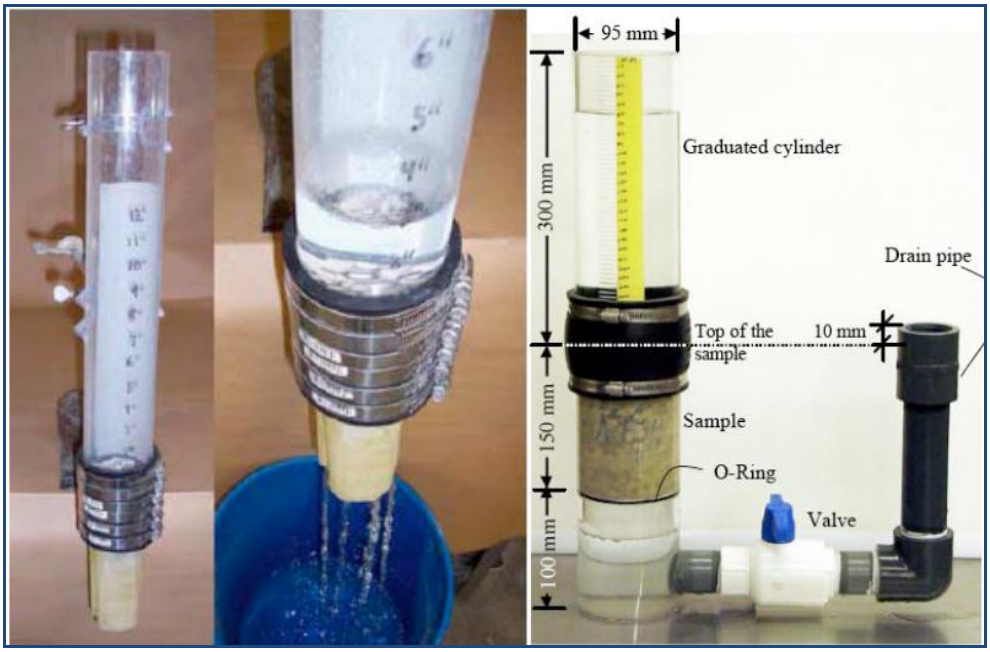


**Figure 2-8. Laboratory Falling Head Permeameters for Pervious Concrete (Adopted from [20, 23, 26])**

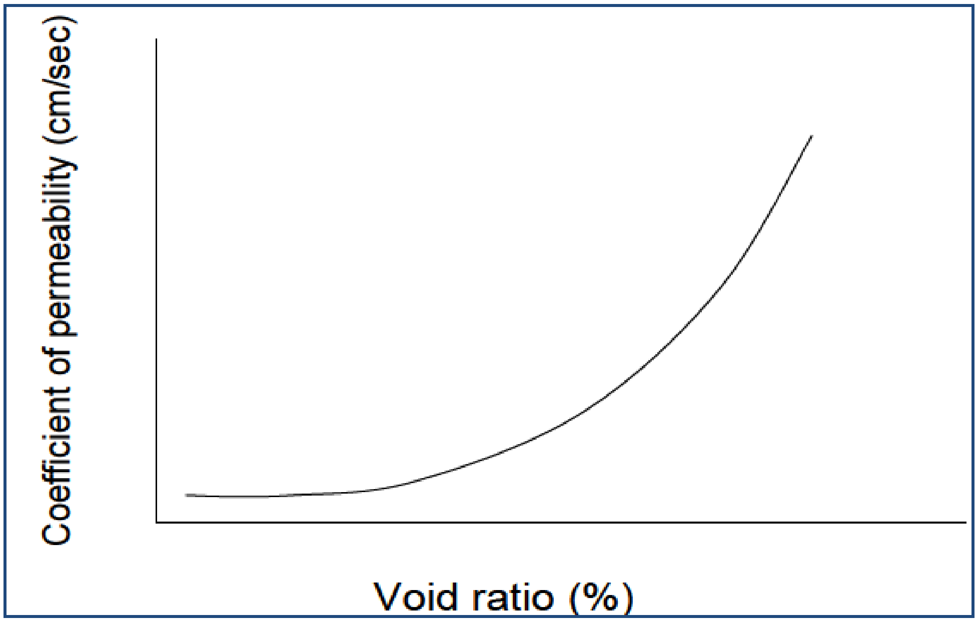


**Figure 2-9. A General Relation between Void Ratios and Permeability Coefficients for PCPC Mixtures [26]**

Previous studies showed that the permeability exponentially increases with measured porosity as shown in Figure 2-9. Several formulas have been established to predict the permeability of pervious concrete based on the measured porosity [17, 19, 56]. However, these formulas may show limited accuracy due to the invalid laminar flow condition and complex pore structures of PCPC [17]. The assumption of lamina flow may not be always valid as shown in Figure 2-10 due to the large pore geometry. When the pore size is about 0.6 cm, the flow conditions within specimen moves from laminar to transition flow, and Reholds numbers range from 10 to 100. Darcy's law may not valid for these cases. Permeability calculated using Carman-Kozeny equation based on measured porosity show fairly good accuracy with the measured values [17].

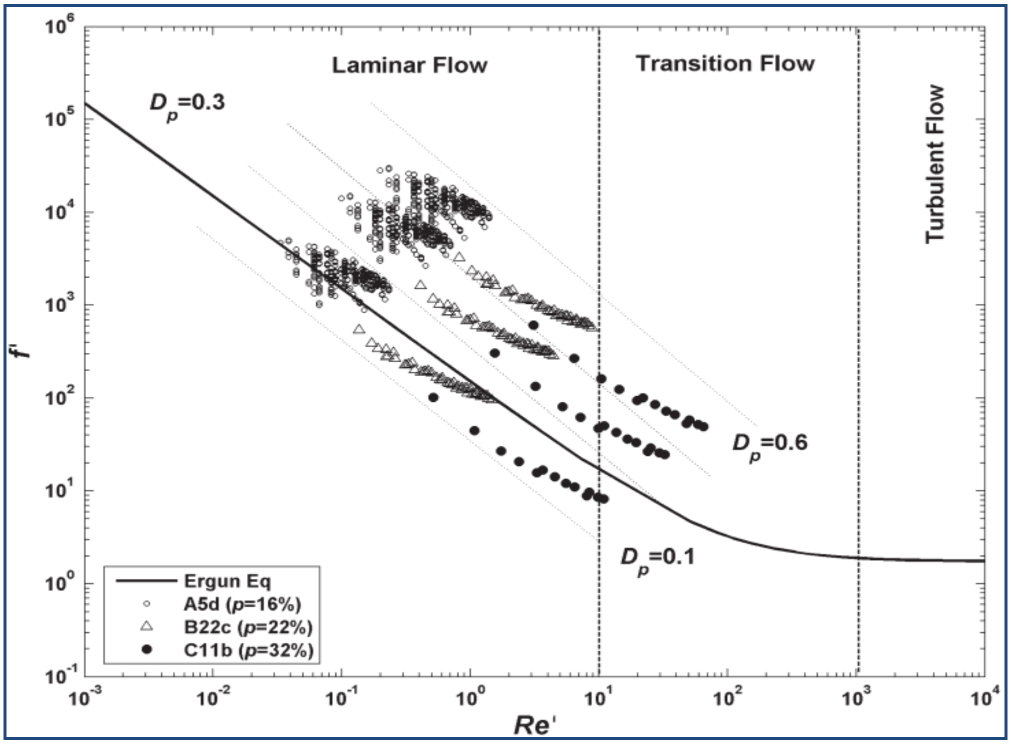


**Figure 2-10. Using Falling Head Permeability Measurements vs. Reynolds Number (Adopted from [18])**

Additionally, the non-destructive electrical method [19] and three-dimension planar images methods [40] were developed to predict the permeability of pervious concrete. Especially for specimens mixed with aggregates sized with 3/8 inches, the theoretical calculated permeability matches well with the measured values.  A brief summary about the porosity data and permeability, and the numerical relationships including best-fit formulas and Carman-Kozeny equations from each reference are presented in Table 2-5. The reasonable range for α factor is from 9 to 43 based on the published data.  It should be noted that the functions of porosity and permeability are different for different references due to the different samples' properties and mixtures. Currently, there is no universal mathematical relationship established between porosity and permeability of PCPC.

### Table 2-5. The Relationship between Measured and Calculated Permeability Coefficients and Porosity from Literatures

| Reference | Samples Description | Testing Methodology | K (cm/sec) = f ( p(%) ) | Carman-Kozeny Equations | |
|---|---|---|---|---|---|
| | | | | **α factor** | **Expression** |
| Felipe, 2005 | 1. Sample Size=19<br>2. Field placed concrete from 3 locations.<br>3. Average porosity: 16%, 18%, and 28%.<br>4. Cylinder cores 4" diameter and 4"-6" height. | 1, 2 | $K = 7.214*e^{(0.1761*p)}$<br>$R^2=0.7258$ | 18.9 | $K(cm/sec)=18.9*\frac{p^3}{(1-p)^2}$ |
| Delatte, 2009 | N/A | | $K=2.8705*e^{(0.1674*p)}$<br>$R^2=0.6748$ | 9 | $K(cm/sec)=9*\frac{p^3}{(1-p)^2}$ |
| Wang, K, 2006 | 1. Sample Size: 19<br>2. Cylinder cores 3" by 3" casted in lab<br>3. Unit Weight: 104.1-132.2<br>4. Porosity: 14.4-33.6<br>5. Permeability:0.015-0.193 in/sec | 1,2 | $K=13.257*e^{(0.1579*p)}$<br>$R^2=0.6522$ | 19 | $K(cm/sec)=19*\frac{p^3}{(1-p)^2}$ |
| V.R. Schaefer, 2009, 2006 & J.T Kevern,2009, 2006 | 1. Sample Size=17<br>2. Cylinder cores 3" by 3" casted in lab for permeability test.<br>3. Cylinder cores 3" by 6" casted in lab for porosity test.<br>4. Compaction Level: Low, Regular.<br>5. Unit Weight: 104.1-138.9 pcf.<br>6. Porosity: 11.2%-38.8%<br>7. Permeability: 0.004-0.59 in/sec | 1,2 | $K=5.8826*e^{(0.1873*p)}$<br>$R^2=0.794$ | 18 | $K(cm/sec)=18*\frac{p^3}{(1-p)^2}$ |
| J.D. Luck, 2006 | N/A | 1,2 | $K=0.066*e^{(0.1121*p)}$<br>$R^2=0.7933$ | 43 | $K(cm/sec)=43*\frac{p^3}{(1-p)^2}$ |
| B.Huang, 2009 | N/A | 1,2 | $K=0.732*e^{(0.1451*p)}$<br>$R^2=0.9991$ | 25.36 | $K(cm/sec)=25.36*\frac{p^3}{(1-p)^2}$ |

*** Note: "1" and "2" indicate for the Falling Head Permeability Test and "Volume Method"**

Infiltration rate is regarded as the most important parameter to evaluate the hydraulic performance of in-place pervious concrete pavement system, which may be affected by the properties of PCPC layer, subgrade layer and subbase soil conditions. A few in-situ infiltration testing methods have been published (See Figures 2-11, 2-12, 2-13, 2-14):

1) ASTM 1701C "Standard Test Method for Infiltration Rate of in Place Pervious Concrete";
2) NCAT (National Center for Asphalt Technology) Field Permeameter;
   Infiltration testing results from NCAT applied on in-place pervious concrete maybe over-predicted due to the lateral migration. Also, the large amount of water supply is required when conducting this method.
3) ERIK (Embedded Ring Sampling Times) method [42];
4) Embedded Single-Ring Infiltrometer method [38];
   This testing method is developed based on Double ring Infiltration (ASTM D3385-03 “Standard Test Method for Infiltration Rate of Soils in Filed Using Double-Ring Infiltrometer”), but eliminate the effect of lateral migration. After the modification, the infiltration of whole pavement system can be measured. This method can be used pre and post construction

**Figure 2-13. Standards for ASTM 1701 C**

**Figure 2-12. Field Permeameter Setup**

**Figure 2-14. Embedded Ring Sampling Times (Adopted from [39])**

**Figure 2-11. Embedded Single-Ring Infiltrometer Method (Adopted from [39])**

### 2.2.5 Freeze-Thaw Durability/Deicing Chemical Resistance

Frost durability is one of the primary factors impeding the wide application of pervious concrete in freezing climates such as Midwest. The volume expansion of water in the void space may break the bonding between the paste and aggregates, and cause the rapid deterioration of paste and/or aggregates, especially for lower porosity pervious concrete [22, 23, 26, 28,].

Currently, two testing methods are widely applied to evaluate the freeze-thaw durability of pervious concrete [22, 27], which are ASTM C 66 “Resistance of concrete and Rapid Freezing and Thawing” and ASTM C 672 “Standard for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals”. These two ASTM procedures the durability of pervious concrete under two frost phenomena, which are rapid freezing and thawing, and the chemical resistance under freezing-thaw condition respectively.

Early research reported that pervious concrete specimens can withstand over 160 freeze-thaw cycles when damp or in air, but only 45 cycles when in fully saturation [66]. Therefore, the saturation levels of the voids and the time for freezing influence the F/T durability significantly.

Mixed aggregate types and gradation show the significant effect on freeze-thaw durability of pervious concrete. The more textured surface of aggregates as limestone show the better freeze-thaw resistance compare to rounded and smooth surface of aggregates as river gravel due to the better aggregate to paste bonding. Current studies also show that addition of fine aggregates up to 7% by aggregates weight and introduction of air entrainment dramatically improves the freeze-thaw durability of pervious concrete [22, 24, 29]. A mixture containing sand and AEA shows the dramatically freeze-thaw compared to the same mixtures without sand and AEA. A similar conclusion was also reported that pervious concrete specimens with air entraining admixture had 50% to 70% of dynamic modulus after 65 cycles. Specimens with AEA had 20% to 70% loss after 70 cycles [24]. More than just engineering considerations in improving the F/T durability, the reduce of likelihood of fully saturating of pervious concrete layer also increases the F/T durability. The adequate storage capacity of subgrade layer, which allows the rapidly discharging infiltrated runoff to storm water sewer, is the key issue [69].

Considering the chemical attack on pervious concrete, pervious concrete is more susceptible to be attacked by aggressive chemicals due to its open structure. A research study [22] shows that on the damage of chemical deicers on pervious concrete pavement show that calcium chloride causes the most severe damage compared to sodium chloride and CMA in terms of surface condition, mass loss, and compressive strength. However, the current testing method as followed by ASTM C 672 “Standard Test Method for Scaling Resistance of Concrete Surface Exposed to Deicing Chemicals” presents the most severe condition.

The clogging effect retards the infiltration time, and cause a longer saturation time within pervious concrete. Therefore, the clogging effect and frost resistance may be related especially in freezing climates. The clogging effect on freeze-thaw resistance of pervious concrete in laboratory condition was reported by [30]. No remarkable signs indicated that frost resistance of pervious concrete was affected by sedimentation materials. However, the relationships between the clogging effect, potential saturation and freeze-thaw resistance have not been well resolved.

### 2.2.6 Flexural Strength/Compressive Strength/Splitting Tensile Strength

The mechanical properties are important for the structural design of pavements. Due to the high void ratio (15% to 35%), often without the fine aggregates in mixing proportions, the mechanical properties including compressive and tensile strength are always lower than conventional concrete. Compressive strength is always used in structural design of PCPC pavement Pervious concrete mixtures can develop compressive strengths from 500 psi to 4000 psi (3.5 MPa to 28 MPa). Typical value of compressive strength is approximately 2500 psi (17 MPa). Flexural strength of PCPC can develop from 150 psi to 550 psi (3.8 MPa). The relationship between splitting tensile strength and compressive strength for pervious concrete is between 12% and 15% of the compressive strength [29].

Degree of compaction and porosity are the two most important factors that influence the mechanical properties of PCPC. It has been found that the increase of fresh unit weight, increase of fine aggregates in mixtures, and the application of high compaction effort can increase the mechanical properties but also decrease the hydraulic performance [27, 48]. Also, aggregate-to-cement (a/c) ratio is important to determine the mechanical properties of PCPC.

Under the clogging condition, the change of mechanical properties of pervious concrete is rarely investigated in literature. When the clogging phenomena occur, the void space may be filled up with the clogging materials. With the compaction energy caused by the repeated traffic loading, the surface pavement materials become more compacted. Therefore, the strength increase of pervious pavement may be nearly negligible.

### 2.2.7 Consolidation and Compaction of PCPC

Compaction levels and methods affect the properties of pervious concrete including unit weight, compressive strength, permeability and void ratio. To get the best surface finish, required strength and permeability, proper compaction is important. Too little compaction may not provide the required strength or smooth surface, and may also cause potential for raveling of the finished pavement. Too much compaction may cause decreased permeability by closing up the void ratios. The same mixture can vary up to 25% of hydraulic performance by different compaction levels or energy [36]. Therefore, controlling the compaction energy accurately and quantitative for determining the performance of pervious concrete is important.

According to pore distribution results obtained by testing in-place pervious concrete cores 6 in. (15 cm) in height, the top third portion of the cores contain less porosity and higher density than the bottom third portion when subjected to a surface compaction finished by a static roller [24] (See Figure 2-14). Studies on the effects of compaction on strength and porosity distribution indicate that the low strength and porosity may be found at the bottom quarter of the pavement, which may cause the rapid crack potential, therefore, 6 in maximum thickness is recommended [65].

Several compaction methods were introduced in the laboratory to determine the relationship between porosity and unit weight: 1) Marshal hammer 2) Protector hammer 3) Roller-compacted concrete described in ASTM C 1176 “Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table” and ASTM C 1435 “Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer” and 4) ASTM C1688“Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete”. Jigging consolidation and rodding procedures introduced in ASTM C 29 "Standard Test Method for Bulk Density and Voids in Aggregates" as presented by ACI 522-08 are always used to determine the linear relationship between density of freshly mixed concrete and porosity, voids and splitting tensile strength. The theory is used in this study to control the properties of testing specimens. However, a large variability of specimens’ properties was produced using this compaction method.

Gyratory compaction testing of PCPC was introduced by [26, 58]. In this study, the different in-situ compaction levels on pervious concrete pavement were simulated in laboratory by using a AFGBI gyratory compactor with different loading pressures and number of gyrations.

Linear relationships between fresh density and void ratios, and fresh density and splitting strength are found. Also, compaction energy applied increase also freeze-thaw durability.

Based on this linear relationship, the viability can be eliminated when samples are casted using other compaction method mentioned above, such as tapping and rodding.

Placement of pervious concrete is always done continuously, spreading and striking-off immediately, commonly with vibrating screeds [17]. A temporary wood spacing strip form is pre-placed in the direction of placement (See Figure 2-15).

**Figure 2-15. A Temporary Wood Spacing is Pre-placed (Adopted from [54])**

Currently, there are two basic pervious concrete placement/compaction methods used in the United States: 1) riser strip method (See Figure 2-16 Left) and 2) roller-screed method (See Figure 2-16 Right). Other methods include either slip forms or a revolving steel cylinder that combines strike-off and compaction. Due to the rapid hardening and high evaporation methods, delays in compaction always cause problems. Generally, it is recommended to complete the compaction within 15 minutes of placement. The detailed information on compaction and construction standards of pervious concrete is readily available [24, 29].

**Figure 2-16. Compacting Pervious Concrete Using Vibratory Screed (Left) and Weight Roller (Right) (Adopted from [54])**

### 2.2.8 Pavement Hydrological Design of PCPC Pavement

The hydraulic performance of PCPC pavement is the primary driving force for the wide application of this special type of pavement. Capturing and storing all or some significant part of anticipated runoff in a given storm is the most important characteristic of PCPC pavement. The Curve Number method and Rational Method are two hydrological design methods [69]. The hydrological design of pervious concrete includes the surrounding environments, flat layout, site design, storage capacity (void ratio), pavement thickness, allowable ponding time, and infiltration rate of sub-grade and pervious pavement as well as the discharge systems.

PCPC pavement can be designed as a "passive" or "active" mitigation system. Reducing the quantity of impervious surface by replacing it with pervious surface is the main consideration for passive mitigation system. An active system, however, is to designed to capture the direct precipitation on pervious concrete and also the stormwater runoff from adjacent areas [27]. Therefore, better hydraulic performance is expected an active mitigation system. It is noted that the clogging effect on active mitigation systems is more critical.

The storage capacity of pervious concrete layer and infiltration rate of underlying soil are the main hydrological design considerations. Storage in the pavement’s reservoir takes the temporary differences between the inflow and outflow [37]. Adequate storage capacity produced from 15% to 30% porosity provides space for the water captured by system once the storm passed, and underlying soil with a typical infiltration rate of 1/2 in/hr (12 mm/hr) allows the water to drain in a fairly short time (typically less than 5 days). The shorter the dragdown time, the more effective or better the hydraulic performance of pervious concrete pavement behaves [57]. The porous sub-base such as open-graded or sandy soils is recommended if the underlying soil is impermeable such as clay layer soils. Another option to increase the drainage of poorly draining time is to install wells or drainage channels. Permeability as another important parameter is not always a limiting factor even though it can be significantly decreased due to clogging effect. Compared to infiltration of underlying soil, the permeability of pervious concrete can be easily much higher [57].

US EPA (1999) [43] provides basic guidelines on the design of PCPS: 1) placed over highly pervious layers of open graded gravel or crushed stones; 2) filter fabric must be placed beneath the gravel or stone sub-grade. From hydrological design considerations, the minimum 6 inches of granular or gravely sandy materials as subgrade shall have the minimum the permeability no less than one inch per hour. The base should be compacted uniformly with the slope less than 5% [38, 41, 65].

### 2.2.9 Pavement Structural Design of PCPC Pavement

The structural design of PCPS is similar to the standard pavement design such as AASHTO, ACI325.12R as the conventional concrete for streets and roads; ACI 330R for parking lots; sometime using structural numbers from asphalt pavement design procedure [15, 36]. Overall, the empirical design methods developed based on traditional concrete still dominated the pervious concrete pavement design practice. The pavement thickness and permeable subgrade are the main considerations in pervious concrete design. Also, the measured compressive strengths and empirical relationship estimated flexural strengths are the strength properties used in structural design of pervious concrete. It should be noted that the finishing, degree of compaction and compaction process also control the strengths and permeability values.

A few important design criterions are listed below [15, 28, 37, 38]:

- Typical pavement thickness is from 4 to 10 in. (125 mm to 250 mm);
- If using conventional concrete design, 25% additional pavement thickness for pervious concrete is required;
- Use a minimum 5 inches for parking area;
- Six inches for industrial driving lanes;

- Eight inches for low truck volumes;
- Every additional one inch of pervious pavement thickness can reduce the design void content by 2%;
- Sub-base materials depth from 6 to 12 inches, and 24 inches for F/T area;

A brief summary on typical structures of pervious concrete pavement for typical cross-section, standard parking lot or driveway, heavy traffic, and sidewalk, cart path are listed in Figure 2-17, Figure 2-18, Figure 2-19, and Figure 2-20.

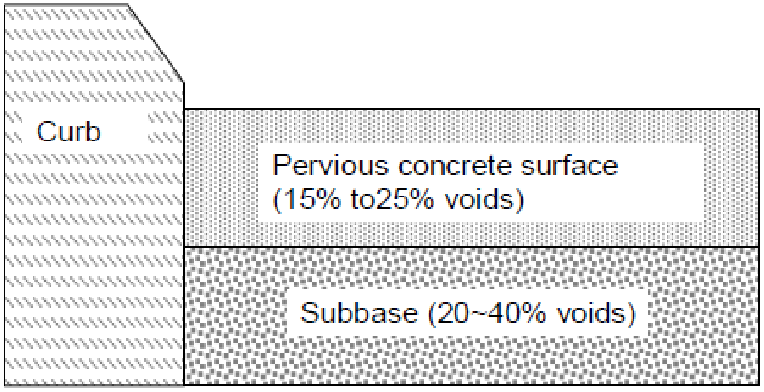


**Figure 2-18.Typical Cross-Section of Pervious Concrete Pavement, after Tennis et al (2004)**

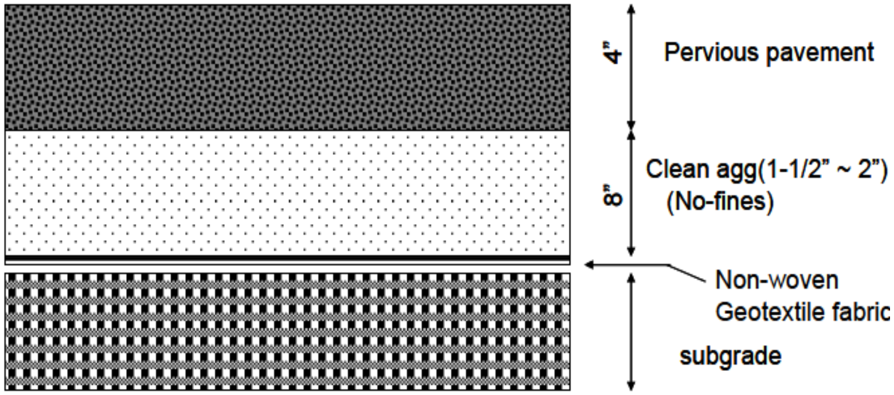


**Figure 2-17. Pervious Concrete Pavement Design for SidewalkCart Path, Hike, and Bike Trails, after (www.stonecreekmaterials.com)**

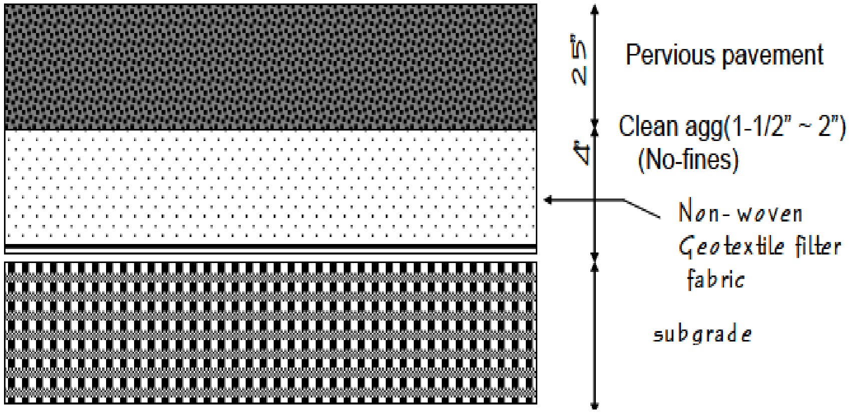


**Figure 2-20 .Typical Parking & Driveway Pervious Concrete Pavement after (www.stonecreekmaterials.com)**

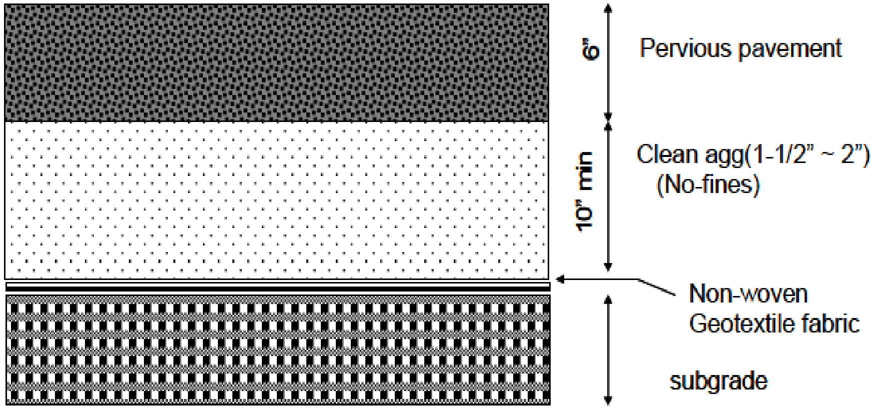


**Figure 2-19. Pervious Concrete Design for Heavy Traffic, after (www.stonecreekmaterials.com)**

## 2.3 Previous Studies of Clogging Effect of PCPC

Clogging has been regarded as another primary reason that causes failure, reduces the effective service life and impedes the widespread application of pervious concrete pavement [13, 36]. Attention has been focused on the clogging effect of pervious concrete, and the great progress that has been made in terms of design regulations and maintenance. The majority of pervious concrete pavements function well with little or no maintenance. Vacuuming sweeping and pressure washing or the combinations of these two are commonly applied as maintenance methods. Based on experience, maintenance is recommended being performed annually [13].

However, the quantitative study and evaluation on clogging effect, design and maintenance used to prevent the clogging effect have not been well established. The relationships among the pervious concrete pavement properties, clogging materials' properties, cleaning efficiency and maintenance schedule have not been established to provide the reliable information for in-place pervious concrete pavement. Ferguson [37] reported that the initial drainage time of unclogged concrete ranged from 25 to 75 seconds, and after nine clogging cycles, drainage time increased from 160 to 400 seconds. As a primary function of pervious concrete is the ability to readily transport water, understanding the clogging issue of pervious concrete is essential for delineating further maintenance and for estimating the quality of pervious concrete pavement. Further studies on clogging effect are recommended [28, 37] in terms of the several aspects listed below:

1) Sediment deposition and segregation;

2) Sediment transport within the pervious concrete;
3) Methods to estimate sediment load;
4) Deposition and transport effects on design methodologies;
5) The clogging-resistance mixtures and design of PCPC;
6) Quantitative estimation of cleaning efficiency of a certain type of cleaning method;

### 2.3.1 The Clogging Effect of PCPC

#### 2.3.1.1 The Clogging Failures of PCPC Pavement

The severe clogging failure may occur to the pervious pavement after the pavement construction in a short period. It has been shown that the rapid decrease in filtration rate of pervious pavement could occur during the first two years of service due to the clogging effect. The in-situ infiltration rate test showed approximately 10% of the initial level after 2-3 years of construction or 87% reduction of permeability after 3 years of construction [58]. The clogging developed very rapidly in the first few years, which cause a significant reduction of infiltration rate, for example, 30% to 50% reduction in country area; 40% to 70% reduction in cities and 60% to 90% reduction in the much polluted areas.

The clogging failures are caused by various reasons on pervious concrete pavements. Landscaping materials such as mulch, sand, and topsoil should not be stored and staged on the completed pervious concrete, even temporarily. Any construction aggregates must be prevented from the spilling onto a completed porous pavement. Ferguson [37] suggested that a pervious concrete may be impractical for public streets under the load of clogging materials. Also, during a construction project pervious concrete should always be the last process. A good site design minimizes surface clogging by locating, and protecting the pavement by pretreating runon (with a vegetative filter strip), as feasible [69].

If the pervious concrete were already paved close to construction site, contractors must pay attention that no construction traffic onto pavement and no construction runoff. The pre-construction plan and surrounding environments are extremely for preventing the clogging failures from happening, as presented in Section 2.1.

Some common clogging failures are shown in the several figures. Figure 2-20 shows that failure caused by construction runoff. Figure 2-21 shows that sedimentation brought by runoff from adjacent unplanted area. Figure 2-23 shows the clogging occurred adjacent to the construction site. Figure 2-24 shows clogging occurring to pathway, and the sedimentation materials brought by vehicles, wind and/or stormwater runoff from surrounding environments. Particularity, this pavement as shown in Figure 2-24 was constructed and finished in March, 2010, and this photo was taken on July, 2010. As can be observed, the clogging started to occur with few months after the construction was finished. The failure case was caused by constriction traffic.

Figure 2-22. Clogging Failure Caused by Construction Runoff

Figure 2-21. Clogging Caused by Surrounding Unplanted Area

Figure 2-23. Clogging Failure Caused by Construction Traffic

Figure 2-24. Common Clogging Failure Caused by Surface Runoff

### 2.3.1.2 The Definition of Clogging Effect

The clogging effect or sedimentation effect has been studied and defined by many researchers and studies [28, 54, 59, 60]. A universal definition that is widely accepted is that clogging materials or sedimentation solids including soil, rock, leaves and other debris, which may be brought by wind or more commonly by stormwater water runoff from the surrounding environments, infiltrate through and/or are retained within the pervious concrete, and enter into the voids space with the water infiltration, and decrease the hydraulic function in terms of the gradual reduction of permeability and storage capacity of this pervious concrete pavement system. Frequent maintenance must be performed to keep or improve the hydraulic performance to an acceptable level.

Chopra [41] defined the clogging effect of the pervious concrete for the whole pavement system as that the permeability of pervious concrete layer decreases lower than the permeability of underlying soil due to the completely or partially clogged during the service life, then the permeability of pervious concrete becomes the limiting factor of the whole pavement system. At this time, the restoration action or application of cleaning methods is required to improve the permeability of pervious concrete layer to achieve the better hydraulic performance.

The clogging degree is found relate to the type of clogging materials, pervious concrete properties, stormwater runoff, environmental surroundings of in-place pavement and the rehabilitation methods [28, 59, 60]. To detail these different aspects, this section on previous clogging studies is organized into 1) the effects of various sediments, 2) different void ratios of PCPC, and 3) comparisons of the rehabilitation methods.

### 2.3.1.3 The Clogging Effects on PCPC Properties

The clogging effect on the performance of PCPC mainly relates to the change of the porosity and the pore structure properties including pore size, pore shape, pore size distribution and tortuosity with the gradual particle retention and the consequent permeability reduction [60]. Studies showed that the clogging materials are trapped in the void space, and block the flow channel, and furthermore, the tortuosity would be increased in terms of the longer flow distance. Limited studies have been conducted to investigate the effect of porosity and pore structure of pervious concrete under clogging condition. Change in porosity and pore structure due to clogging is the internal cause, and the changes in hydrological behaviors are the results, which are manifested three ways:

1) Clogging can reduce surface permeability of the pervious concrete layer;
2) Clogging can affect the infiltration rate into the subgrade, that is, exfiltration from the system to underlying soil;
3) Clogging can slightly reduce storage capacity;

   Mata and Neithalath [28, 61] described the influence of clogging mechanism, and the studies show that the clogging could cause the loss of 3-5% of initial total storage capacity.

The clogging effect on hydraulic performance reduction of PCPC pavement has been studied in laboratory and in-place condition, but the effect on the mechanical properties and freeze-thaw durability has not been studied.

### 2.3.1.4 The Effects of Different Types of Sediments

Different type of sediments cause different deposited patterns, retained locations and the different effects on hydraulic performance reduction and maintenance recovery. The effect of different type of sediments on clogging is discussed fairly well in Mata (2008) [28]. The types and quantity estimation of sedimentation employed in this study were calculated based on the Universal Soil Loss Equation (USLE), which also provide a good reference for the other researchers. In this study, three types of sediments 1) sand sediments 0.08 in (2 mm) and #200 sieve size(75 µm), 2) fine sediments smaller than #200 sieve size (75 µm), and 3) the combination of these two were used as clogging materials to investigate the effect on hydraulic performance of pervious concrete. More detailed discussion can be found in section 2.3.2.1.

Sediments from various locations are also different [28, 37]. In the Pacific Northwest, organic debris is a more likely the clogging material. The cool moist climate promotes net accumulation of organic matter. The suspended inorganic soil particles in stormwater were used as sedimentation materials in clogging test [30].

The well-known phenomena was found that larger particles tend to be retained on the top or near the surface, the finer sand particles penetrate the pavement and were trapped within the concrete, the even finer particles could infiltrate though pavement, and deposited between the surface concrete layer and underlying soil (See Figure 2-25) [28, 59, 60]. This phenomenon also could explain that surface washing and vacuuming sweeping have a good efficiency in cleaning the clogged pavement subjected to larger sedimentation materials [17] as presented in Section 2.2.3. Research Studies [62, 63] reported coarser particles took more time to clog the pavement than finer particles. The clay materials tend to retain on or near the pavement surface, and reduce the infiltration rate gradually [59]. Recent placement technique results a lowest porosity on the top, which could filter the clay materials effectively by the smaller pores. Lower levels with simple maintenance such as surface sweeping or rinsing can restore the serviceability to acceptable. Higher sediments loading rate or the density of the clay suspensions for the same clay increased the rate of loss. The difference in the conclusions summarized by the various studies [28, 59] would be confirmed in this study.

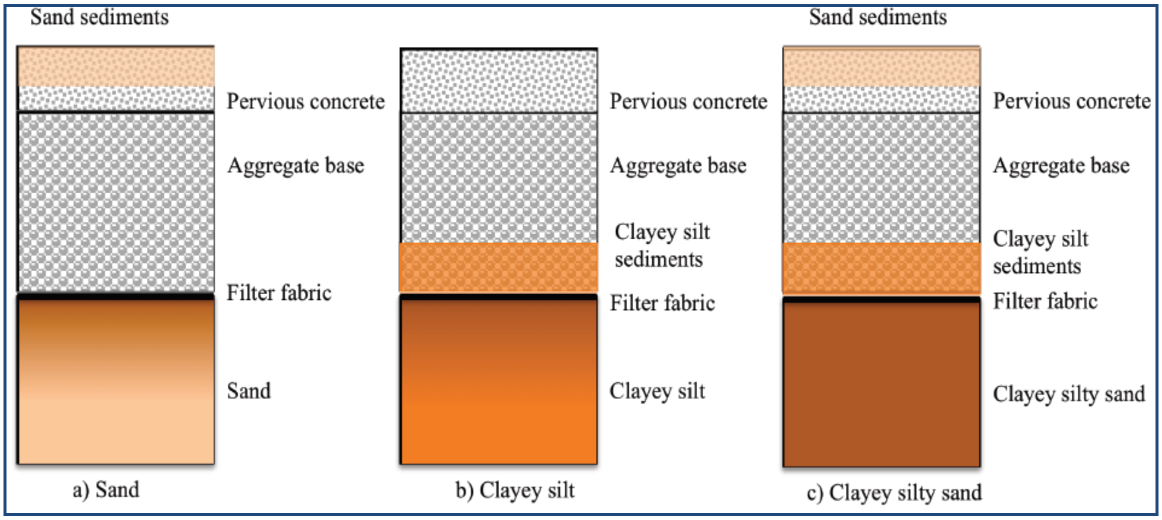


**Figure 2-25. Different Cases of Sediment Deposition in Pervious Concrete Depending on Soil Type (Adopted from [28])**

Various sediments were found to cause the different magnitudes of permeability reductions. In terms of maintenance efficiency, the larger size of solids as sand could be removed effectively by using pressured wash. Rocks, leaves and other debris which have fairly larger size than pore size are easier to clean using the traditional cleaning method such as sweeping or pressure washing. However, the fine solid, such as clay or silts that are easily trapped within the void space of pervious concrete pavement at the certain depth is hard to clean Approximate 60% to 70% of initial permeability was lost [28]. Shown in Figure 2-26, the comparison of two specimens confirms that coarser and finer sediments tend to be retained at different locations. The same conclusion was also reported [29] that sand as a cohesionless material generally with a larger size than the pore size, may be easily trapped. From Figure 2-26, little amount of coarser sediments was found at the bottom of specimens, which indicate that most were tapped on the surface or within the specimens. In contrast to coarser sediments, significant amounts of fine sediments such as clays were found at the bottom of specimens.

In general, studies on the effect of sedimentation type are recommended [28, 59]. Better understanding of linking the sediment's characteristics such as the particle size and particle types to clogging effect and the rehabilitation methods recovery efficiency should be obtained.

**Figure 2-26. Pervious Concrete Specimens Subjected to Sand (Left) and Clay (Right) as Sedimentation Materials (Adopted from [28])**

#### 2.3.1.5 The Effects of Properties of PCPC

The relationships between clogability and properties of PCPC such as the mixtures, mixing materials, void ratios and initial permeability have been discussed by several studies [29, 17, 28, 62, 64] reported that the increasing amount of #4 aggregates in mixtures increased the propensity of clogging under fine sand sedimentation load. The blended mixing aggregates show the best clogging resistance. The mixtures which cause larger pore size than clogging materials tend to have lower permeability reduction. The effective pore size to sedimentation particles size ratio ranges between 10 and 12 leads the highest reduction on permeability of testing specimens, and also leads the highest clogging potential. More detailed discussion is presented in Section 2.3.2.2. However, one limitation is that only fine and coarse find as sedimentation materials was studied in this study.

By studying the clogging effect on soil filters [64], the results indicated that the soil filters which contained a more uniformly sized distribution particles tends to cause a faster reduction in permeability compared to those with large variability in particle size distribution. This finding implies the conclusion from Omkar (2009) [29] that the narrower mixed aggregates are preferred for clogging resistance design of pervious concrete. Additional research is recommended to quantify and verify this relationship between mixed aggregates size and clogability. The density effect on clogging resistance has been studied [41]. The testing results showed that the lower the concrete density, the better of infiltration rate and infiltration recovery rate for the specimens being exposed to the same semimetal loading and rehabilitations method. The reasonable high porosity of pervious concrete may indicate the better the cleaning efficiency.

The host of parameters such as the total pore volume, pore characteristics including the pore size and the connectivity affect clogability of pervious concrete significantly [29]. Porosity, currently regarded as the most important one, has been studied. Testing specimens studied in literatures mainly contained approximate 20% void ratios [28, 29] and the additional study on the effect of void ratios on clogability was recommended by many research studies [17, 28, 29]. The important findings and recommended study are helpful for developing the design methodology of pervious concrete, which is less susceptible to clogging.

#### 2.3.1.6 The Efficiencies of Different Rehabilitation Methods

Maintenance of pervious concrete pavement primarily consists of prevention of clogging of void structure, winter maintenance and distress remediation [37]. For the winter maintenance, like all other Portland cement product, avoiding use of salts and deicers for a minimum of one year is recommended. The hydraulic function of pervious concrete maintenance is the main consideration in this master thesis.

Three rehabilitation methods 1) vacuum sweeping and 2) pressure washing are most commonly used in practice, and show good efficiency in rehabilitating a clogged pavement. Sometimes the two are used in combination (pressured washing followed by vacuuming sweeping) and this combination shows the best recovery of hydraulic performance. Ferguson [37] reported that the infiltration of pervious concrete specimens subjected to sand sediments can be immediately restored with pressure washing and immediate brooming. Also, vacuuming without pressure washing could be more effective for sand as sedimentation materials.

The important issues about pervious concrete pavement maintenance are: 1) prevent heavy sediment accumulations within the pavement structure; 2) clean debris off from the pavement surface quickly; and 3) schedule regular maintenance to provide greatest effectiveness of the pavement. Currently, there is no universal rehabilitation method standard for pervious concrete cleaning. The mechanism can be summarized below [13, 37, 41]:

### ***Pressure Washing***

As shown in Figure 2-27, the “power head cone nozzle” is used to concentrate water in a narrow cone (other types of nozzle did not work as well), and loose or weaken the bonds between the clogged particles and concrete, and push the clogging particles well inside the core or even to the bottom pavement, or the underlying soil or gravel reservoir. However, there is the risk of contamination of underground water. High volume-low pressure water has proven to be most effective as shown in Figure 2-28. Pressure washing of a clogged pervious concrete pavement has restored 80% to 90% of the permeability in some cases [65]. The typical pressure applied should be carefully determined, which is normally approximately 20.7 MPA (3,000 psi) [41].

**Figure 2-27. Pressure Washing (Adopted from [22])**

***Vacuuming***

Vacuuming is also called suction. The clogged particles near the pavement surface are sucked out and make the partial surface and interconnected pores open. It should be noted that only the particles close to the surface can be extracted and doesn't include the deep portion of pavement. A typical street vacuuming sweeper and a dry/wet vacuuming are shown in Figure 2-28 and 2-29. Vacuum sweeping annually or more often may be necessary to remove debris from the surface of the pavements. For most of the cases, the vacuum sweeping is faster than but not as effective as pressuring washing [13, 37, 41].


04/22/2009

Figure 2-28. Typical Street Sweeper (Adopted from [22])

Figure 2-29. Vacuuming Sweeper (Adopted from [22])

### *Pressure Washing & Vacuuming*

The vacuum sweeping followed by the high pressure washing shows the best cleaning efficiency for most cases in terms of the infiltration rate recovery percent [36, 37, 41]. ACI 522R-2008 reported that the most effective cleaning scheme is to combine the two techniques: power vacuum after pressure washing. Table 2-6 shows the testing data [41], which was based on 18 testing specimens obtained from the field (public parking lots) with service lives from 6 to 18 years. Vacuum sweeping using 4.85 kW (6.5-HP) wet/dry vacuum sweeper and pressure washing using 20.7-MPa (3,000-psi) pressure washer were applied. The restoration of the infiltration rate, which was defined as the ratios of post-rejuvenation infiltration to rejuvenations infiltration, was listed. The higher numbers are the better cleaning efficiency of the applied methods is under this clogging condition. A similar conclusion was reached in Ferguson (2005) [36] that the highest permeability recovery was achieved by using pressure and vacuuming swept (See Figure 2-30).

**Table 2-6. Restoration of Infiltration Rate (%) By Different Rehabilitation Methods [37]**

| | **Vacuum Sweeping Only** | **Pressure Washing Only** | **Vacuum sweeping followed by pressure washing** |
|---|---|---|---|
| Minimum | 1.9 | 1.9 | 4.1 |
| Maximum | 31 | 360 | 379 |
| Mean | 10.4 | 56.7 | 66.9 |

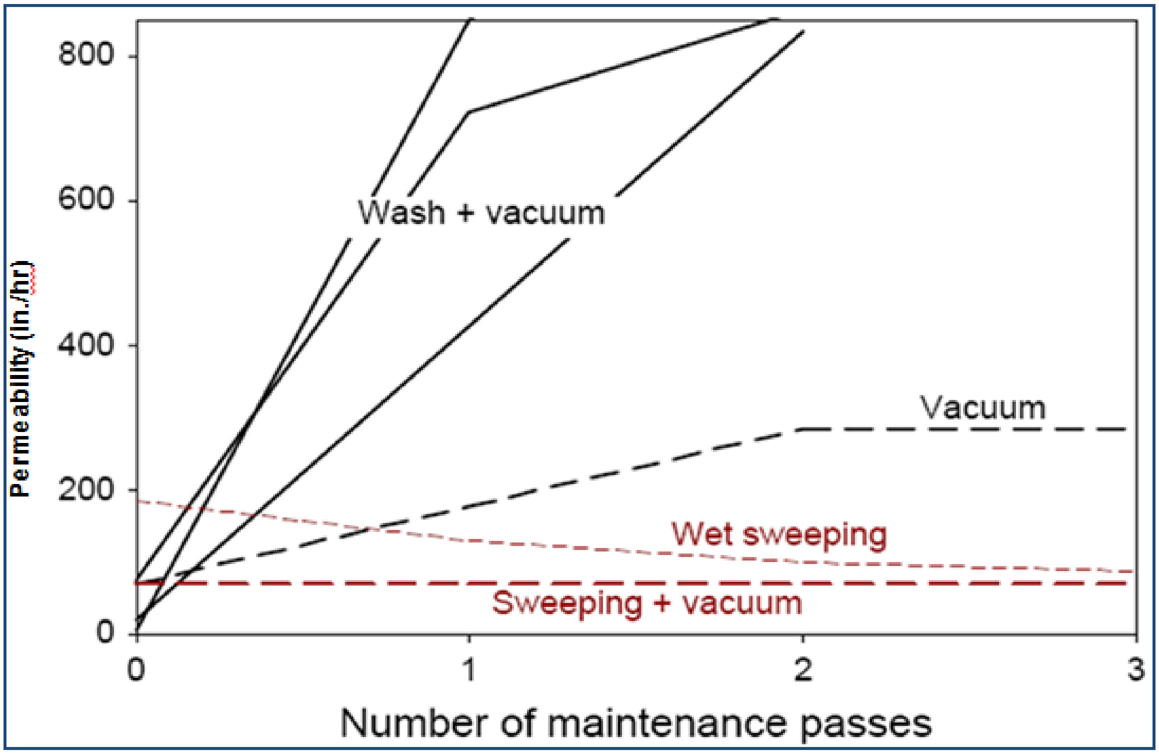


**Figure 2-30. The Permeability Recovery by Different Rehabilitation Methods (Adopted from [38])**

Scheduled maintenance after construction may be also required with time. Four inspections each year with appropriate jet hosing and vacuuming sweeping treatments are recommended by US EPA (1999) [43]. Studies show that if maintenance has not been applied on time or after a serious clogging phenomenon occurs or when the permeability rate is below 0.1 cm/s, there would be no improvement in infiltration rate with sweeping followed by vacuuming because of the fully clogging [42]. In most cases, maintenance is performed according to empirical evidence and/or experience; there are no universal standards to be followed. The maintenance for pervious concrete is still being developed. The additional studies on quantitative determination of recovery efficiency and maintenance schedule based on pervious concrete pavement and sedimentation materials should be investigated.

#### 2.3.1.7 The Clogging Effects on Hydrological Design of PCPC Pavement

Current studies on clogging effects on hydrological design of PCPC pavement focus on the exfiltration and storage capacity reduction and maintenance procedures of pavement subjected to various types of sedimentation materials [28]. Depending on the estimation of sediment volume, site characteristics, requirement of end of service (EOS) hydrological performance, deposition patterns of sediments in PCPC pavement and clogging potentials of different sediments, a few design criterions have been established [28]. These recommendations are based on the sedimentation test on three sediments; 1) clayey silt 2) clayey silty sand and 3) sand. However, most of the design criterion still follows the current practical standard of pervious concrete construction [57].

The addition of one inch (25 mm) of base layer is recommended to overcome the storage capacity loss and keep an acceptable hydraulic performance under typical loads of clayey silt or sandy sediments. The traditional methods pressured washing; vacuuming sweeping and the combination of these two are effective under this clogging load.

When PCPC pavement is subjected to clayey silty or slty soils and, the flow rate loss is considerable, the traditional maintenance methods have proved to be ineffective [37]. The clayey silty formed a sedimentation layer at the surface layer bottom retained by the filter fabric are the controlling factor of the exfiltration of the system. Immediate cleaning action is recommended once the mulch or small particles or organic are accumulated on pervious pavement. However, pressure washed and vacuuming is still applied based on experience. The design guidelines for PCPC pavement under this case still follow that described as cited in [57]. Mata [38] provided the following considerations:

1) Conduct the initial hydrologic analysis based on the surrounding environments. Determine the composition and total volume of the sediments anticipated over the simulated service life time.
2) The sedimentation loads=1000 lbs/acre/year (typical value) or 860 lb/acre/year (industrial site)
3) Predict the sedimentation load in mass per unit area, and conduct the simulated clogging test as the preliminary study in laboratory.
   Check the hydrological behaviors (permeability and storage capacity) to see if the initial design is still acceptable to provide adequate drainage ability under the sedimentation loading. If not, it is necessary to re-design the pavement structure.
4) On-site permeability (minimum) = 290 in/hr (0.2 cm/s)

In general, the additional of one inch of base layer is recommended under clogging load, and traditional cleaning methods are recommended to under the different clogging loads. The additional research is this area is recommended [38].

### 2.3.2 The Previous Studies on Clogging Effects of PCPC

There have been some researches discussing the clogging effects of pervious concrete pavement. The clogging testing methods, sample preparations, sedimentation assumptions, conclusions and weakness are slightly different for each of these studies. However, most of these experiments were conducted based on the principle similar to falling head permeability cell, and the gradual reduction of permeability of specimens was measured. The simulation of the clogging condition in the field was the main objective in clogging test in laboratory. For instance, three types of sedimentation materials are used [28], and the water mixed with sediments as clogging fluid was allowed draining through the specimens for 24 hours. Pressurized washing was applied to clean the clogged samples. In Pezzaniti (2009) [30], the clogging fluid employed contained the average suspended solids concentration of 200 mg/L. A total of 1110 g sedimentation materials were used based on the simulated time of 35 years or 420 month for in-place condition and two mixers were used to keep the suspended state of solids in the liquid. In Neithalath (2009) [61], a total of 25g clogging materials was spread evenly on the specimen, which represented the “first flush” of the runoff. The test took a relative long period until these were no noticeable change of permeability with additional clogging materials adding in this simulated “first flush”.

The difference between the clogging test and falling head permeability test is to infiltrate the clogging fluids through pervious concrete specimens rather than the pure water. In this session, the difference between each method is discussed and summarized. The results of recent research studies are reviewed below.

#### 2.3.2.1 Mata (2008)

The objective of this study [28] was to identify and analyze the effects of sediment deposition and segregation, and the effects of sediments transport within the PCPS layers. The appropriate design guidelines for storage capacity under the sedimentation conditions were discussed. Also, the appropriate maintenance strategies corresponding with the actual sedimentation conditions were investigated. Additionally, the frost resistance of PCPC with the realistic freezing rate under sedimentation conditions was investigated.

This is the first paper study to investigate the performance and functionality of pervious concrete pavement system in the simulated sedimentation conditions, and it helps engineers to take the clogging effect into account when design the pervious concrete pavement. Importantly, different with other clogging tests in literatures, the sedimentation materials were divided into three types, which are sand, clayey silt and clayey silty sand according to the EPA regulations, which was to simulate the actual environments. Each type of sedimentation materials was applied in clogging test. The conclusions from this study are:

1) For sand sediments as clogging materials, the decrease of permeability and storage capacity are negligible. The traditional cleaning methods can clean and improve the drainage ability to an acceptable level.
2) For clayey silt as clogging materials, the presence of finer grained sediments on the fabric filter affects the serviceability significantly. The sedimentation layer retained by the fabric filter at the bottom of the PCPS affects the exfiltration strongly. The traditional

maintenance methods are not applicable in this case. Therefore, the effects should be considered in design.

3) For clayey silty sand as clogging materials, the worst permeability loss and lowest permeability recovery occur in this condition. The finest materials deposited at the bottom affect the effective permeability. The traditional maintenance methods are also not applicable.
4) The traditional cleaning methods such as vacuuming, sweeping and pressure washing are not effective when the clogging materials are either clayey silt or clayey silty sand.
5) It is confirmed that the effects of sand and AEA are effective on frost resistance.
6) 7% of the sand by weight in mixing proportions is effective to improve the frost resistance of PCPC.

**Testing procedures:**

The testing was divided into three phases: 1) sedimentation condition with low flow and high sediment load; 2) sedimentation condition with high low flow and moderate sediment load; 3) F/T durability test. For phase 1 and 2, the sedimentation loads and amount of clogging fluids infiltrated were different accordingly. For the total clogging and cleaning cycles, it is based on the on the service life of 20 years. The general testing steps are listed as below:

1) Measure the initial permeability of the testing specimen before sedimentation test.
2) Apply the sedimentation and cleaning cycles.
3) Repeat the sedimentation and cleaning cycles according to the simulated service life.
4) Check the distribution of the sedimentation along the depth of pavement

### 2.3.2.2 Neithalath (2009)

The objective of this study [61] was to understand the influence of pore structures features (porosity and pore sizes) on clogging resistance and permeability reduction. Three types of coarse aggregates (#4, #8 and 3/8”) were used to mix three types of specimens, and 20% of porosity remains constant for all testing samples. The fine and coarse sand used as clogging materials mixed with pure water at the certain concentration were used as clogging fluids in the falling head permeability cell.

Also, the new parameter “clogging potential” was defined in this paper described the ease of the certain PCPC pavement get clogged. The study results show that:

1) The clogging is related with the pore size and the mixed aggregates size of pervious concrete as well as the gradation of clogging materials.
2) The finer clogging material tends to have more severe effects than coarse clogging material on permeability reduction.
3) Exposed the same clogging conditions, the PCPC samples made with smaller size aggregates tend to have higher residual permeability than the PCPC samples made with larger size aggregates due to the higher pore size distribution.
4) The permeability decrease for the samples mixed with 3/8” aggregates is smallest among the three types of samples.
5) The blended aggregates tend to have more severe clogging than any single sizes aggregates.

6) The permeability reduction is fairly small in both cases when pervious concrete contain either the very large or very small pores. However, the reduction is significant when the pore size to clogging particle size ratio is within the range from 10 to 12.

**Testing procedure**

1) Determine the porosity by image analysis and the hydraulic conductivity by the falling head permeability.
2) Fine and coarse sand applied as the sedimentation materials, and keep the materials constant for every testing sample
3) 25g of clogging material either coarse or fine sand which represents the first run were applied in clogging experiment.
4) Repeat Step 3 or add the same clogging material until the clogged permeability tent to a constant value or no noticeable change with addition of clogging materials or approach to zero.

#### 2.3.2.3 Tan et al. (2001)

By examining the effect of sand and residual soil as sedimentation materials on hydraulic performance reduction of permeable bases, and taking the gradation of potential sediments particles and mixed aggregates into consideration of clogging phenomena, the following are the main conclusions from this study [29]:

1) A narrower particle size distribution of mixed materials or small $D_{85}/D_{15}$ ratio leads to the larger voids and more open base, and higher residual permeability.
2) The empirical coefficient α is defined in this study as a function of ratio of $D_{15}$ of permeable size to $d_{85}$ clogging materials, and the coefficient uniformity of clogging materials. This empirical coefficient is found to be inversely related to $D_{15}/d_{85}$, and directly related to coefficient uniformity of clogging materials.
3) A higher α-factor implies a more rapid decrease in permeability under clogging condition.
4) The gradation and amount of clogging material, and particle shape is recommended to be studied in terms of clogging effect.

**Testing procedures:**

1) The 150 mm tall cylindrical specimens with crushed granite aggregate are prepared.
2) Measure the initial permeability of the specimens by using Volume method 2.2.2.
3) Clogging procedure (addition of clogging material in the water that passing through the specimens)
4) Measure the permeability of the testing specimen after the clogging.
5) Compare the measured permeability with 1milimeter/s. If not, redo the clogging cycles until the permeability is smaller than 1mm/s, and collect the clogging materials. If yes, stop the experiment.

### 2.3.2.4 Haselbach (2006)

This study [31] determined the relationship between the permeability of clogging materials, the porosity of the un-clogged materials and the effective–permeability of sand-clogged block.

Then, the test results are compared with the estimated results based on the numerical methods. The results show that:

1) The system permeability is considered and measured including the concrete layer and subbase.
2) The system permeability for unclogged pervious concrete pavement is always limited by the permeability of the subbase or soil subgrade below.
3) The permeability of pervious concrete block without a subbase or sand clogging ranges from 0.2 to 1 cm/s.
4) The system permeability over an extra fine sand subbase without sand clogging is about 0.02 cm/sec.

**Testing procedures:**

1) An adjustable wooden flume with 158 cm long and 28 cm wide was constructed in the laboratory.
2) The pervious concrete pavement system was placed in the flume, which contains the sub base, pervious pavement layer, and the clogging materials coverage on the top.
3) The various depth of sand coverage and surface slopes of the flume are applied.

4) The simulations of various amount of rainfall runoff are carried in the lab.
5) Measure the water runoff amount at the both ends of the flume with and without the sand coverage both.
6) The permeability of the pervious concrete system are calculated by using the theoretically equations from the derivation.
7) Compare the estimated permeability results with the measured results.

#### 2.3.2.5 Pezzaniti (2008)

The effective life or service life or useful lifespan under the sediment loadings and the water quality improvement treated by pervious concrete pavement were the main objectives in this study [35]. Both tests in laboratory and in field were conducted. The actual sediments loading conditions over 35 years of service life was simulated and applied to three types of pervious concrete pavements. The results show that the hydraulic conductivity of the testing pavements reduced 59 to 75% with the average sediment retention of 94%. The traditional cleaning methods sweeping and vacuuming show the little effect on suspend solid concentration in outflow.

In the field studies, the concentrations of sediments in runoff related with the clogging effect. The high coarse sediment and organic sediments cause the clogging of pavement rapidly, particular where runoff flowing onto the pavement was concentrated.

### 2.3.2.6 Y. Joung (2008) [62]

In this study, the effects of mixture on permeability and clogging of pervious concrete were investigated. The falling head test was used as clogging test to determine the relationship between the reduction of permeability of the specimens and the amounts of added clogging materials. The testing specimens contained the different void contents.

The results mainly show that the clogging reduced the permeability of the specimen with void ratio from 23% to 31% more significantly compared to the specimen with the void ratio about 33% higher. More research was recommended to further study the effect of initial porosity and/or initial permeability of pervious concrete on clogging potential.

**Testing procedures:**

1) Place the clogging materials (4 types in this test) per unit weight of the water and mix roughly
2) Pour clogging fluid into the ready sample in the clogging apparatus
3) Drain mixed water from the cylinder
4) Repeat step 1, 2 five times that the pervious concrete cylinder becomes well clogged with sand.
5) Set the clogged sample in the falling head permeameter
6) Measure the time for water head to fall from initial level to final level while draining. Repeat five times and average the results.

## 2.4 Important Findings from Literature Review

1) Pervious concrete is regarded as an “environmental friendly” building materials and is increasingly applied due to the environmental, structural and cost benefits.
2) There are still deficiencies in PCPC, which are low compressive strength, flexural strength, clogging, freeze-thaw resistance and other durability, that limit its application as a pavement. However, a great progress has been made in the past few years.
3) Studies show the in-place compacted pervious concrete contains higher porosity at bottom which may cause the weak strength and potential crack at the bottom.
4) The pore structure analysis has been found important to predict the hydraulic performance as permeability and storage capacity of pervious concrete pavement.
5) The clogging potential of pervious concrete depends on the gradation of sedimentation materials and mixed aggregates, pore size, initial porosity and sediments type.
    - When the sediment particles’ size is close to the pore size of pervious concrete, the clogging potential is highest.
    - A narrower particle size distribution of mixed coarse aggregates retains the better clogging resistance and higher residual permeability; blended mixed aggregates have more clogging potential.
    - Different types of sediments cause different clogging effects on pervious concrete based on the deposited patterns and locations.

    - Clogging reduced the permeability of the specimen with void ratio from 23% to 31% more significantly compared to the specimen with the void ratio about 33% higher.
    - Further research is recommended.
6) Sedimentation effect could significant reduce the permeability but fairly negligible effect on storage capacity of pervious concrete.
7) Traditional cleaning methods show very limited recovery on finer sediments, but better efficiency on coarser sediments.
8) The combination of vacuuming swept and pressure washed show the best efficiency based on empirical evidence and experience. The quantitatively and accurately study is recommended.
9) The additional one inch of subbase is recommended to clogging hydrological design of pervious concrete.

## 2.5 List of Uniqueness of This Study

The shortcomings of previous studies have been discussed. A more comprehensive study on clogging effects by considering the effects of void ratios, sedimentation types and cleaning methods has not been well established yet. Therefore, according to the review and recommendations from previous studies on this topic, the developments and uniqueness of this study are listed:

1) Three variables including three types of sediment materials, three designed void ratios and three selected cleaning methods are considered in the developing consideration of testing matrix in this study.
2) The design parameter of PCPC pavement, that is void ratio, is considered in terms of clogging issue. The conclusion established based on testing results can be used as reference in terms of clogging issue for pervious concrete design.
3) Understanding the deposition patterns of different sedimentation materials can lead to the better understanding of clogging mechanisms, and furthermore, to determine the relationship between pore structure of pervious concrete and properties of sedimentation materials as well as its transportation within the pavement.
4) The designed clogging test was used to simulate the actual clogging condition, and the results may be used to predict to residual permeability in reality.
5) The applications of three most commonly used cleaning methods on clogged specimens that were exposured to various clogging conditions are evaluated in terms of permeability recovery.

# Chapter 3. LABORATORY EXPERIMENTAL WORK

## 3.1 Introduction and Design Principles

The objective of experimental work is to examine the clogging effect of pervious concrete at different design void ratios subjected to three types of sedimentation materials, and to provide a quantitative evaluation in terms of permeability reduction. Additionally, the comparisons of rehabilitation methods are presented in terms of permeability recovery of clogged specimens. The influence on hydraulic performance related to pore structure and the clogging mechanisms is also discussed. A maintenance schedule established based on laboratory clogging test results could be used as the reference guide for the pervious concrete pavement maintenance in field.

Based on the findings from this study, a better understanding on the quantitative evaluation of clogging effect on pervious concrete is obtained. The important finding are presented and discussed in Chapter 4. Also, in this chapter, an overview of test parameters and the concrete materials and mixtures is provided. Descriptions of the mixing procedures, preparations and curing of the specimens and the test methodologies are also reviewed.

The design principle of the experimental study is to simulate the in-place field clogging of pervious concrete in the laboratory. A clogging cycle which is explained later in this chapter is defined to simulate the clogging of in-place pavement in each service year. Based on this simulation, the permeability reduction of in place pervious concrete due to clogging effect can be determined, and also the permeability recovery by cleaning methods is also found.

## 3.2 Testing Matrix

The experimental program can be divided into two steps: 1) the testing specimen preparation; 2) the clogging testing, which includes two cases. In the step 1, through the proper casting and compaction, only the testing specimens that contained the anticipated design void ratios were selected for further clogging test in step 2. The detailed casting and compaction procedure and method is discussed in Section 3.2.5. For the two clogging cases (Case A and Case B), the testing matrix and testing procedure are developed based on the previous studies [37, 59, 62].

A clogging cycle is defined in this study. For each cycle, an equal amount of clogging material is spread evenly on the testing specimen top, and the permeability is measured by allowing the water to flow through the specimen along with the suspended clogging material within. This procedure is refereed to clogging. After the water is completely drained, a tested rehabilitation method was selected to clean the clogged specimen. After cleaning, the permeability test is conducted again by allowing pure water flow through this "cleaned" specimen, and permeability was recorded. This procedure is refereed as cleaning. Therefore, each clogging cycle includes a clogging and a cleaning operation.

In Case A clogging, the testing specimens were subjected to the sedimentation with a typical sedimentation load, as a reasonable case for in-place pavement. The clogging procedure was repeated up to 20 times. Permeability was determined and recorded for each clogging procedure. Case A simulates the clogging condition without any cleaning maintenance applied on pervious pavement. In Case B clogging, the specimens were subjected to a large sediment load, as a reasonable but worst-case scenario. In contrast with case A, in case B, the specimens were subjected to a repeated clogging cycle including both clogging and cleaning procedure up to 20 cycles. Permeability was determined and recorded in each clogging and cleaning procedure. Twenty cycles was selected to simulate an assumed 20 years of service life of the pavement.

To simulate the reasonable loadings for a PCPS in variety of geographical area [43, 45, 37], it was necessary to estimate of amount of sediments and the volume of runoff. The sedimentation load for case A and case B are listed in Table 3-1. The testing matrix of this study is shown in Table 3-2.

**Table 3-1. Sedimentation Load (Adopted from [38])**

| | **Case A (Typical or small sediment load)** | **Case B (High or worst sediment load)** |
|---|---|---|
| Total Sedimentation Materials | 0.22 lb | 1.76 lb(0.82 Kg) |
| Water Heads | 20 in-4 in | 20 in- 4 in |
| Simulated Service Life (year) | 20 | 20 |

**Table 3-2. Testing Matrix for Case A and Case B**

| **Testing Matrix (Total Sample Size: 108)** | | | | |
|---|---|---|---|---|
| **Test** | **Testing Standard** | **Specimen Type** | | |
| | | **15%** | **20%** | **25%** |
| Porosity | Volume Method | 36 | 36 | 36 |
| Permeability | Falling Head | 36 | 36 | 36 |
| | | | | |
| **Phase I Typical Sedimentation Load (0.01 lb/cycles)** | | | | |
| Permeability | Falling Head | **Specimen Number** | | |
| **Sedimentation Type** | | | | |
| Sand | | 3 | 3 | 3 |
| Clayey Silt | | 3 | 3 | 3 |
| Clayey Silty Sand | | 3 | 3 | 3 |
| | | | | |
| **Phase II High Sedimentation Load (0.088 lb/cycles)** | | | | |
| Permeability | Falling Head | **Specimen Number** | | |
| **Sedimentation Type** | | | | |
| Sand | | 9 | 9 | 9 |
| Clayey Silt | | 9 | 9 | 9 |
| Clayey Silty Sand | | 9 | 9 | 9 |
| | | | | |
| **Rehabilitation Methods (Apply Clogged Samples From Phase II)** | | **Specimen Number** | | |
| Permeability | Falling Head | | | |
| Pressure Washed | | 3 | 3 | 3 |
| Vacuum Swept | | 3 | 3 | 3 |
| Pressure Washed & Vacuum Swept | | 3 | 3 | 3 |

## 3.3 Materials and Mix Proportions

### 3.3.1 Binder Properties

LaFarge Type I/II cement was used in this study. Table 3-3 lists the cement properties provided from the mill report.

**Table 3-3. Physical Properties and Chemical Analysis of Cement**

| **Physical Properties** | |
|---|---|
| Finess-Blaine | 1878 $ft^2/lb$ |
| Specific Gravity | 3.15 |
| Vicat Setting Time | 90 min |
| Compressive Strength | 7-day 4460 psi |
| | 28-day 6300 psi |
| Autoclave | 0.02% |
| **Chemical Properties & Analysis wt. %** | |
| Silicon Dioxide | 20.5 |
| Aluminum Oxide ($Al_2O_3$) | 4.2 |
| Ferric Oxide (CaO) | 3.3 |
| Ferric Oxide (CaO) | 62.3 |
| Calcium Oxide (MgO) | 2.9 |
| Sulfur Trioxide ($SO_3$) | 3.0 |
| Loss on Ignition | 1.2 |
| Insoluble Residue | 0.23 |
| Free Lime | 1.0 |
| Tricalcium Silicate ($C_3S$) | 57 |
| Tricalcium Aluminate ($C_3A$) | 6 |
| Total Alkali as NaEq | 0.53 |

A densified silica fume from Degussa, USA was also used at 5% binder replacement to improve strength and paste bonding characteristics of selected mixes. The specific gravity of the silica fume 2.2 with a bulk density of 30-40 lb/ft3. The mechanical properties are not a major concern in this study.

### 3.3.2 Aggregates Properties

#### 3.3.2.1 Coarse Aggregates

The aggregate used in this study was 3/8 inch crushed granite with a specific gravity of 2.65, absorption of 0.59 %, and 18% passing the No.4 Sieve. A fine river sand with fine modulus of 2.9, specific gravity of 2.62 and the absorption of 1.1% was used as fine aggregate. The gradation curves for the coarse aggregates, fine and combined aggregates are shown in Figure 3-1. For both coarse and fine aggregates, the grading, specific gravity and absorptions were measured according to ASTM D 448 "Standard Classification for Sizes of Aggregates for Road and Bridge Construction" and ASTM C 128 "Standard Test Method for Density, Relative Density, and Absorption of Fine Aggregates", respectively. The coarse and fine limit represents for the potential failures of the casted pervious concrete due to the aggregates gradations.

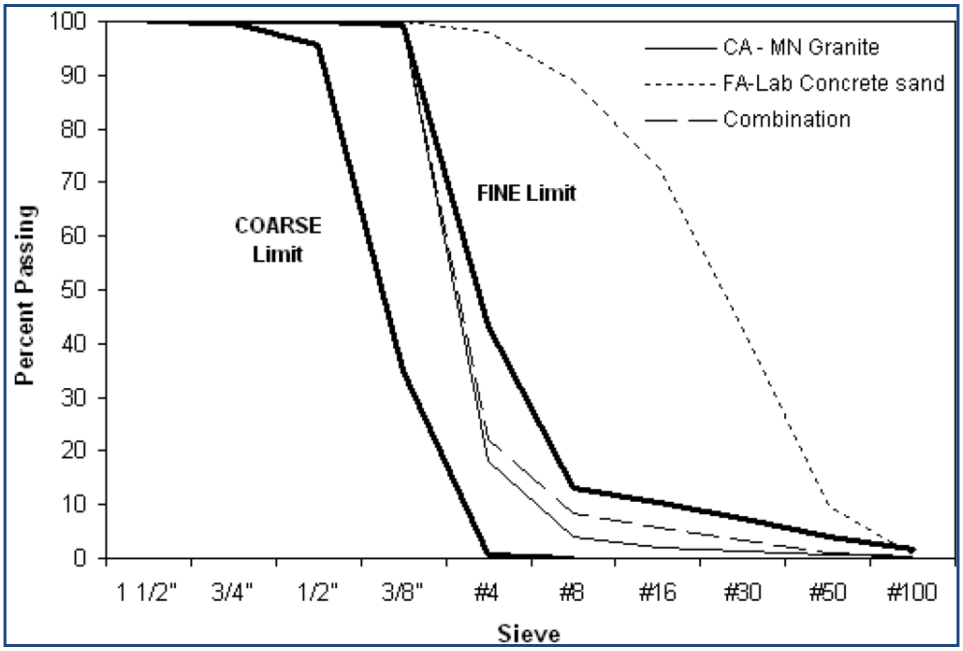


**Figure 3-1. The Gradation Curve of Grainite, Fine Sands, and the Combination of Mixed Aggregates (Adopted from [25])**

### 3.3.3 Admixtures

A high-range water reducer agent (HRWR), viscosity modify agent (VMA), air entraining agent and hydration stabilizer were used in the mixing proportions. Also variable-length fibrillated polypropylene fibers were used in the mixtures. The related information is shown in Table 3-4:

**Table 3-4. Admixture Chemical Properties**

| Name | Type | Color | Specific Gravity | pH | Recommended Dosage |
|---|---|---|---|---|---|
| Glenium 3400 NV | High-range water reducing admixtures | Dark brown | 1.07 | 7.8 | 2-12 fl.oz/100lb cement |
| Everair Plus | Air-entraining agent | Brown | 1.01 | 10 | 0.8-2.3 fl.oz/100 lb cement |

### 3.3.4 Mix Designs

The mix design as shown in Table 3-5 used was one of the most durable freeze-thaw mix designs as developed in conjunction with the overall research project [22, 27]. This mix design has been proved to be freeze-thaw durable after 180 F/T cycles. Also, the replacement of the viscosity modifying workability agent with a latex polymer admixture was employed to increase tensile strength and improve workability of the mix.

**Table 3-5. Pervious Concrete Mix Proportions**

| Materials | Amount |
|---|---|
| **Coarse Aggregate (3/8” granite, oven dry) (pcy)** | 2245 |
| **Fine Aggregates (concrete sand, oven dry) (pcy)** | 225 |
| **Portland Cement (Type I//II) (pcy)** | 296 |
| **Slag (pcy)** | 207 |
| **Fly Ash (pcy)** | 89 |
| **Propex Fibermesh 300**<br>**Buckeye UltraFiber 300** | 1.5<br>1.5 |
| **Water-Cement Ratio** | (w/c=0.29) 20.6 gallons (maybe adjusted at the time of batching for actual moisture) |
| **Glenium 7500 (HRWR) (oz)** | 25.5 |
| **Air Entraining Agent (oz)** | 12.0 |
| **Delvo Hydration Stabilizer (oz)** | 71.0 |
| **Viscosity Modifying Agent (oz)** | 20.0 |

### 3.3.5 Fabrication and Curing of Specimens

Cylindrical specimens were casted for clogging tests in this study. The cylindrical specimens were casted in a plastic mold with the dimensions of 4 in (101mm) in diameter by 8 in (203mm) tall, and the specimens were demolded after 24 hours. The curing procedure was conducted according to ASTM C192. After being cured in a moist environment for 7 days, all the specimens were trimmed to 6 inches tall by sawing 1 in from the top and bottom (See Figure 3-2)

**Figure 3-2. Untrimmed Specimen (Left) and Trimmed Specimen (Right)**

The compaction method is an important consideration in the specimen preparation procedure. As presented in Section 2.2.7, to achieve the designed total porosity, the different levels of compaction effort was applied to cast the specimens. However, it should be noted that the rodding and tapping as the compaction method would cause the large variability in total porosity and also depend on the operators. Therefore, a similar casting method based on the fresh unit weight was used in this study. The casting and compaction procedure used was based on with ASTM C 1688 “Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete”. The necessary rodding and tapping was used to ensure the specific amount of fresh materials to fill up the mold. The top surface was stroked off so the concrete surface was level with the top of mold. The desired weight of the sample was maintained by not adding/removing material during the finishing of the top surface. Each mold was filled with a specific weight/amount of fresh materials. The specific amount of fresh materials could be determined as stated below.

From Kevern [56], a general linear relationship between unit weight and porosity of pervious concrete mixtures was found. To achieve the design porosity, the linear relationship between the fresh unit weights particularly for this mixture and design porosity was also established, which is reported in Figure 3-5. From the literature, the fresh density of pervious concrete is roughly 100 to 130 lb/ $ft^3$ (1601 $kg/m^3$ to 2082 $kg/m^3$). The plastic mold is 8 in by height and 4 in by diameter, and the volume is 0.058 $ft^3$. The weight of the fresh mixing materials in this mold was roughly 2500 to 3500 gram based on the portion of volume.

The casting procedure is summarized as below:

1) The first step is to establish the general relationship between porosity and unit weight. To do so, the filling materials for each mold increase by 50 gram from 2500 gram in mold No.1 to 20 samples were casted (Figures 3-3 and 3-4).
2) After the proper curing procedure, the samples were trimmed into 4 in by 6 in diameter uniformly (See Figure 3-2).
3) The void ratio of trimmed specimens was measured using Volume method.

4) Repeat from Step 1 to Step 3, and establish the general relationship between the porosity and fresh unit for the particular mixture and mixing material, as shown in Figure 3-5.

**Figure 3-3. Different Amount of Fresh Filling Material in Each Mold Compacted by Roding and Tapping Method to Achieve Designed Porosity**

**Figure 3-4. Hardened Specimens**

The design void ratios are 15%, 20% and 25%. Therefore, according to Figure 3-5, the unit weights of fresh materials are estimated, which are approximately 123, 117 and 113 pcf, respectively. The unit weights of fresh materials were converted into the weight of filling materials in each mold. This linear relationship as established in Figure 3-5 between the fresh unit weight and void ratio was developed according to the theory introduced in [25] only represents for this mixing proportioning and materials. The similar linear relationship between the unit weight and total porosity of hardened specimen should be found for different batch designs. It should be noticed that development of this relationship is important to control and predict the hardened properties of pervious concrete by using fresh unit weight, especially for achieving the uniform properties of pervious concrete in the placement process.

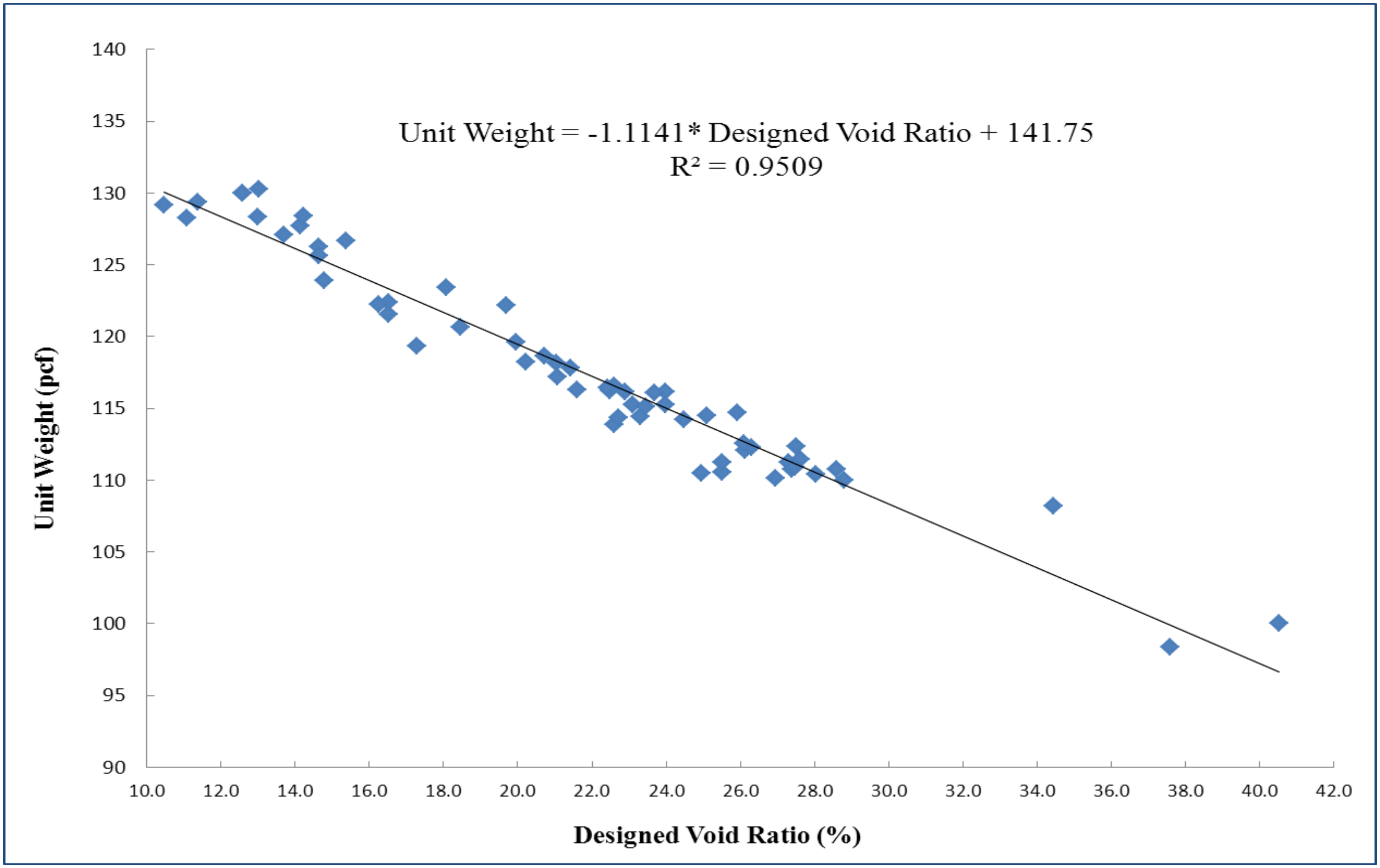


**Figure 3-5. Linear Relationship between Fresh Unit Weight (pcf) and Design Void Ratio (%)**

## 3.4 Clogging Methods

### 3.4.1 Sedimentation Particles Characteristics

The types of soils used for sedimentation in this study were selected to have the most significant effects on reduction of exfiltration, and a fairly large range of particles size distribution was studied. In addition, a soil with both coarse and fine particles will likely be retained on the pervious concrete with the larger size remaining on or in surface region, and the finer particle susceptible to transport through the pavement vertically [37]. The three soils used in this study are shown in Figure 3-6**.**

**Figure 3-6. Three Sedimentation Materials: Sand (left), Clayey Silt (middle), and Clayey Silty Sand (right).**

Particle size analysis of sediments was conducted in general accordance with ASTM D 422 "Standard Test Method for Particle-Size Analysis of Soils". The coarse sediments contain medium to fine sand as classified by the United Soil Classified by Unified Soil Classification with particles between 0.08 in (2 mm) and the #200 sieve size (75 um). Finer grained particles, those passing the #200 sieve size (75 µm), contained approximately 25% clay as measured by the hydrometer testing is general accordance with ASTM D 422. The clayey silty sand was composed approximately 60% coarse sediments and 40% fine sediments.

### 3.4.2 Case A Typical (Small) Sedimentation Load

For 20 years of simulated effective service life and the surface area corresponding to the sedimentation test in 3.4.2, a total of 0.22 lbs (0.1 kg) of sediments was used for Case A for each specimen. For each clogging procedure run, the amount of sediments is approximate 0.01 lb, which is one twentieth of the total 0.22 lb.

The clogging testing apparatus and methodology used in this study is similar to the previous studies [37]. After the initial permeability measurement of the unclogged specimens, water from the graduated cylinder was drained off completely. Then, 0.01 lbs of sediments was spread evenly on the specimen’s surface and the permeability test was conducted by allowing the water to flow through the specimen along with the clogging materials on the surface. Time was recorded for water level to drop from the constant initial head (h1) of 20 inch to a constant final head (h2) of 4 inch above the specimen top. This procedure is refereed as clogging procedure as stated in Section 3.2. Such clogging procedure run was repeated up to 20 times for each sample using one type of sediment.

### 3.4.3 Case B High Sedimentation Load

The difference between Case A and B is the greater amount of sedimentation materials in clogging procedure (See Table 3-2), and the followed cleaning by three rehabilitation methods: pressure washing, vacuuming, and the combined of these two methods.
A total of 1.76 lbs (0.82kg) of soil sediments, corresponding to the specimen surface area, was used simulate the total sedimentation load during 20 years of service life. Therefore, in each clogging cycle, 0.088 lbs of clogging materials which is one twentieth of the total were spread evenly on the specimen top, and water allowed to flow through. Then, the sediments were removed with a selected cleaning method and permeability was measured again. This procedure was conducted up to 20 times for each specimen to examine the effects of sedimentation and cleaning efficiency. Based on statistical analysis, for each void ratio and one type of sediment, three samples were tested, and the average values were presented as output.

Pressure washing as used in this study the “power head cone nozzle” is shown in Figure 3-7. The tap water was concentrated in a narrow cone (other types of nozzle did not work as well), and directly sprayed on the sample surface (See Figure 3-8). The pressure is measured at 1000 Mpa (psi). The vacuuming was effected by the 4.85 kW (6.5-HP) wet/dry vacuum sweeper shown in Figure 3-7. The sealed pressure is 120” or 4 psi, which is smaller than the commonly used for vacuuming swept pressure in-place pavement. Therefore, a better performance than the testing results found in this study is expected in the field. For each sample, approximately 60 seconds of vacuuming is applied. The pressure washing method followed by vacuum sweeping is also used due to the best permeability recovery as recommended in literature. It should be pointed out that the pressure washing followed vacuuming involved two steps.

**Figure 3-7. Vacuuming the Clogged Specimen**

**Figure 3-8. Pressure Washer Applied in This Study**

### 3.4.4 Testing Method

#### 3.4.4.1 Porosity

The porosity measurements applied in this research were conducted by following “Volume Method” or so-called “Water-Displacement Method”. The detailed testing procedures have been well discussed in previous studies [16, 17, 62]. The weights of the specimen are measured under surface saturated dry (SSD) condition, totally dry condition and immersed condition, which were recorded as $W_3$, $W_2$ and $W_1$; the equations for calculating the total, open and close porosity are below:

$$P_{total}(\%) = (1 - \frac{W2 - W1}{\rho \times V}) \times 100\% \qquad \textbf{Eqn. 3-1}$$

$$P_{open}(\%) = (1 - \frac{W3 - W1}{\rho \times V}) \times 100\% \qquad \textbf{Eqn. 3-2}$$

$$P_{close}(\%) = P_{total}(\%) - P_{open}(\%) \qquad \textbf{Eqn. 3-3}$$

Where,

$P_{open}$ = Total porosity, %
$P_{close}$ = Closed porosity, %
$W_1$= Weight immersed, (lbs or kg)
$W_2$= Dry weight, (lbs or kg)
$W_3$= Surface saturated dry, (lbs or kg)
$V$= Normal sample volume based on dimensions of the sample, (ft3 or m3)
$\rho$ = Density of water, (pcf or kg/m$^3$)

### 3.4.4.2 Permeability

Permeability tests of cylindrical specimens were conducted using conventional falling head permeability test apparatus illustrated in Figure 3-8. The concrete specimen was enclosed in a rubber sleeve, directly attached to the pipe as shown in Figure 3-9. Flexible sealing gum was used around the top perimeter of the sample to prevent water from leaking along the sides of the sample.

**Figure 3-9. Falling Head Permeability Testing Used in This Study**

The samples were then confined in a membrane and sealed in the rubber sleeve, which was surrounded by the adjustable hose clamps. The 16 inches of water used in the test was from the 20th inch to the 4th inch markings to provide a constant head and to permit more accurate measurement of elapsed time.  For each individual sample, the initial permeability before clogging test, and permeability coefficient changing with clogging cycles were determined and recorded. The following equation was used to calculated of permeability K (in/hr).

$$K = \frac{A1 * L}{A2 * t} \ln\left(\frac{H1}{H2}\right)$$ **Eqn. 3-4**

**Where,**

K= coefficient of permeability. in/sec

$A_1$= cross sectional area of the pipe, $in^2$

L= length of the sample, in

$A_2$=cross sectional area of specimen, $in^2$.

t=time in second from $H_1$ to $H_2$

$H_1$=initial water level, in

$H_2$= final water level, in

# Chapter 4. TESTING RESULTS AND ANALYSIS

In this section, the laboratory testing results including the hydraulic properties of testing specimens and clogging testing results from Case A and Case B are presented. The testing results found in this study are:

1) The initial permeability coefficients and void ratio measurements for all testing specimens,
2) The results of the sedimentation tests of the results of Case A and Case B.

In preliminary analysis, changes in permeability of cylindrical specimens after sedimentation test are the main measurements, and their graphical representations are used to interpret the trends of the effects of the three types of sedimentation materials, clogging cycles and permeability recovery after cleaning. Using the percentages of initial permeability for each specimen, however, allows easier comparisons between each rehabilitation methods. As noted previously, each clogging cycle simulates the clogging occurring during one service year of pavement. This simulation is important to determine the trends of permeability changing with time and sedimentation types for both Case A and Case B.

## 4.1 Hydrological Properties of the Pervious Concrete Specimens

The specimen’s identification code for all the properties follows the following designation: a) the first letters corresponds to the sedimentation type that is applied on this type, C for clay, S for sand, and CS for clayey silty sand; b) second letters corresponds to the rehabilitation method that is applied on this sample, P for pressure washed, V for vacuuming swept and P&V for the combined two methods; c) first number corresponds to the group number, 1 for

15% void ratio group, 2-20% void ratio group, 3-25% void ratio group; d) second number corresponds to sample ID in each group. For example, sample No. 1 at 15% design void ratio was subjected to sand sedimentation and pressure wash as rehabilitation method is designated as S-P-1-1.

The porosity and initial permeability for cylindrical specimens was determined by following the method called “Volume Method " and “Falling Head Permeability Test” as described in Section 3.4.4.1 and 3.4.4.2, respectively**.** The testing specimens were divided into three groups, and can be identified as Group 1, Group 2 and Group 3, which contained the anticipated porosity 15%, 20% and 25%, respectively. A total 27 specimens were prepared in each group, and the average porosity for group 1, 2, and 3 is 14.94%, 21.21% and 25.13%, respectively. The standard deviation is 0.82, 1.05 and 1.05, for group 1, 2, and 3 respectively. Group 1 showed the lowest standard deviation of 0.82, which indicated the more uniform porosities of specimens. In the contrast, Group 2 and 3 showed the higher standard deviations for higher anticipate void ratios, and the void ratios are more inconsistently distributed. This finding may indicate that the laboratory compaction method shows the better uniformity in quality and property control on denser specimens with low porosity. The porosity of specimens is more consistent with greater compaction energy applied. The testing measurements are shown in Table 4-2, 4-3, 4-4, 4-5.

Through statistical analysis, the actual void ratios of these specimens in Group 1, 2 and 3 are not statistically different with their corresponding designed void ratios, which also confirmed and proved the average porosity for each group. The effect of void ratios on sedimentation is anticipated based on this confirmation.

As briefly shown in Table 4-1, the average permeability (standard deviation) for Group 1, 2 and 3 is 477.07 (104), 917.56 (232) and 1477.37 in/hour (167), respectively. Much higher values of permeability were measured for group 3 at 25% average porosity, and the lower permeability and lower standard deviation are consistent with the lower porosity as well known. However, for group 2 and 3, a larger standard deviation of 232 was calculated and the considerable large difference in hydraulic conductivity is found while the void ratios are not significantly different. This finding confirmed that the hydraulic conductivity of pervious concrete can’t be measured based on porosity even though the mixing, batching and curing procedures are same.

**Table 4-1. Average Porosity and Permeability Coefficients for Group 1, 2 and 3**

| | **Average Porosity** | | **Average Permeability** | |
|---|---|---|---|---|
| | **(%)** | **Std. Dev** | **(in/hr)** | **Std. Dev** |
| **Group 1** | 14.94 | 0.82 | 477.1 | 104.9 |
| **Group 2** | 20.83 | 1.05 | 917.6 | 232.8 |
| **Group 3** | 25.08 | 1.09 | 1477.4 | 169 |

**Table 4-2. Fresh Density, Porosity Initial Permeability Coefficients for Case A Cylinder Specimens**

| Group ID. | Sample No. | Height | | Fresh Density | Porosity | Std. | Average | Initial Hydraulic Conductivity |
|---|---|---|---|---|---|---|---|---|
| | | (in) | (cm) | pcf (kg/m3) | (%) | Deviation | Porosity (%) | Coefficient K, in/hr (cm/sec) |
| 1 | S-1-1 | 6.02 | 15.3 | 108 (1730) | 15.6 | 0.404 | 15.17 | 333.6 (0.2) |
| | S-1-2 | 6.1 | 15.5 | | 14.8 | | | 475.8 (0.3) |
| | S-1-3 | 6.04 | 15.3 | | 15.1 | | | 268.4 (0.2) |
| 2 | S-2-1 | 5.94 | 15.1 | 119 (1913.5) | 19.7 | 0.451 | 20.17 | 548.2 (0.4) |
| | S-2-2 | 6.04 | 15.3 | | 20.6 | | | 647.5 (0.5) |
| | S-2-3 | 6.08 | 15.4 | | 20.2 | | | 431.5 (0.3) |
| 3 | S-3-1 | 6.03 | 15.3 | 125 (2010) | 24.6 | 0.557 | 25.20 | 1607.2 (1.1) |
| | S-3-2 | 6.08 | 15.4 | | 25.7 | | | 1558.6 (1.1) |
| | S-3-3 | 6.06 | 15.4 | | 25.3 | | | 1476.8 (1) |
| 1 | CS-1-1 | 6.0 | 15.3 | 108 (1730) | 16.1 | 0.709 | 15.33 | 339.5 (0.2) |
| | CS-1-2 | 6.0 | 15.3 | | 14.7 | | | 506 (0.4) |
| | CS-1-3 | 6.0 | 15.3 | | 15.2 | | | 358.6 (0.3) |
| 2 | CS-2-1 | 6.1 | 15.4 | 119 (1913.5) | 21.6 | 0.404 | 21.23 | 1121.3 (0.8) |
| | CS-2-2 | 6.1 | 15.4 | | 21.3 | | | 1041 (0.7) |
| | CS-2-3 | 6.0 | 15.3 | | 20.8 | | | 854.3 (0.6) |
| 3 | CS-3-1 | 6.1 | 15.4 | 125 (2010) | 24.1 | 0.929 | 25.13 | 1634.8 (1.2) |
| | CS-3-2 | 6.0 | 15.3 | | 25.9 | | | 1365.2 (1.0) |
| | CS-3-3 | 6.1 | 15.4 | | 25.4 | | | 1414.2 (1.0) |

## Table 4-3 Fresh Density, Porosity and Initial Permeability Coefficients for Case B Cylinder Specimens

| Group ID. | Sample No. | Height | | Fresh Density pcf (kg/m3) | Porosity (%) | Std. Deviation | Average Porosity (%) | Initial Hydraulic Conductivity Coefficient K, in/hr (cm/sec) |
|---|---|---|---|---|---|---|---|---|
| | | (in) | (cm) | | | | | |
| 1 | S-P-1-1 | 5.9 | 15.1 | 108 (1730) | 16.2 | 0.866 | 15.7 | 404.7 (0.3) |
| | S-P-1-2 | 5.9 | 15.1 | | 14.7 | | | 361.8 (0.3) |
| | S-P-1-3 | 6.0 | 15.2 | | 16.2 | | | 448.7 (0.3) |
| 2 | S-P-2-1 | 6.0 | 15.3 | 119 (1913.5) | 20.7 | 0.624 | 20.9 | 835 (0.6) |
| | S-P-2-2 | 5.9 | 15.0 | | 20.4 | | | 833.9 (0.6) |
| | S-P-2-3 | 6.0 | 15.3 | | 21.6 | | | 1031.9 (0.7) |
| 3 | S-P-3-1 | 6.0 | 15.3 | 125 (2010) | 25.4 | 0.289 | 25.6 | 1560.3 (1.1) |
| | S-P-3-2 | 6.0 | 15.3 | | 25.9 | | | 1437.4 (1.0) |
| | S-P-3-3 | 6.1 | 15.4 | | 25.4 | | | 1223.8 (0.9) |
| 1 | C-P-1-1 | 6.1 | 15.4 | 108 (1730) | 15.2 | 0.569 | 14.6 | 491.8 (0.3) |
| | C-P-1-2 | 6.0 | 15.3 | | 14.1 | | | 318.6 (0.2) |
| | C-P-1-3 | 6.1 | 15.4 | | 14.4 | | | 454.1 (0.3) |
| 2 | C-P-2-1 | 6.1 | 15.4 | 119 (1913.5) | 20.8 | 0.416 | 21.3 | 1099.1 (0.8) |
| | C-P-2-2 | 6.0 | 15.3 | | 21.6 | | | 926.7 (0.7) |
| | C-P-2-3 | 6.0 | 15.3 | | 21.4 | | | 1170.6 (0.8) |
| 3 | C-P-3-1 | 6.0 | 15.2 | 125 (2010) | 24.1 | 1.044 | 24.6 | 1561 (1.1) |
| | C-P-3-2 | 5.8 | 14.8 | | 25.8 | | | 1614.3 (1.1) |
| | C-P-3-3 | 5.9 | 15.1 | | 23.9 | | | 1218.6 (0.9) |
| 1 | CS-P-1-1 | 5.9 | 15.1 | 108 (1730) | 15.6 | 0.458 | 15.2 | 565.8 (0.4) |
| | CS-P-1-2 | 6.0 | 15.2 | | 14.7 | | | 684.3 (0.5) |
| | CS-P-1-3 | 6.0 | 15.3 | | 15.3 | | | 548.7 (0.4) |
| 2 | CS-P-2-1 | 5.9 | 15.0 | 119 (1913.5) | 21.6 | 0.850 | 21.3 | 936.7 (0.7) |
| | CS-P-2-2 | 6.0 | 15.3 | | 21.9 | | | 1048.9 (0.7) |
| | CS-P-2-3 | 6.0 | 15.3 | | 20.3 | | | 1137.2 (0.8) |
| 3 | CS-P-3-1 | 6.0 | 15.3 | 125 (2010) | 25.4 | 0.681 | 26.2 | 1183.4 (0.8) |
| | CS-P-3-2 | 6.1 | 15.4 | | 26.7 | | | 1049.4 (0.7) |
| | CS-P-3-3 | 5.9 | 14.9 | | 26.4 | | | 1597.6 (1.1) |

## Table 4-4 Fresh Density, Porosity and Initial Permeability Coefficient for Case B Cylinder Specimens

| Group ID. | Sample No. | Height | | Fresh Density pcf (kg/m3) | Porosity (%) | Std. Deviation | Average Porosity (%) | Initial Hydraulic Conductivity Coefficient K, in/hr (cm/sec) |
|---|---|---|---|---|---|---|---|---|
| | | (in) | (cm) | | | | | |
| 1 | S-V-1-1 | 6.1 | 15.4 | 108 (1730) | 16.4 | 0.800 | 15.6 | 569.9 (0.4) |
| | S-V-1-2 | 6.0 | 15.3 | | 15.6 | | | 618.3 (0.4) |
| | S-V-1-3 | 6.1 | 15.4 | | 14.8 | | | 591.3 (0.4) |
| 2 | S-V-2-1 | 6.1 | 15.4 | 119 (1913.5) | 22.4 | 0.850 | 22.1 | 714.6 (0.5) |
| | S-V-2-2 | 6.0 | 15.3 | | 22.7 | | | 805.4 (0.6) |
| | S-V-2-3 | 6.0 | 15.3 | | 21.1 | | | 697.6 (0.5) |
| 3 | S-V-3-1 | 6.0 | 15.2 | 125 (2010) | 25.6 | 1.168 | 25.4 | 1661.2 (1.2) |
| | S-V-3-2 | 5.8 | 14.8 | | 26.4 | | | 1539.4 (1.1) |
| | S-V-3-3 | 5.9 | 15.1 | | 24.1 | | | 1318.7 (0.9) |
| 1 | CS-V-1-1 | 6.1 | 15.4 | 108 (1730) | 14.2 | 0.945 | 14.5 | 494 (0.3) |
| | CS-V-1-2 | 6.0 | 15.3 | | 13.8 | | | 513.6 (0.4) |
| | CS-V-1-3 | 6.1 | 15.4 | | 15.6 | | | 358.3 (0.3) |
| 2 | CS-V-2-1 | 6.1 | 15.4 | 119 (1913.5) | 21.8 | 0.721 | 21.6 | 724.8 (0.5) |
| | CS-V-2-2 | 6.0 | 15.3 | | 22.2 | | | 691.2 (0.5) |
| | CS-V-2-3 | 6.1 | 15.5 | | 20.8 | | | 548.6 (0.4) |
| 3 | CS-V-3-1 | 6.0 | 15.2 | 125 (2010) | 24.6 | 0.351 | 24.3 | 1501.5 (1.1) |
| | CS-V-3-2 | 5.9 | 15.0 | | 23.9 | | | 1489.2 (1.1) |
| | CS-V-3-3 | 5.8 | 14.8 | | 24.3 | | | 1748.6 (1.2) |

### Table 4-5. Fresh Density, Porosity and Initial Permeability Coefficient for Case B Cylinder Specimens

| Group ID. | Sample No. | Height | | Fresh Density pcf (kg/m3) | Porosity (%) | Std. Deviation | Average Porosity (%) | Initial Hydraulic Conductivity Coefficient K, in/hr (cm/sec) |
|---|---|---|---|---|---|---|---|---|
| | | (in) | (cm) | | | | | |
| 1 | S-VP-1-1 | 6.0 | 15.1 | 108 (1730) | 13.8 | 0.473 | 14.0 | 459.4 (0.3) |
| | S-VP-1-2 | 6.0 | 15.3 | | 13.6 | | | 509.4 (0.4) |
| | S-VP-1-3 | 6.1 | 15.5 | | 14.5 | | | 538.5 (0.4) |
| 2 | S-VP-2-1 | 6.0 | 15.3 | 119 (1913.5) | 21.6 | 1.159 | 21.8 | 1130.2 (0.8) |
| | S-VP-2-2 | 5.9 | 15.1 | | 20.7 | | | 1256.7 (0.9) |
| | S-VP-2-3 | 6.0 | 15.3 | | 23 | | | 1097.5 (0.8) |
| 3 | S-VP-3-1 | 6.1 | 15.4 | 125 (2010) | 25.4 | 1.168 | 25.6 | 1683.8 (1.2) |
| | S-VP-3-2 | 6.0 | 15.3 | | 26.9 | | | 1544.6 (1.1) |
| | S-VP-3-3 | 6.1 | 15.4 | | 24.6 | | | 1627.6 (1.1) |
| 1 | CS-VP-1-1 | 6.1 | 15.4 | 108 (1730) | 15.4 | 0.917 | 14.4 | 494.4 (0.3) |
| | CS-VP-1-2 | 6.0 | 15.3 | | 13.6 | | | 598.6 (0.4) |
| | CS-VP-1-3 | 6.0 | 15.3 | | 14.2 | | | 574.6 (0.4) |
| 2 | CS-VP-2-1 | 6.0 | 15.2 | 119 (1913.5) | 21.5 | 0.850 | 20.6 | 1025.6 (0.7) |
| | CS-VP-2-2 | 5.8 | 14.8 | | 19.8 | | | 1128.6 (0.8) |
| | CS-VP-2-3 | 5.9 | 15.1 | | 20.6 | | | 1289.6 (0.9) |
| 3 | CS-VP-3-1 | 6.1 | 15.4 | 125 (2010) | 24.1 | 0.764 | 24.3 | 1428.4 (1.1) |
| | CS-VP-3-2 | 6.0 | 15.3 | | 23.6 | | | 1384.5 (1.0) |
| | CS-VP-3-3 | 6.0 | 15.3 | | 25.1 | | | 1458.9 (1.0) |

## 4.2 Case A: Typical (Small) Sedimentation Results

The changes in permeability of specimens under the sedimentation from three types' sedimentation materials are shown in Table 4-6. The cylinder specimens subjected to sand, clayey silt and clayey silty sand are shown with the respective permeability determined initially and finally after 20 clogging repetitions. It is realized that fine particles would cause the negligible permeability reduction; therefore, clay sedimentation tests were not necessary to be finished completely.

## Table 4-6. Changes in Coefficient of Permeability in Specimens at Different States of the Case A Sedimentation Test

| Group ID | Specimen | Initial Permeability Coeff. (In/hr) | Decrease Permeability After Sedimentation | Average Residual Permeability Coeff. (in/hr) | Average Decrease of Permeability (in/hr.) | Average Residual Permeability (in/hr.) | Average Decrease of Permeability (%) | Design Porosity (%) | Sedimentation Materials |
|---|---|---|---|---|---|---|---|---|---|
| 1 | S-1-1 | 333.7 | 118.6 | 64 | 335 | 119 | 63 | 15 | Sand |
| | S-1-2 | 250.3 | 112.5 | 55 | | | | | |
| | S-1-3 | 421.8 | 126.4 | 70 | | | | | |
| 2 | S-2-1 | 794.5 | 107.2 | 87 | 830 | 118 | 86 | 20 | |
| | S-2-2 | 748.3 | 118.6 | 84 | | | | | |
| | S-2-3 | 948.3 | 128.4 | 86 | | | | | |
| 3 | S-3-1 | 1607.2 | 142.6 | 91 | 1643 | 143 | 90 | 25 | |
| | S-3-2 | 1408.2 | 138.6 | 90 | | | | | |
| | S-3-3 | 1374.6 | 147.3 | 89 | | | | | |
| 1 | C-1-1 | 458.2 | 457.3 | 0 | 413 | 411 | 0 | 15 | Clay Silty |
| | C-1-2 | 421.6 | 419.5 | 0 | | | | | |
| | C-1-3 | 358.4 | 357 | 0 | | | | | |
| 2 | C-2-1 | 587.2 | 587.6 | 0 | 601 | 600 | 0 | 20 | |
| | C-2-2 | 614.3 | 613.2 | 0 | | | | | |
| | C-2-3 | - | - | - | | | | | |
| 3 | C-3-1 | - | - | - | - | - | - | 25 | |
| | C-3-2 | - | - | - | | | | | |
| | C-3-3 | - | - | - | | | | | |
| 1 | CS-1-1 | 506 | 29.8 | 94 | 504 | 35 | 93 | 15 | Clayey-Silty Sand |
| | CS-1-2 | 471.2 | 32.6 | 93 | | | | | |
| | CS-1-3 | 536.2 | 41.5 | 92 | | | | | |
| 2 | CS-2-1 | 1041.2 | 39.5 | 96 | 1038 | 37 | 96 | 20 | |
| | CS-2-2 | 1157 | 35.9 | 97 | | | | | |
| | CS-2-3 | 917 | 36.8 | 98 | | | | | |
| 3 | CS-3-1 | 1634.8 | 36.4 | 96 | 1497 | 53 | 96 | 25 | |
| | CS-3-2 | 1528.2 | 68.5 | 96 | | | | | |
| | CS-3-3 | 1326.5 | 54.8 | 96 | | | | | |

### 4.2.1 Clay or "Fine Particles" as Sedimentation Materials

When clayey silt or very fine particles were used as sedimentation materials, the clogging effect is fairly negligible (less than 1%) in terms of permeability coefficient reduction for all three groups of specimens at 15%, 20% and 25% void ratios. For Group 1, 2 and 3, the average reduction of permeability is 0.6%, 0.4% and 0.6% after being exposed to 20 repeated clogging procedures with typical amount of sedimentation load, respectively.

These results show that the fine particles can hardly clogged the pores and reduce the permeability of pervious concrete with the void ratios ranging from 15% to 25% tested in this study. This finding indicates that the fine particles with the size of passing sieve No.200 (75 µm) most likely would transport through the sample with water, and be retained in the space between the pervious concrete layer and filter fabric layer. With the building up of this fine deposition layer between the pavement layer and filter fabric layer, the system permeability could decrease gradually. However, for concrete itself, the clay sedimentation effect is fairly negligible. Since this study mainly focused on the permeability reduction of the pervious concrete specimens from the sedimentation effect rather than the whole pavement system, it is not necessary to discuss the sedimentation effect from clay materials in the later sections due to findings in Case A. More information regarding to clay sedimentation on pervious concrete pavement system can be found in Mata (2008).

As expected, the very little amount of clay was observed at the top of the specimens after sedimentation test (See Figure 4-2), and most of sedimentation clay particles were flushed through the specimens with water (See Figure 4-3**)**. This observation is consistent with Mata

(2008) that significant permeability recovery of clogged pervious pavement was achieved after the removal of filter fabric layer at the bottom of concrete layer (See Figure 4-1).

With the very low permeability of clay material, the formation of clay layer would considerably reduce the system permeability even though the hydraulic function of pervious concrete layer still works well. Also, this finding may also explain that traditional cleaning methods as pressure washing and vacuuming sweeping may not work effectively for this sedimentation case since the depth of deposition layer always equal or greater than the pavement thickness. With the formation of clay layer between pavement and filter layer, the system permeability would decrease gradually. Vacuum machines with larger concealed pressure maybe working, but research on this issue is recommended. Therefore, this clogging effect issue caused by fine particles with size less than sieve No.200 size (75 μm) should be taken into the pavement hydraulic design consideration, and the minimum opening of filter fabric is 75 μm recommended.

**Figure 4-1. Specimens at Exposure to Clayey Silt (This photo was adapted from [28])**

**Figure 4-2 Specimens at Exposure to Clayey Silt in This Study (Left: Before Test; Right: After Test)**

**Figure 4-3. The Clayey Silt Sedimentation Test is in Progress**

### 4.2.2 Sand as Sedimentation Materials

When sand was used as the sedimentation material, a significant decrease of permeability occurred to all three groups of specimens. The average remaining permeability for Group 1, 2 and 3 is 29.5 in/hr., 203.5 in/hr. and 547.3 in/hr. after the specimens being subjected to 20 repeated clogging procedure runs, respectively. This is 34.1%, 20.8% and 6.8% of initial permeability for Group 1, 2 and 3, respectively (See Table 4-5 (B)). The specimens in Group 1 contained the lowest initial porosity and permeability, which may result the lowest residual permeability compared to the specimens that contained the highest initial porosity in Group 3.

The residual permeability directly increases with initial void ratio of specimens. At least 60% of initial permeability was lost for all three groups subjected to sand sedimentation.

Less than 3% of the amount of applied sedimentation materials was found passing though the testing specimens and captured by the No.200 Sieve. This finding confirmed that most of the sand sediments were retained either on the surface or within the specimens. The void size of the concrete ranging from 0.08 to 0.32 in (2 to 8 mm) is not large enough to allow most of the sand sediments to be transported through the specimen. In this case, the pervious concrete act as a filter to eliminate the solids within water is confirmed with the reduction of permeability.

A linear relationship between the initial permeability and the residual permeability or remaining percentage of initial permeability was found as shown in Figure 4-4. This finding appears to indicate that the higher initial permeability achieves the higher residual permeability compared to other specimens with lower initial permeability under the same sand sedimentation load. Therefore, the clogging effect and permeability reduction of pervious concrete is influenced by the initial void ratio of pervious concrete because as well known that high void ratio generally leading the high permeability.

The general minimum requirement for pervious concrete is a permeability of 15-20 in/hr of permeability is a general minimum requirement of pervious pavement. Also, generally at 75% loss of initial permeability, maintenance should be performed [63, 65]. Based on this observation and the simulation of 20 years of service life of pavement, Group 1 showed the lowest residual permeability about 20 in/hr, that is, approximately 5% of the initial value at the end of the clogging test, which is regarded having the highest risk of clogging failure among three groups. Group 2 with 20% initial void ratio resulted in approximate 200 in/hr of residual permeability, which could still satisfy the hydraulic function at the end of service year. With a residual permeability of 143 in/hr, Group 3 may be overdesigned on hydraulic performance.

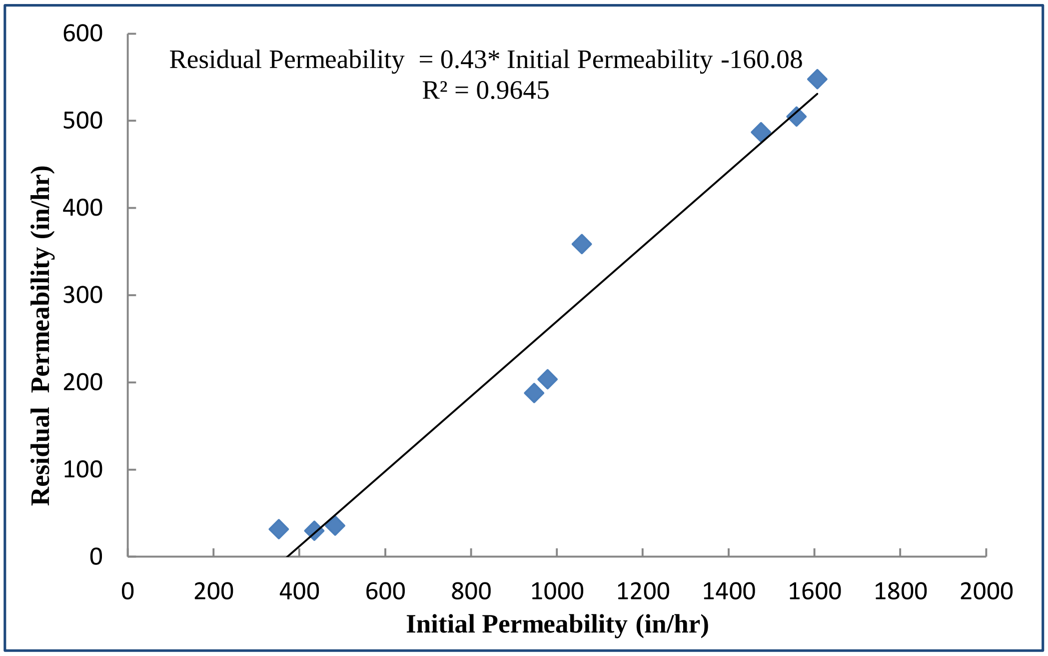


**Figure 4-4 (A). Initial Permeability of Specimens Affects the Residual Permeability Due to Sand Sedimentation**

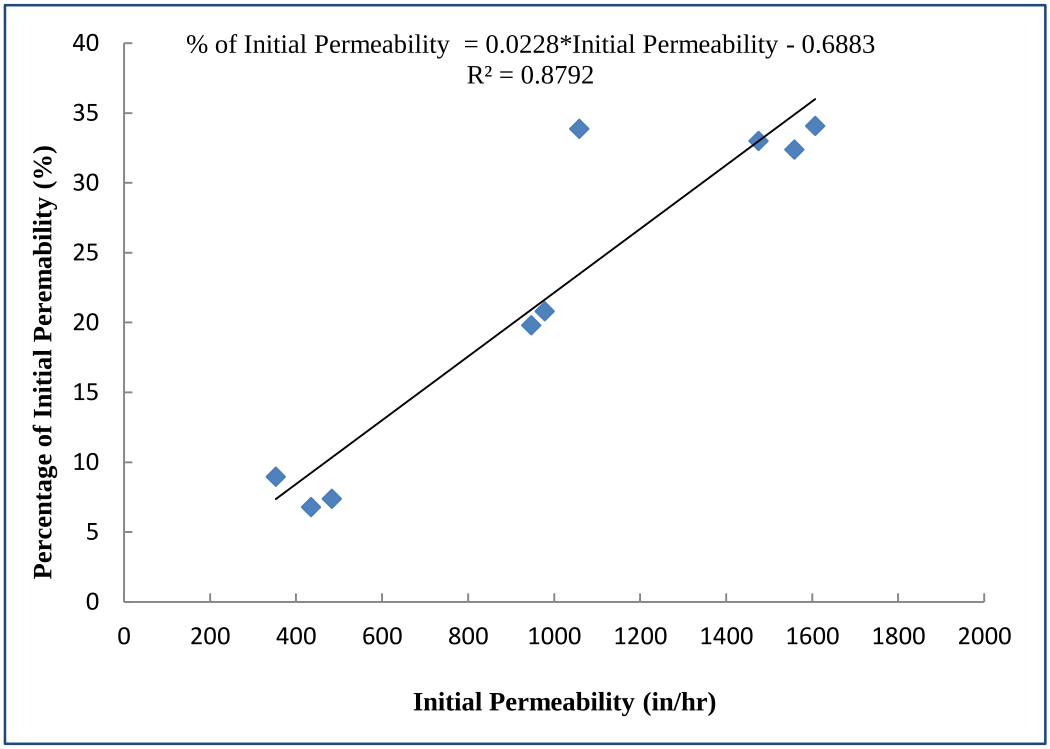


**Figure 4-4 (B). Initial Permeability of Specimens Affects the Percentage of Remaining Permeability Due to Sand Sedimentation**

The amount of applied sediments in each clogging repetition simulates clogging occurring each year of service life of pavement up to 20 years, which is the key assumption in this study based on Mata's [28]. With sand as sedimentation, at least 20% initial permeability was lost after the first 1-2 cycles of constriction. Depending on the void ratios, approximate 55% of initial permeability was lost for specimens in all three groups until 7th year after construction for group 2 and 3. Then, total permeability reduction for group 2 and group 3 tend to be constant, and end with 79.2% and 65.9% reduction at 203 in/hr and 547 in/hr, respectively. This finding may indicate that at least 85% of total permeability reductions occur during the first 10 cycles of service life for the pervious concrete pavement with initial porosity higher than 20%. For group 3 with the lowest void ratios and initial permeability, however, permeability reduction is more uniformly distribution with time, and 90% of initial permeability was lost up to 12th year after construction. Then, the total permeability reduction tends to be constant and reach at 5% of initial permeability about 20 in/hr (Figure 4-5).

According to the definition of “critical pore radius” [61], there exists a certain pore radius for every mixture and independent with the compaction procedure, for which the number of particles that deposited is the maximum and any increase of the pore radius does not contribute a further increase in particle deposition. For convenience, the pores with size close and smaller to the critical pore size has higher clogging suspect than other pores, and the volume of these pores is defined as critical pore volume. For a certain specimen, the total volume of pore includes the critical pore volume and also the volume of pores with size greater than critical pore size. For a certain mixture, the critical pore volume is approximately the same for all the specimens using the same mixture, and only slightly influenced by the compaction energy applied and total void ratio. In other words, the applied compaction energy on specimens most likely affects the volume of large pores or so called “non-critical pores” rather than the small pores and/or critical pore volume. For specimens subjected to sand sedimentation, the critical pores tend to get fully clogged first, and the larger pores may still stay open after finishing all the clogging cycles. The specimens with greater void ratios contain the larger volume of large pores, which can still efficiently transport water through compared to the specimens with low void ratio containing smaller volume of large pores. This may explain that why the specimens in Group 3 with higher initial void ratios would finally reach the higher residual permeability coefficients. The difference of the remaining permeability coefficients of Group1, 2 and 3 may indicate the difference of the volumes of large pores in the specimens with different void ratios.

Also, a proper maintenance schedule may be established based on Figure 4-5 (B). Maintenances are always required when the permeability coefficients were reduced by 75% of the initial value due to clogging [63, 65]. Therefore, for Group 1, 2 and 3, the time for regular maintenance is at 9nd years after construction based on experiences, and Group 1 may still need maintenance to prevent the clogging failure from occurring. However, for Group 2 and 3, the satisfied hydraulic performance can still be provided due to the higher residual permeability without any further maintenance under this condition.

Therefore, the empirical regulation on performing annually maintenance [43] may not be necessary. It should be pointed that the sedimentation test conducted in lab might be very different with the actual clogging condition in the field due to the great variability of infiltration rate, therefore, this finding may only provide a general idea that how hydraulic performance of pervious concrete would change with time after opening.

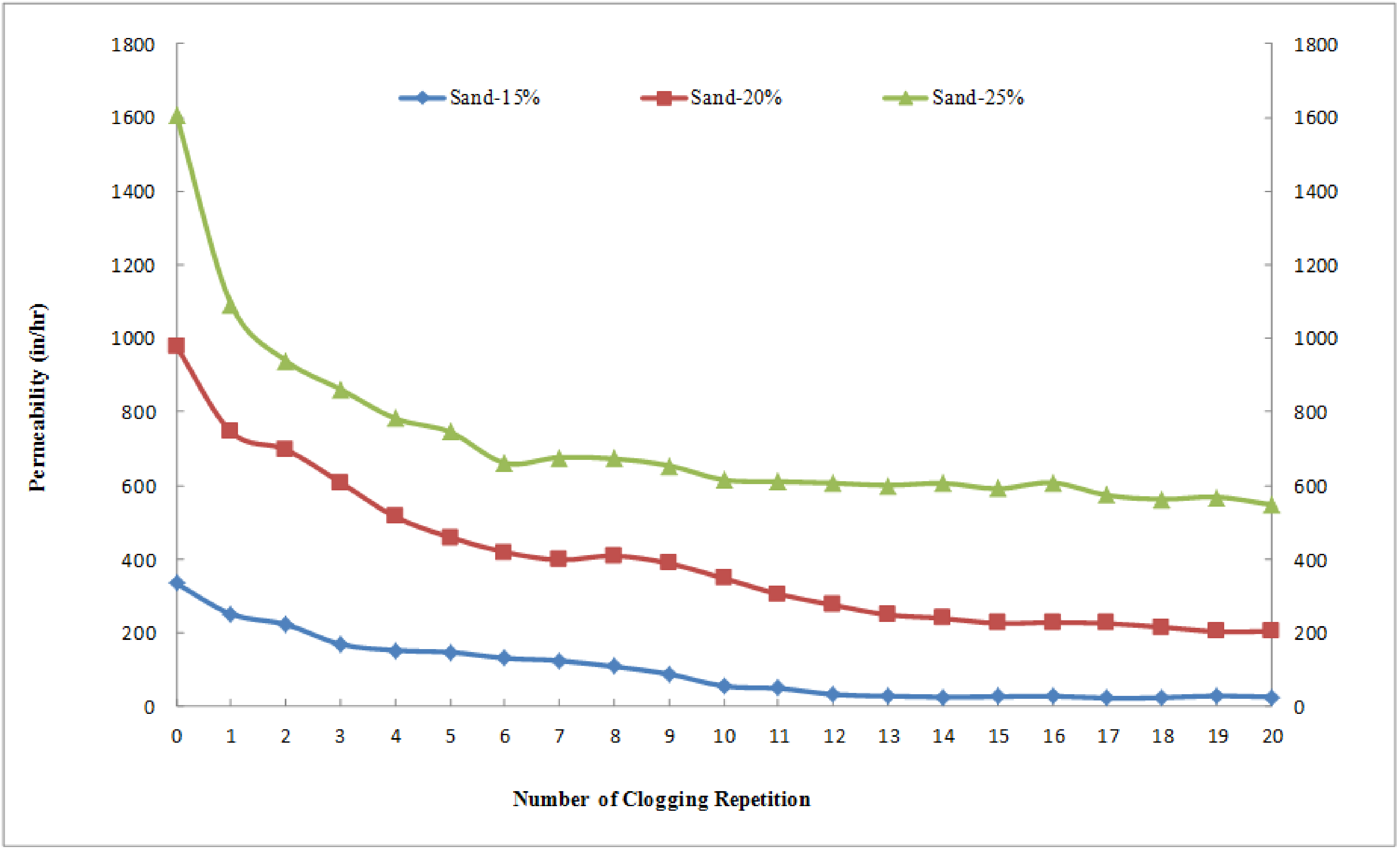


**Figure 4-5 (A). Permeability Changes with Number of Clogging Repetition under Sand Sedimentation**

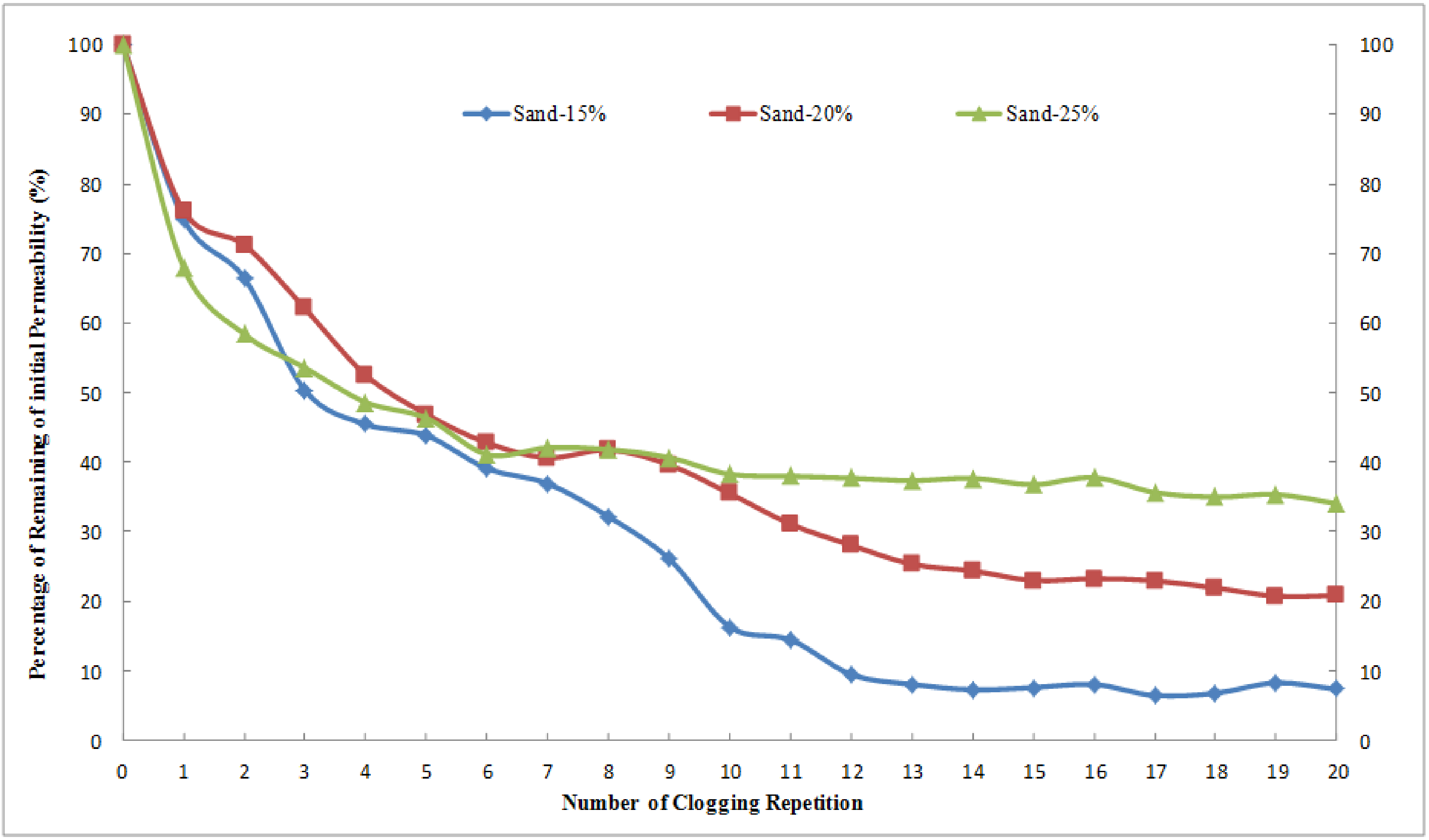


**Figure 4-5 (B). Percentage of Remaining Permeability Change with Number of Clogging Repetition under Sand Sedimentation**

### 4.2.3 Clayey Silty Sand as Sedimentation Materials

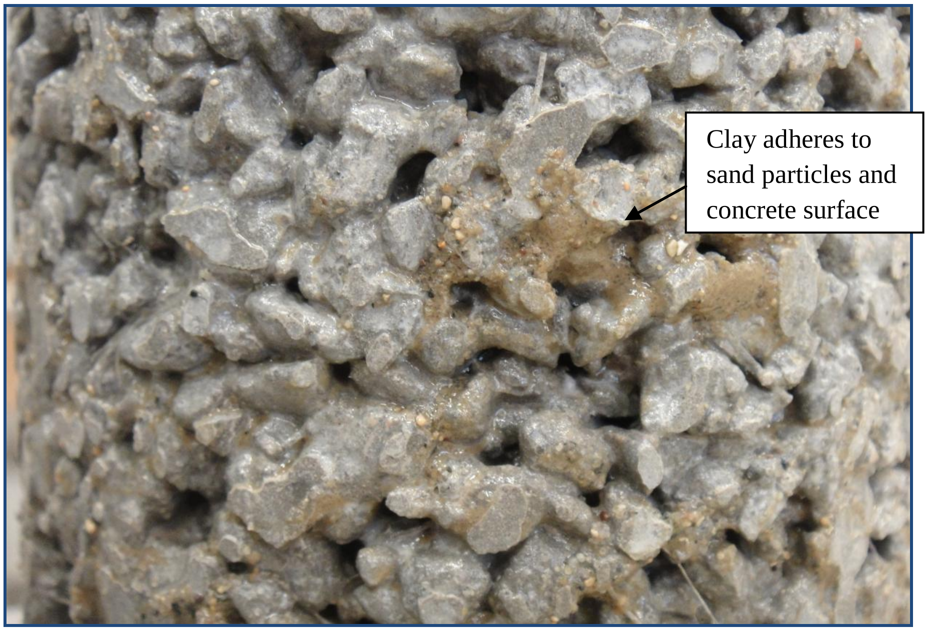
The blended soils that used as sediments were investigated in terms of clogging effect. When clayey silty sand was used as the sedimentation materials, similar with sand but even worse, significant permeability reductions occur to all three groups. For Group 1, 2 and 3, the permeability reductions are 92%, 94% and 98%. More interestingly, the average remaining permeability coefficients of all three groups are all approximately equal at about 20 in/hr (See Figure 4-8 (A)) independent on the initial void ratios and initial permeability coefficients. This is the most remarkable difference compare to sand sedimentation.

Additionally, the changes in permeability with the increase of clogging cycles are shown in Figure 4-8 (A) & (B). Specimens in Group 1 containing the lowest void ratios again showed the lowest clogging resistance and total permeability reduction increases up to 90% at 5th repetition or 5th years after construction. Group 2 and Group 3 showed better conditions and reached the 90% of permeability reduction at 13th and 18th clogging procedure or 13th and 18th years after construction.

It was observed that clay particles were flushed through and the sand particles were retained on the surface of the specimens. The permeability reductions of specimens subjected to clayey silty sand are the highest, and this observation has good agreement with Mata's [28] (See Figure 4-6). The reasons the observations are similar with those used in Section 4.2.2. However, the differences are noted that 1) the much lower remaining permeability 2) the different trends of permeability changing with increased number of clogging repetitions. Regarding to the first difference, the reasons are the wider range of particle size distribution and cohesion of clay. Clayey silty sand contains a wider range of particle size distribution compared to the narrowly particle size-ranged materials such as sand or clay used in the previous cases, which increases their chances of being retained within or passed through the specimens. More pores within the specimens may get clogged by the blended materials. Another important reason is due to the cohesion property of clayey silty materials. Due to the significant amount of clay in this blended sedimentation materials around 40% by weight and its cohesion property, clay particles may flow through the specimen with sand particles, and adhere on the sand particle surface that was retained. Especially, with the increase of clogging repetitions and decrease of flow rate, the clay particles are more easily to "touch and adhere" the sand particles compare to the initial condition with a relatively high flow rate. Finally, the void space would be occupied gradually by the sand deposition and adhered clay particles. Secondly, the reason is the difference of pore volumes in specimens with different void ratios. The specimens with higher void ratios containing the larger volume of pores than the specimens with lower void ratios; the gradual increase of volume sediments within the pore with the accumulation of trapped clay and sand particles; therefore, it may take more clogging cycles to fully clog those pores. However, once the samples get fully clogged, the remaining permeability for all the specimens become very low and equally same.

A proper maintenance schedule may be established based on Figure 4-8 (B). Maintenances are always required when the permeability coefficients reduced up to 75% of the initial value [65, 63]. Therefore, for Group 1 and Group 2, the time for regular maintenance is at 2nd year after construction; however, for Group 3, the time for regular maintenance is at 3rd year after construction. All Groups had the clogging failure risk. To prevent this failure, at least an additional maintenance is required for Group 1 at 5th year, Group 2 at 12th year and Group 3 at 16th year of service.

Figure 4-6. Specimen After Exposure to Clayey Silty Sand (Adapt from [28])



Clay adheres to sand particles and concrete surface

Figure 4-7. Specimens Exposed to Clayey Silty Sand

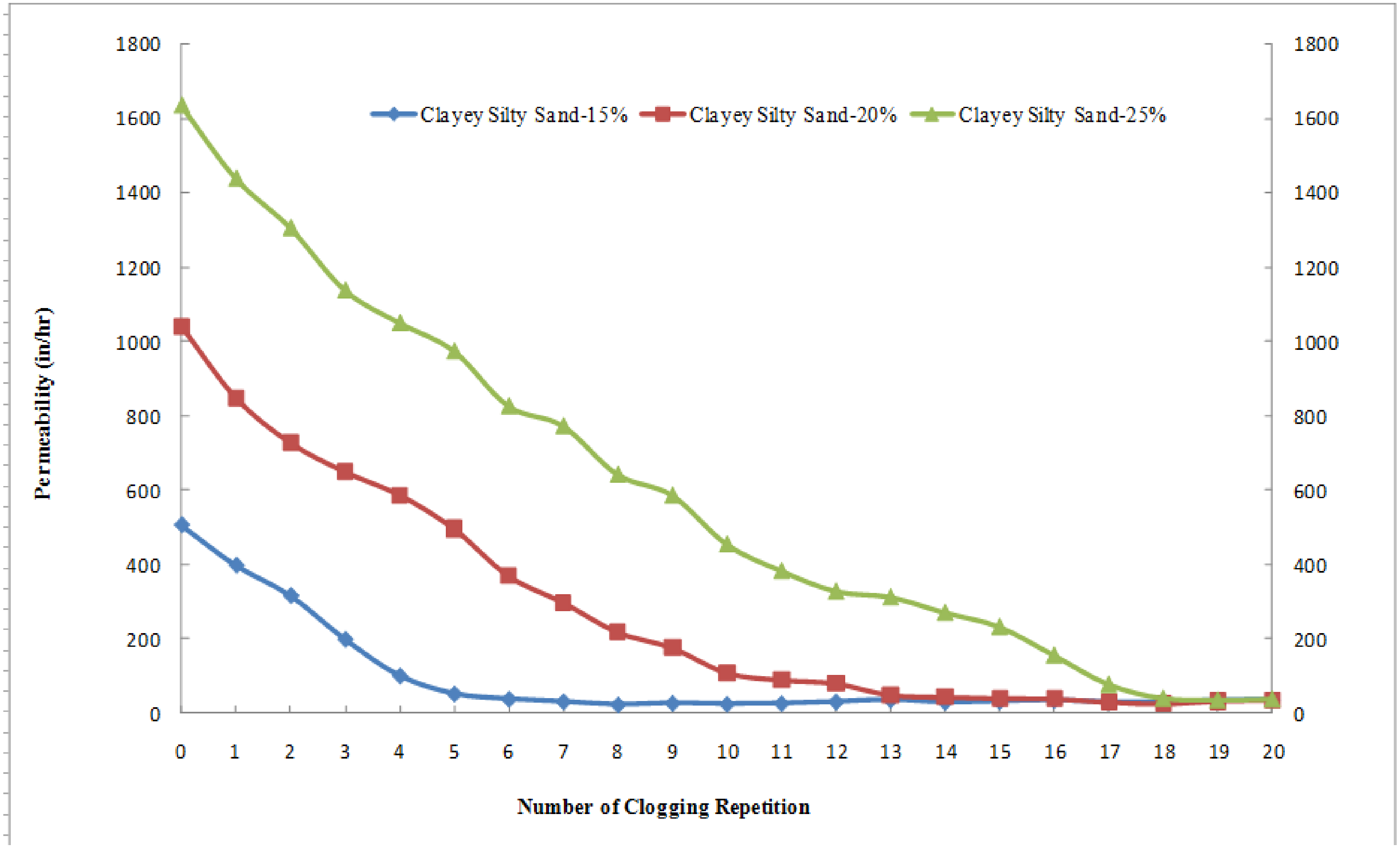


Figure 4-8 (A). Permeability Changes with the Number of Clogging Repetition under Clayey Silty Sand

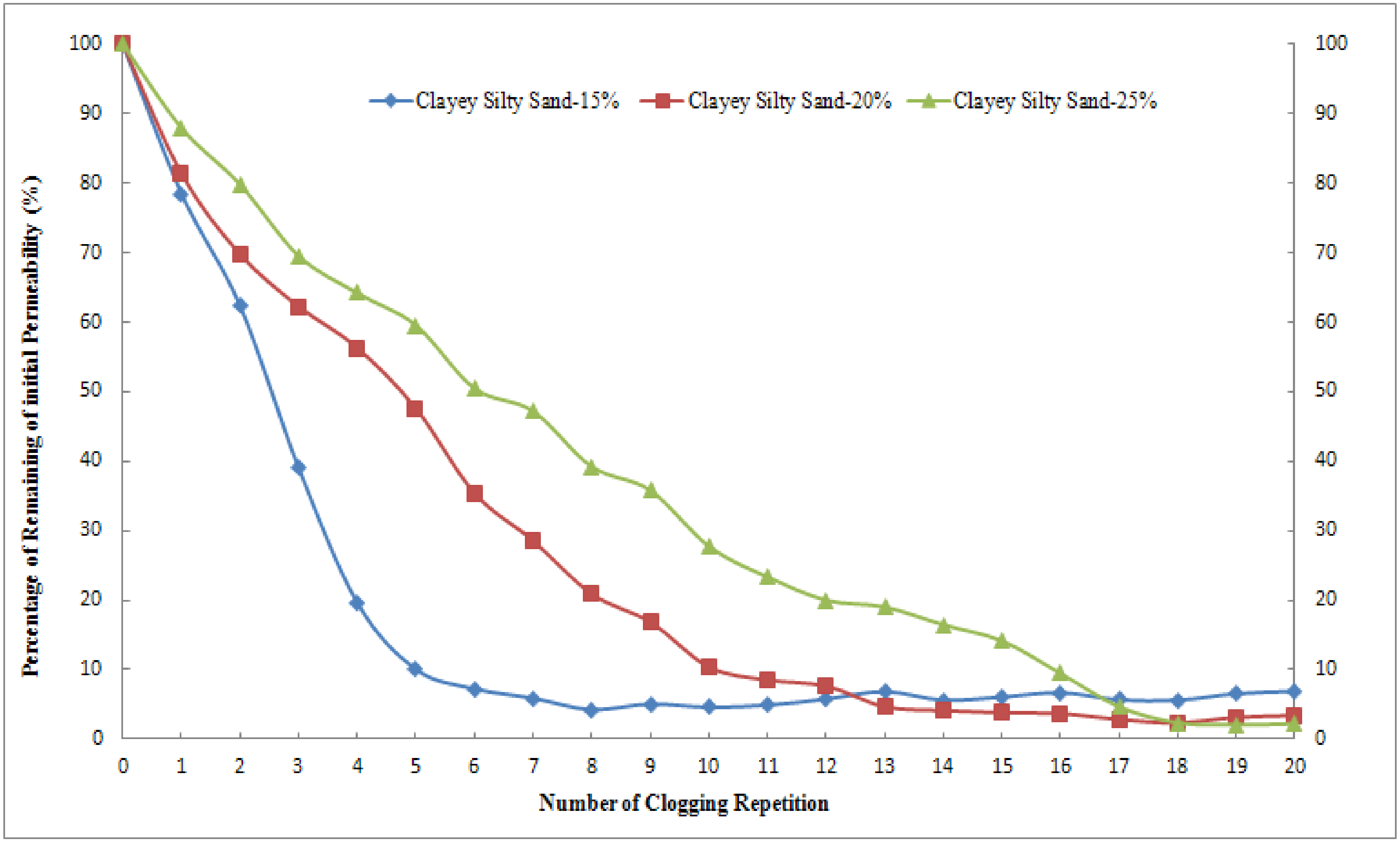


**Figure 4-8 (B). Percentage of Remaining Permeability Change with the Number Clogging Repetition under Clayey Silty Sand Sedimentation**

### 4.2.4 Case A Conclusion

The following important findings are listed based on observation in Case A:

1) Initial void ratios affect the residual permeability under clayey silt and sand sedimentation, which are narrowly graded materials.
2) Clayey silty sand as blended clogging materials cause the most significant permeability reduction compared to sand and clayey silt, more than 90% of initial permeability was reduced with time for the three groups. The specimens with different void ratios all become fully clogged and reached remaining permeability (35in/hr).
3) The higher the void ratio (approximate 25% in this study), the higher remaining permeability under sand and clayey silty sedimentation.
4) For clay sediments, no significant permeability reduction for concrete itself, but the simulation of deposited clay layer between pavement and filter fabric is critical, and should be taken into consideration.
5) For sand sediments, at least 60% of initial permeability was reduced for all three groups.
6) The maintenance of pervious concrete may be established according to sedimentation type and pervious concrete pavement property. However, laboratory sedimentation test may not be able to predict the actual clogging condition.

## 4.3 Case B: Worst (Large) Sedimentation Results

The sedimentation effects from clay on pervious concrete were confirmed to be negligible in Case A (See Table 4-6), Therefore, this type of sedimentation effect is not discussed in this section. Testing specimens would only be subjected to sand and clayey silty sand sediments. Sediment load for Case B was considered the reasonably worst case as introduced in Section 3.4.3. A total of 1.76 lbs (0.82 kg) was used, corresponding to the cylinder surface area to simulate the total sedimentation load for 20 years.

The definition of clogging cycles is first developed in this study including clogging procedure run and then cleaning. In each clogging run, 0.088 lbs of clogging materials were spread evenly on specimen surface, and water allowed flowing through. The permeability was measured when the dirty water was flowing through the specimen. Then, the sediments were removed with a selected cleaning method and permeability was measured again. This procedure, involving clogging and then cleaning, as one clogging cycle, was conducted a total of 20 times for each specimen to examine the effects of sedimentation and cleaning efficiency.

Sedimentation tests in Case A confirmed that higher initial void ratio of pervious concrete showed the higher remaining permeability after being subjected to a typical sedimentation loads without rehabilitation methods applied. However, when using clayey silty sand as sedimentation material, the residual permeability approached a constant value for three groups. In this section, the rehabilitation methods were taken into consideration and three sedimentation were still used but with a greater amount of sediment. The effects of different rehabilitation methods on the permeability of specimens subjected to sand and clayey silty sand are provided in Table 4-7, Table 4-8, and Table 4-9. The permeability loses and recoveries changing with number of clogging cycles are provided in Figure 4-9, Figure 4-12 and Figure 4-15.

This section is organized into three sections based on the application of rehabilitation methods, they are, pressure washing, vacuuming and the combination of these two. Since the test results and analysis for pressure washing and vacuuming swept are similar, the analysis of test results will be detailed as discussed in “Pressure washing” in Section 4.4.1, and a brief discussion will be provided in “Vacuuming” in Section 4.4.2 any unless there is significant difference. In Section 4.4.3, the effects of the combinations of two methods are presented. Lastly, the effects of void ratios of PCPC, sedimentation materials type and rehabilitation methods on sedimentation are presented in Section 4.4.4.

**Table 4-7. Changes in Coefficient of Permeability at Different Stages of the Case 2 Sediments Test (By Pressure Washing)**

| Group ID | Specimen | Initial Permeability Coeff. (In/hr) | Decrease Permeability After Sedimentation | Average Residual Permeability Coeff. (in/hr) | Average Decrease of Permeability (in/hr.) | Average Residual Permeability (in/hr.) | Average Decrease of Permeability (%) | Design Porosity (%) | Sedimentation Materials |
|---|---|---|---|---|---|---|---|---|---|
| 1 | S-P-1-1 | 404.8 | 26.4 | 93 | 405 | 54 | 87 | 15 | Sand |
| | S-P-1-2 | 361.8 | 60.3 | 83 | | | | | |
| | S-P-1-3 | 448.74 | 74.3 | 83 | | | | | |
| 2 | S-P-2-1 | 835.1 | 145.5 | 83 | 900 | 182 | 80 | 20 | |
| | S-P-2-2 | 833.9 | 228.8 | 73 | | | | | |
| | S-P-2-3 | 1031.9 | 171.5 | 83 | | | | | |
| 3 | S-P-3-1 | 1560.4 | 513.4 | 83 | 1407 | 588 | 57 | 25 | |
| | S-P-3-2 | 1437.4 | 422.9 | 67 | | | | | |
| | S-P-3-3 | 1223.8 | 480.9 | 71 | | | | | |
| 1 | C-P-1-1 | 491.9 | 317.2 | 2 | 422 | 416 | 1 | 15 | Clay Silty |
| | C-P-1-2 | 318.6 | 450.7 | 0 | | | | | |
| | C-P-1-3 | 454.1 | 1080.7 | 1 | | | | | |
| 2 | C-P-2-1 | 1099.1 | 887.9 | 2 | 1065 | 1046 | 2 | 20 | |
| | C-P-2-2 | 926.8 | 1168.4 | 4 | | | | | |
| | C-P-2-3 | 1170.6 | 1535 | 0 | | | | | |
| 3 | C-P-3-1 | 1561 | 1610.5 | 2 | 1465 | 1454 | 1 | 25 | |
| | C-P-3-2 | 1614.3 | 1217.5 | 0 | | | | | |
| | C-P-3-3 | 1218.6 | 86.1 | 0 | | | | | |
| 1 | CS-P-1-1 | 565.8 | 74.6 | 85 | 600 | 70 | 88 | 15 | Clayey-Silty Sand |
| | CS-P-1-2 | 684.3 | 49.3 | 89 | | | | | |
| | CS-P-1-3 | 548.7 | 217.6 | 91 | | | | | |
| 2 | CS-P-2-1 | 936.7 | 237.5 | 77 | 1041 | 232 | 78 | 20 | |
| | CS-P-2-2 | 1048.9 | 238.6 | 77 | | | | | |
| | CS-P-2-3 | 1137.2 | 239.5 | 79 | | | | | |
| 3 | CS-P-1-1 | 1183.1 | 255.7 | 78 | 1277 | 285 | 77 | 25 | |
| | CS-P-2-2 | 1048.4 | 302.6 | 71 | | | | | |
| | CS-P-3-3 | 1597.6 | 297.6 | 81 | | | | | |

### Table 4-8. Changes in Coefficient of Permeability at Different Stages of the Case 2 Sediments Test (By Vacuuming)

| Group ID | Specimen | Initial Permeability Coeff. (In/hr) | Decrease Permeability After Sedimentation | Average Residual Permeability Coeff. (in/hr) | Average Decrease of Permeability (in/hr.) | Average Residual Permeability (in/hr.) | Average Decrease of Permeability (%) | Design Porosity (%) | Sedimentation Materials |
|---|---|---|---|---|---|---|---|---|---|
| 1 | S-V-1-1 | 569.9 | 69.3 | 88 | 593 | 87 | 85 | 15 | Sand |
| | S-V-1-2 | 618.3 | 84.6 | 86 | | | | | |
| | S-V-1-3 | 591.3 | 108.5 | 82 | | | | | |
| 2 | S-V-2-1 | 714.6 | 236.9 | 67 | 739 | 232 | 69 | 20 | |
| | S-V-2-2 | 805.4 | 265.1 | 67 | | | | | |
| | S-V-2-3 | 697.6 | 194.3 | 72 | | | | | |
| 3 | S-V-3-1 | 1661.3 | 464.7 | 72 | 1506 | 497 | 67 | 25 | |
| | S-V-3-2 | 1539.4 | 494.5 | 68 | | | | | |
| | S-V-3-3 | 1318.7 | 531.9 | 60 | | | | | |
| 1 | CS-V-1-1 | 494 | 39.1 | 92 | 455 | 48 | 89 | 15 | Clayey-Silty Sand |
| | CS-V-1-2 | 513.6 | 43.6 | 92 | | | | | |
| | CS-V-1-3 | 358.3 | 61.3 | 83 | | | | | |
| 2 | CS-V-2-1 | 724.8 | 245.6 | 66 | 655 | 174 | 74 | 20 | |
| | CS-V-2-2 | 691.2 | 138.2 | 80 | | | | | |
| | CS-V-2-3 | 548.6 | 136.9 | 75 | | | | | |
| 3 | CS-V-3-1 | 1501.6 | 196.4 | 87 | 1580 | 216 | 86 | 25 | |
| | CS-V-3-2 | 1489.2 | 239.4 | 84 | | | | | |
| | CS-V-3-3 | 1748.6 | 213.5 | 88 | | | | | |

**Table 4-9. Changes in Coefficient of Permeability at Different Stages of the Case 2 Sediments Test (By Pressure Washing and Vacuuming)**

| Group ID | Specimen | Initial Permeability Coeff. (In/hr) | Decrease Permeability After Sedimentation | Average Residual Permeability Coeff. (in/hr) | Average Decrease of Permeability (in/hr.) | Average Residual Permeability (in/hr.) | Average Decrease of Permeability (%) | Design Porosity (%) | Sedimentation Materials |
|---|---|---|---|---|---|---|---|---|---|
| 1 | S-VP-1-1 | 459.4 | 98.6 | 79 | 458 | 121.5 | 76 | 15 | Sand |
|  | S-VP-1-2 | 509.4 | 135.6 | 73 |  |  |  |  |  |
|  | S-VP-1-3 | 538.5 | 130.6 | 76 |  |  |  |  |  |
| 2 | S-VP-2-1 | 1130.2 | 347.6 | 69 | 956 | 372 | 68 | 20 |  |
|  | S-VP-2-2 | 1256.7 | 428.6 | 66 |  |  |  |  |  |
|  | S-VP-2-3 | 1097.5 | 338.6 | 69 |  |  |  |  |  |
| 3 | S-VP-3-1 | 1683.9 | 508.9 | 70 | 1428 | 449 | 70 | 25 |  |
|  | S-VP-3-2 | 1544.6 | 438.5 | 72 |  |  |  |  |  |
|  | S-VP-3-3 | 1627.6 | 517.5 | 68 |  |  |  |  |  |
| 1 | CS-VP-1-1 | 494.4 | 58.6 | 88 | 614 | 80 | 86 | 15 | Clayey-Silty Sand |
|  | CS-VP-1-2 | 598.6 | 94.5 | 84 |  |  |  |  |  |
|  | CS-VP-1-3 | 574.6 | 87.6 | 85 |  |  |  |  |  |
| 2 | CS-VP-2-1 | 1025.6 | 284.6 | 82 | 1120 | 229 | 78 | 20 |  |
|  | CS-VP-2-2 | 1128.6 | 247.5 | 78 |  |  |  |  |  |
|  | CS-VP-2-3 | 1289.6 | 227.5 | 82 |  |  |  |  |  |
| 3 | CS-VP-3-1 | 1428.5 | 328.4 | 77 | 1359 | 364 | 75 | 25 |  |
|  | CS-VP-3-2 | 1384.5 | 374.9 | 73 |  |  |  |  |  |
|  | CS-VP-3-3 | 1458.6 | 369.5 | 75 |  |  |  |  |  |

### 4.3.1 Pressure Washing

#### 4.3.1.1 Sand

Using sand as the sedimentation material, the average permeability reductions for Groups 1, 2 and 3 are relatively close and not significantly different with each other, which are 84.6%, 81.2%, and 82.8%, respectively (See Figure 4-10). The residual permeabilities are 43.2 in/hr, 181.95 in/hr and 421.3 in/hr after 20 clogging cycles. Group 3 achieved the highest residual permeability after sedimentation due to its highest initial void ratio (See Figure 4-9).

Pressure washing was applied as a rehabilitation method to remove the sediments from the specimens, and the average permeability recovery per clogging cycle is 9.3%, 9.8% and 15% for Group1, 2 and 3. The average permeability recovery is lowest for Group 1 containing the lowest void ratio and initial permeability. Also, the permeability recovery slightly increases with the initial void ratio. However, among the three groups, the permeability recoveries are not statistically significantly different with each other and all less than 10%.

The most significant permeability drops about 60% to 70% of initial values for all three groups occur in the first 5 clogging cycles (See Figure 4-9). After the 5th cycle, the permeability approaches a consistent value, which are 150 in/hr, 300 in/hr and 500 in/hr. The permeability reduction and recovery all approach a constant value about 2-4% of the initial value for Group 1, 5% and 10% for Group 2 and 3. The permeability recovery magnitudes with clogging cycles were also decrease gradually.

A significant amount of sand was observed at the top of the specimens after the each clogging procedure, which can be completely removed by pressure washing or vacuum sweeping. Only very limited amount of sand was observed flushing though the specimen with water (See Figure 4-10).

**Table 4-10. Specimens Subjected to Sand Sedimentation and Cleaned by Pressure Washing**

| Group ID Void Ratio | Permeability Recovery Mean (%) | Std Dev | Upper 95% Mean | Lower 95% Mean | Average Initial Permeability (in/hr) | Average Residual Permeability (in/hr) |
|---|---|---|---|---|---|---|
| Group 1 15% | 4 | 3.35 | 5.56 | 2.42 | 395.2 | 43.2 |
| Group 2 20% | 7.8 | 7.7 | 11.4 | 4.2 | 864.6 | 181.9 |
| Group 3 25% | 9.4 | 2.06 | 10.4 | 8.4 | 1408.3 | 421.3 |

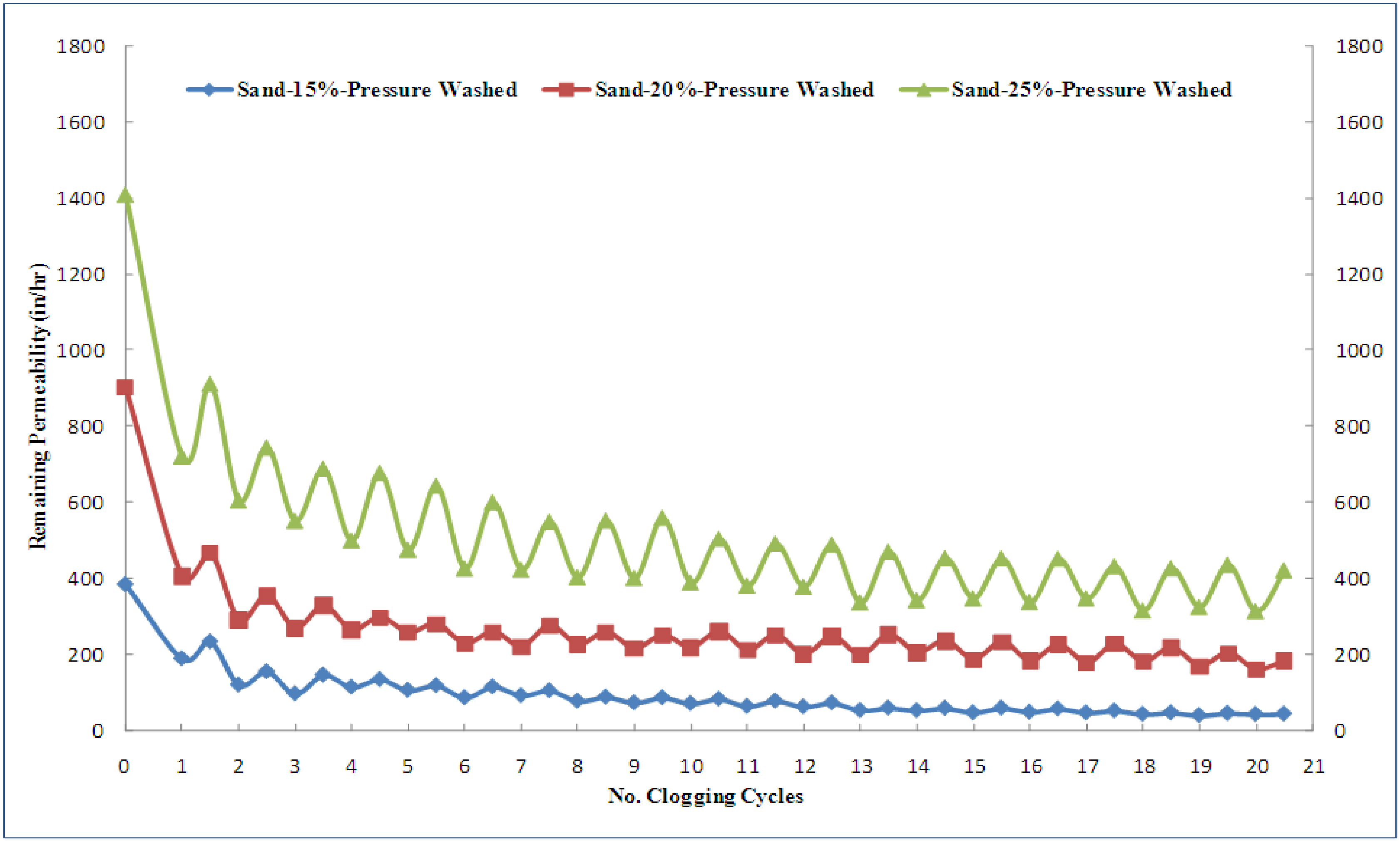


Figure 4-9. Permeability Coefficient of Permeability of Specimens Subjected to Sand Sediments and Cleaned by Pressure Washing

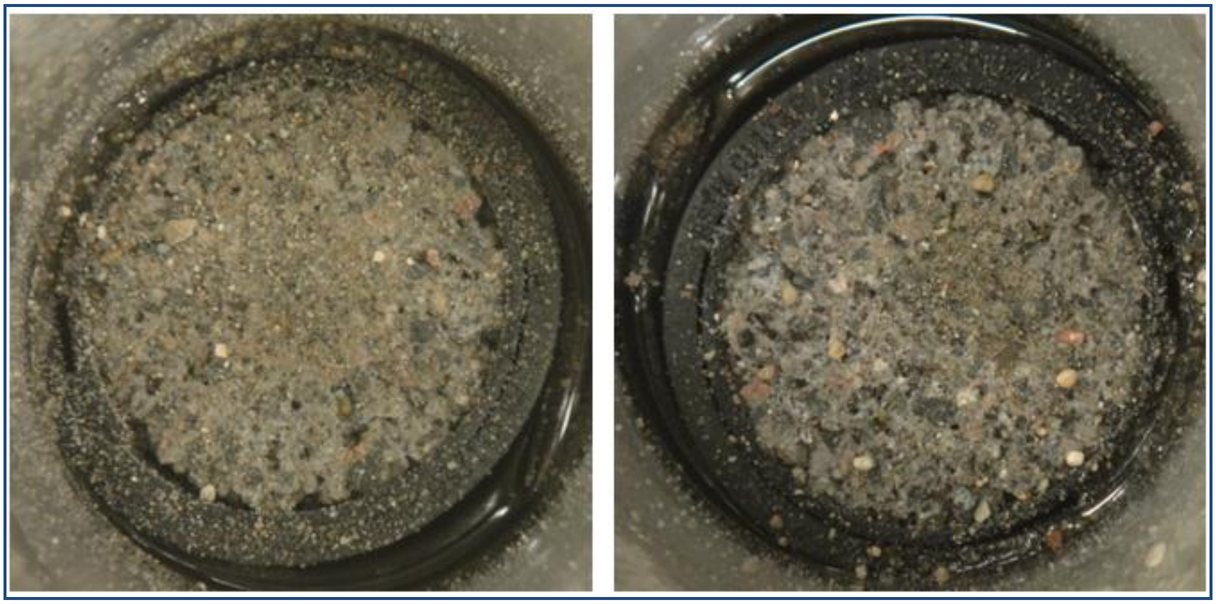


Figure 4-10. Specimens Exposed to Sand Sediments before (Left) and After Sedimentation Test

Figure 4-11. Sand Sedimentation Test is in Progress

According to Deo' s [61], the higher residual permeability may be attributed the larger pore sizes, and increased pore connectivity in the specimens. Therefore, the highest residual permeability of Group 3 may indicate the largest pore size and increased pore connectivity caused by the highest porosity as compared to Group 1 and 2 with lower porosity. The finding may show that the high porosity indicates the pore connectivity and large average pore size.

As predicted, sand sediments were generally trapped on the surface and near the top zone of specimens after sedimentation test, and only the sediments trapped on the surface were completely removed by pressure washing. The critical pores were clogged by gradual accumulation of sediments and the deposition depth also increased with clogging cycles. Therefore, the permeability decreased accordingly. With more clogging cycles repeated, the critical pores approached being completely clogged by sand sediments, and finally, the clogged critical pores tended to a relatively steady state, and no further permeability reduction would occur with repeated clogging cycles because no further sediments would be retained within the pores in specimens. Group 3 showed the highest residual permeability due to its highest non-critical pore volume among Group 1 and 2. Therefore, even though the pressure washing was applied to clogged pavement to open the surface pores, there would not be any significant permeability improvement if the critical pores were filled up.

As discussed previously (See Figure 4-12), the total volume of pervious concrete roughly equal to the summation of open (or also called “effective”) and close pore volume, and the open pore volume roughly equals to the summation of critical pore and non-critical pore.

With the deposition of sediments in critical pore, the specimens with high total porosity may reach the higher residual permeability comparing to the specimen with lower total porosity due to the higher volume of non-critical pore, which always has the large pore size than critical pore, and allows the faster transportation of water through. However, for a certain mixture, the critical pore volume for various specimens are roughly equal (See Figure 4-12)

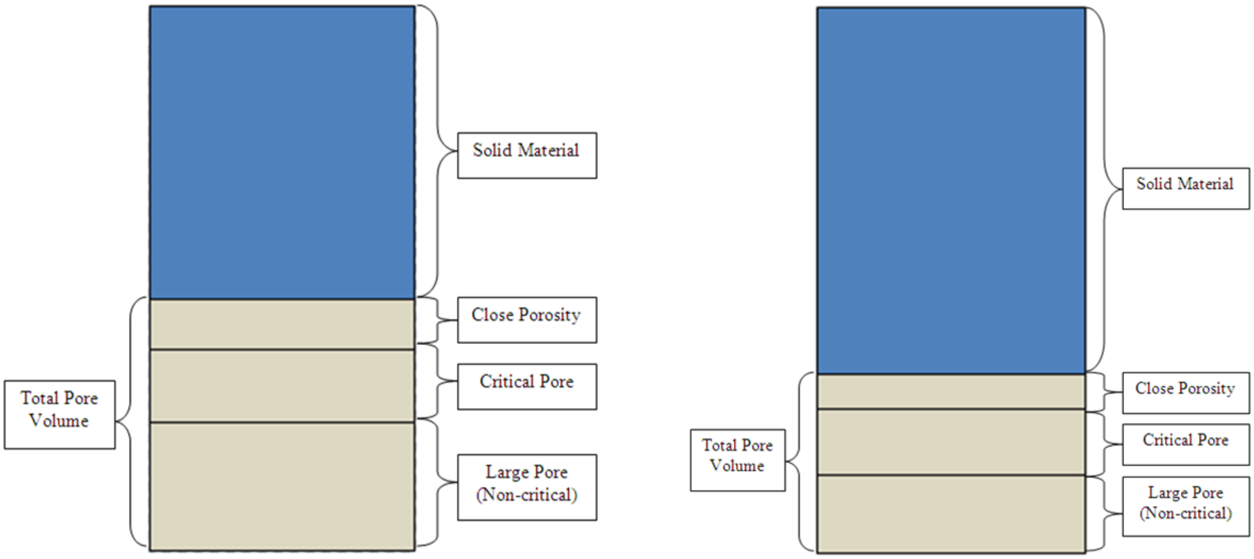


**Figure 4-12. Pore Volume of Pervious Concrete Specimens: High Porosity (Left) and Low Porosity (Right)**

Regarding the average permeability, specimens at high void ratios contain large pores as confirmed previously, and the removal of the sediments clogging these surface open pores may contribute to the permeability improvements. Therefore, as anticipated, the specimens at higher porosity would achieve the higher permeability recovery. This phenomenon would explain why the permeability values and permeability recoveries would approach being constant values.

The rapid permeability reduction during the first 5 clogging cycles may indicate the faster accumulation rate of sediments in the critical pores within the specimens at the beginning of clogging process. However, with time most critical pores would be filled up and no longer hold more sedimentation materials, which could cause slow accumulation rate.

#### 4.3.1.2 Clayey Silty Sand

Clayey silty sand was confirmed in Case A as the most “dangerous” sedimentation materials which can cause the highest loss of hydraulic performance of pervious concrete specimens in terms of permeability reduction. Approximate 90% of initial permeability was lost for all three groups after 20 clogging cycles, which is 39.5 in/hr., 185.3 in/hr., 217.6 in/hr. for Groups 1, 2 and 3, respectively (See Table 4-11). The trends of permeability changing with clogging cycles are shown in Figure 4-13. The remaining permeability are fairly equivalent, particularly for Group 2 and Group 3. This observation is not consistent with the results presented in Section 4.3.1.1, but similar with the observations obtained in Section 4.2.3.

Though statistical analysis (See Table 4-11), the average permeability recovery for Group 1 and Group 2 is not statistical significantly different. However, for Group 3, with 25% initial void ratio, the highest average permeability recovery was achieved. In each clogging cycle, at least 15% of the initial permeability was recovered by applying the pressurized water to remove the sand sediments from specimens. This finding may indicate that if the pervious concrete specimen contain the initial void ratios ranging from 15% to 20%, the permeability recovery achieved by pressurize water are approximately equivalent. 25% of void ratios show the significantly higher permeability recovery. The significant permeability reduction more than 60% of initial permeability lost during the first 5 to 6 clogging cycles was observed. Especially for Group 1, more than 90% of permeability was lost after the first clogging cycle. This finding has good agreement with Section 4.2.3.

A significant quantity of sand with a fine layer of clayey silty sediments was observed on the surface of the cylinder after the sedimentation tests. Due to cohesion of clay materials, the clay grains adhered to sand particles surface and built up a mud layer on the specimens' surface. The application of vacuum sweeping and pressure washing completely removed this material. Visual observation did not show a significant amount of sediments flow through the specimen, very similar to the observation with the sand sediment sedimentation test.

**Table 4-11. Specimens Subjected to Clayey Silty Sand Sedimentation and Cleaned by Pressure Washing**

| Group ID (Void Ratio) | Permeability Recovery Mean (%) | Std Dev | Upper 95% Mean | Lower 95% Mean | Average Initial Permeability (in/hr) | Average Residual Permeability (In/hr) |
|---|---|---|---|---|---|---|
| Group 1 (15%) | 9.4 | 6.4 | 6.34 | 12.4 | 565.8 | 39.5 |
| Group 2 (20%) | 9.8 | 2.8 | 11.1 | 8.4 | 926.7 | 185.3 |
| Group 3 (25%) | 15 | 5.1 | 17.4 | 12.6 | 1584.3 | 217.6 |

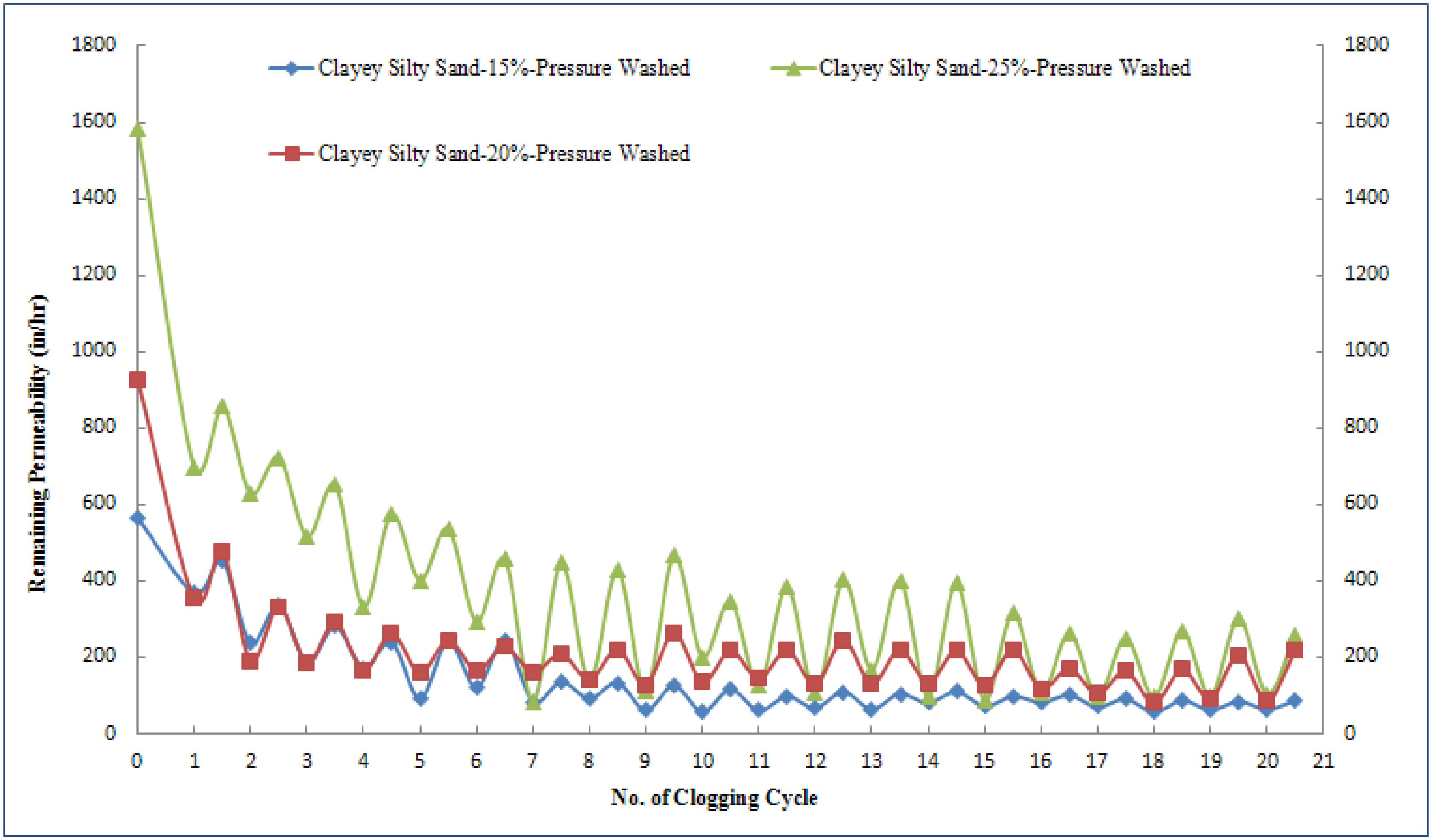


**Figure 4-13. Permeability Coefficient of Permeability of Specimens Subjected to Clayey Silty Sand Sediments and Cleaned by Pressure Washing**

The residual permeability for all three groups tended to achieve a constant value, especially for Group 2 and 3. This result is unlikely with sand sedimentation test but very similar with typical clayey silty sand sedimentation test, presented in Section 4.2.3, therefore, the similar theory and explanation were applied that the gradual accumulation of sand particles with adhered clay grains filled the critical pores up. Due to the wider range of particle size distribution than pure sand and heavy load of sedimentation materials applied, the larger volume pores were clogged up and became impermeable, which may explain that the residual permeability are approaching constant but lower than the values measured at the end the sand sedimentation test. It should be noted that the constant residual permeability is independent void ratio of specimens.

Regarding the average permeability recovery, opening of clogged surface pores by removing sediments that are trapped near the top zone using pressure washing may still attribute the permeability improvements. The distribution and frequency of larger pores are higher in specimens at higher porosity than at lower porosity. Therefore, the larger surface pores on the surface specimens in Group 3 were cleaned and opened to allow the larger amount of water infiltration than the specimens from Group 1 and 2. A similar explanation is introduced in sand sedimentation test in Section 4.2.2.

The highest permeability reduction around 90% for Group 1 and lowest around 60% for Group 3 up to 5 or 6 clogging cycles may indicate that the permeability reduction rate relates to the deposition rate of sedimentation materials, which depended on the pore size and sediments particle size. Sand particles adhered by cohesive clay grains could build up the deposition and filled up the critical pores faster than pure cohesiveless sand. Therefore, the faster permeability drop could be properly explained.

Pressure washing applied cleaned the sediments surface fairly well but only showed the very limited effect on the part clogging within the specimens based on visual observation. Therefore, by removing the surface sediments, approximately 10% of average permeability recovery was achieved for Group 1 and 2, and 15% for Group 3. However, the permeability recovery magnitude and residual permeability were strongly influenced by specimens’ void ratio, clogging degree and sedimentation type.

Figure 4-14. Specimens Exposed to Clayey Silty Sand Sediments before (Left) and after Sedimentation Test

Figure 4-15. Clay Silty Sand Sediments Is In Progress

### 4.3.2 Vacuuming

Vacuuming as another rehabilitation method investigated in this study is used and compared to other cleaning methods based on the permeability recovery under the same sedimentation load. Unlike the vacuuming machine used in the field, the pressure installed on this one is lower than the vacuum actually used in filed. Therefore, the cleaning efficiency from the laboratory test may be underestimated.

#### 4.3.2.1 Sand

The changes in permeability of the specimens subjected to sand with 20 clogging cycles of the test procedure are shown in Figure 4-16. Three specimens lost at least 70% of the initial permeability while for Group 1; the average permeability reduction is about 84%. The average residual permeability for Groups 1, 2 and 3 is 69 in/hr, 291 in/hr and 465 in/hr, respectively.

The average permeability recovery by vacuuming of the most affected specimens is Group 3, reaching, approximate 10% of the initial value. However, for Group 1 and Group 3, the permeability recoveries are relatively low, which are 2.4% and 7.1%, respectively. Similar results were observed that the remaining permeability and average permeability recovery increased directly with initial void ratio and permeability.

Applying vacuuming to pervious concrete specimens at 25% void ratio is more efficient than applying to at 15% and 20% void ratios under the sand sedimentation, but it is not statistically different (See Table 4-13). The permeability lost reached at 70% of the initial value for three groups up to 5th clogging cycles, which showed a similar trend as introduced in Section 4.3.1.1.

The similar phenomenon of the deposited materials on the top of specimens after sedimentation was observed as described in Section 4.3.1.1 (See Figure 4-10). The visible sedimentation materials on sample specimens were removed from the top by vacuuming. It was expected that sedimentation materials within the top zone were also partially removed.

**Table 4-12. Specimens Subjected to Sand Sedimentation and Cleaned by Vacuuming**

| **Group ID (Void Ratio)** | **Permeability Recovery Mean (%)** | **Std Dev** | **Upper 95% Mean** | **Lower 95% Mean** | **Average Initial Permeability (in/hr)** | **Average Residual Permeability In/hr** |
|---|---|---|---|---|---|---|
| Group 1 (15%) | 2.4 | 0.7 | 2.7 | 2.1 | 509.9 | 69.3 |
| Group 2 (20%) | 7.1 | 1.9 | 8 | 6.17 | 1018.6 | 291.4 |
| Group 3 (25%) | 9.6 | 9.3 | 15 | 5.2 | 1661.3 | 461.8 |

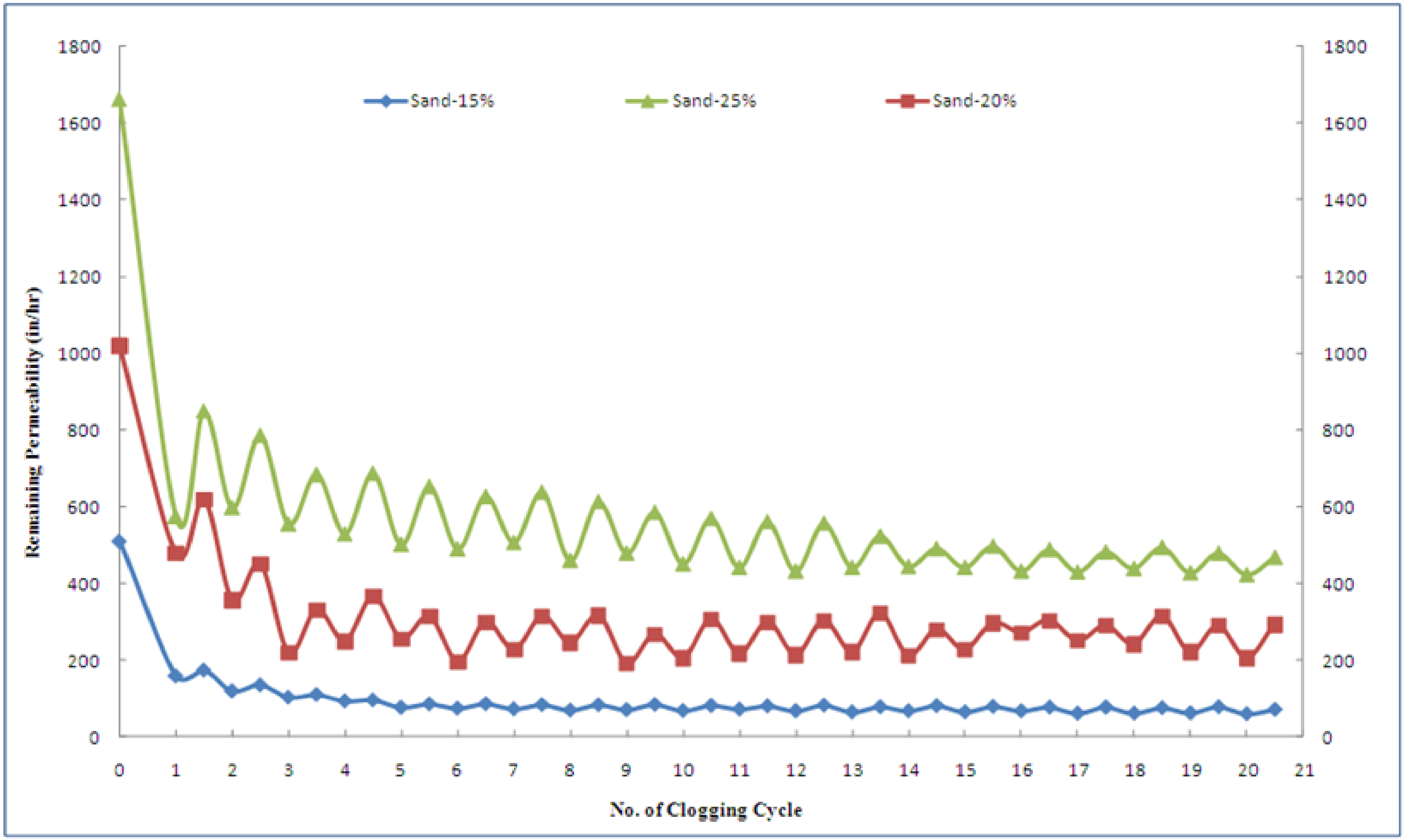


**Figure 4-16. Permeability Coefficient of Permeability of Specimens Subjected to Sand Sediments and Cleaned by Vacuuming**

It should be noted that the results on permeability reduction, permeability recovery, and even the permeability changing trends with clogging cycles for three groups are relatively similar with the results obtained in Section 4.3.1.1. The principles and theories to interpret these testing results in Section 4.3.1.1 are also applied to this section.

The lower tortuosity and higher pore connectivity as well as the higher volume of large pore were found in the specimens at high void ratios [61, 20]. The greater volume and higher frequency of large pore, lower tortuosity and higher pore connectivity obtained in specimens at higher void ratios are the important factors for achieving the higher residual permeabilities and permeability recoveries comparing to specimens at lower void ratios. These important pore structure characteristics allow the easier movements of retained cohesieless sand particles in the pores within the specimens, which can achieve the better cleaning efficiency and residual permeability as predicted.

Different with the cleaning mechanism of pressure washing, vacuuming could remove the retained particles on specimen surface but also the particles retained within the top one inch of the specimen. The effective cleaning depth depends on the pressure that is applied on specimen surface by vacuuming machine. As cited in [37] and [60], the permeability recovery only by vacuuming is normally slightly higher or approximately equivalent with pressure washing (See Section 2.3.1.6). However, the applied pressure in this study is lower than the one actually used in filed, which may indicate the smaller cleaning depth than that in field. Therefore, the permeability recovery and cleaning efficiency in this study may be underestimated.

#### 4.3.2.2 Clayey Silty Sand

The change in permeability of specimens subjected to clayey silty sand sediments and cleaned by vacuuming with 20 clogging cycles of the test procedure are shown in Figure 4-17. Three groups lost more than 80% of the initial permeability after 20 clogging cycles and all achieved a constant low value at about 200 in/hr.

The average permeability recoveries per cycle for three groups are almost equivalent at approximate 11%. It is noted that the permeability recovery magnitude decreases with clogging cycles increases. As clearly shown in Figure 4-17, from 1st to 5th cycles, the average permeability recovery is 20%, 15% and 22% for Group 1, 2, and 3. However, from 6th to 20th clogging cycles, the average permeability recovery drops to 9.1%, 8.7% and 9.3% for Group 1, 2 and 3. Also, all specimens in three groups approach the constant remaining permeabilities ranging from 110 in/hr to 280 in/hr after 20 clogging cycles.

The similar phenomenon of the deposited materials on the top of specimens after sedimentation was observed as described in Section 4.3.1.2 (See Figure 4-15). This material was completely removed from the top by vacuuming.

Under clayey silty sand sedimentation, the residual permeability tends to approach a constant value for all specimens approximate 200 in/hr at the end of clogging test. The permeability recovery by vacuuming is relatively close at 11%. For all three groups, more than 50% of initial permeability was lost within the first clogging cycle, and more than 80% of initial permeability was lost up to 2nd clogging cycles. These important observations confirm the results obtained in Section 4.3.1.2, and as expected, the similar interpretation was also applied in this section.

**Table 4-13. Specimens Subjected to Clayey Silty Sand Sedimentation and Cleaned by Vacuuming**

| Group ID Void Ratio | Permeability Recovery Mean (%) | Std. Dev | Upper 95% Mean | Lower 95% Mean | Average Initial Permeability (in/hr) | Average Residual Permeability (In/hr) |
|---|---|---|---|---|---|---|
| Group 1 (15%) | 11.8 | 7.5 | 15.2 | 8.4 | 479.3 | 43.5 |
| Group 2 (20%) | 10.27 | 4.76 | 12.5 | 8.1 | 1234.6 | 107 |
| Group 3 (25%) | 12.54 | 10.21 | 14.02 | 9.2 | 1528.5 | 142.3 |

Sand particles with adhered cohesive clay grains can easily build up the deposition in the pores within the specimens, and reduce the permeability during a short time. Cohesive clay behaves as a cementatious material adhering to sand particles, and establishes the bonding between the concrete and sand particles in the pores. This bonding could stabilize the sand sediments that were retained in the pores, which could reduce the cleaning efficiency.

Also, as noted, the significant sedimentation appeared within about the bottom two thirds of the specimen on visual observation, and, very little amount of sedimentation materials was observed within the top third of this specimen cleaned by vacuuming. This may be the good indicator of effective cleaning depth.

The removal of sedimentation materials retained on the surface and within the top few inches of specimens indicated the higher permeability recovery than only removing the surface retained sediments by using pressure washing but not statistical significantly greater. Also, comparing to Section 4.3.1.2, the average permeability recoveries approximately remain constant. The higher permeability recovery is expected using a higher pressure applied by vacuuming.

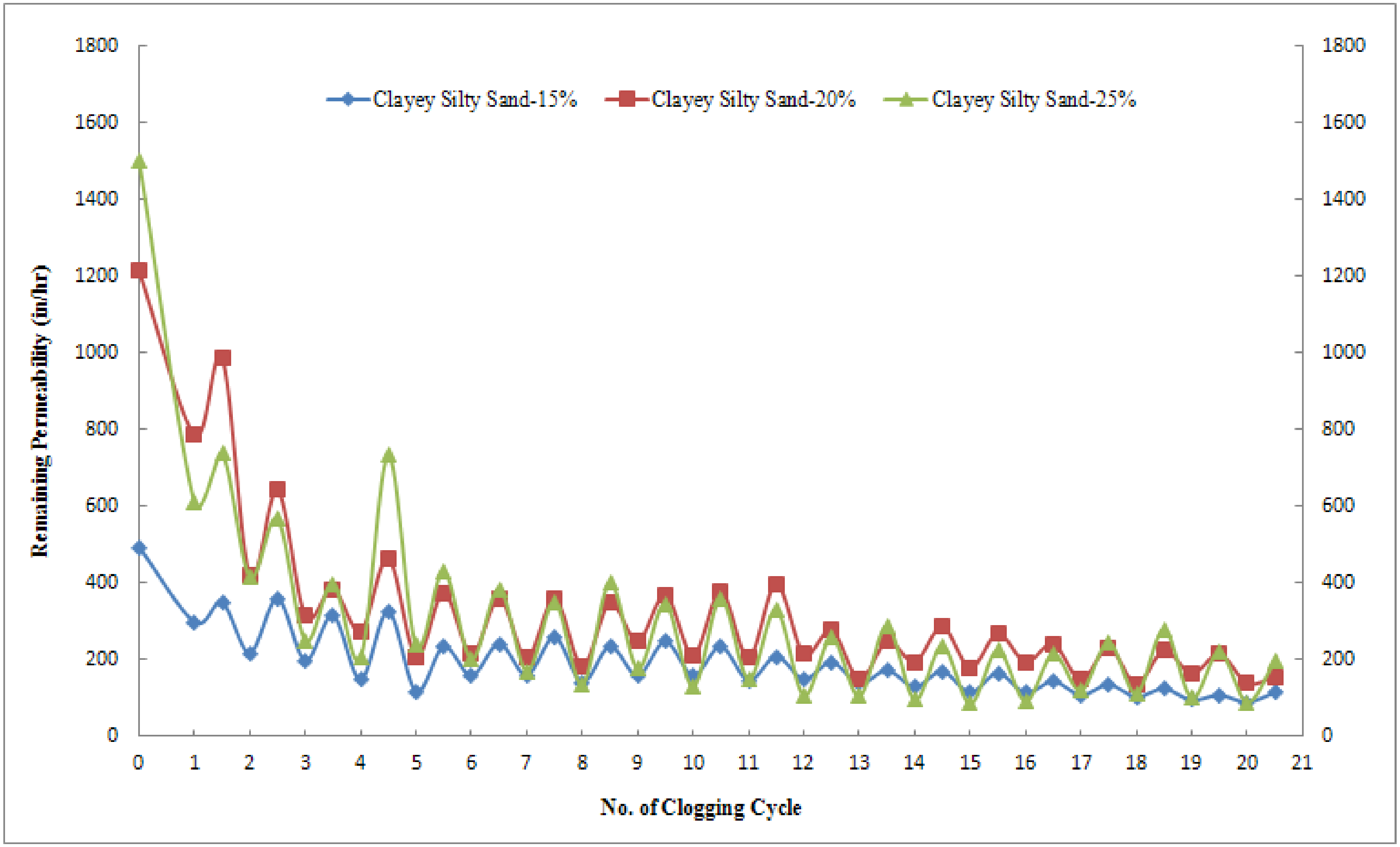


**Figure 4-17. Permeability Coefficient of Permeability of Specimens Subjected to Clayey Silty Sand Sediments and Cleaned by Vacuuming**

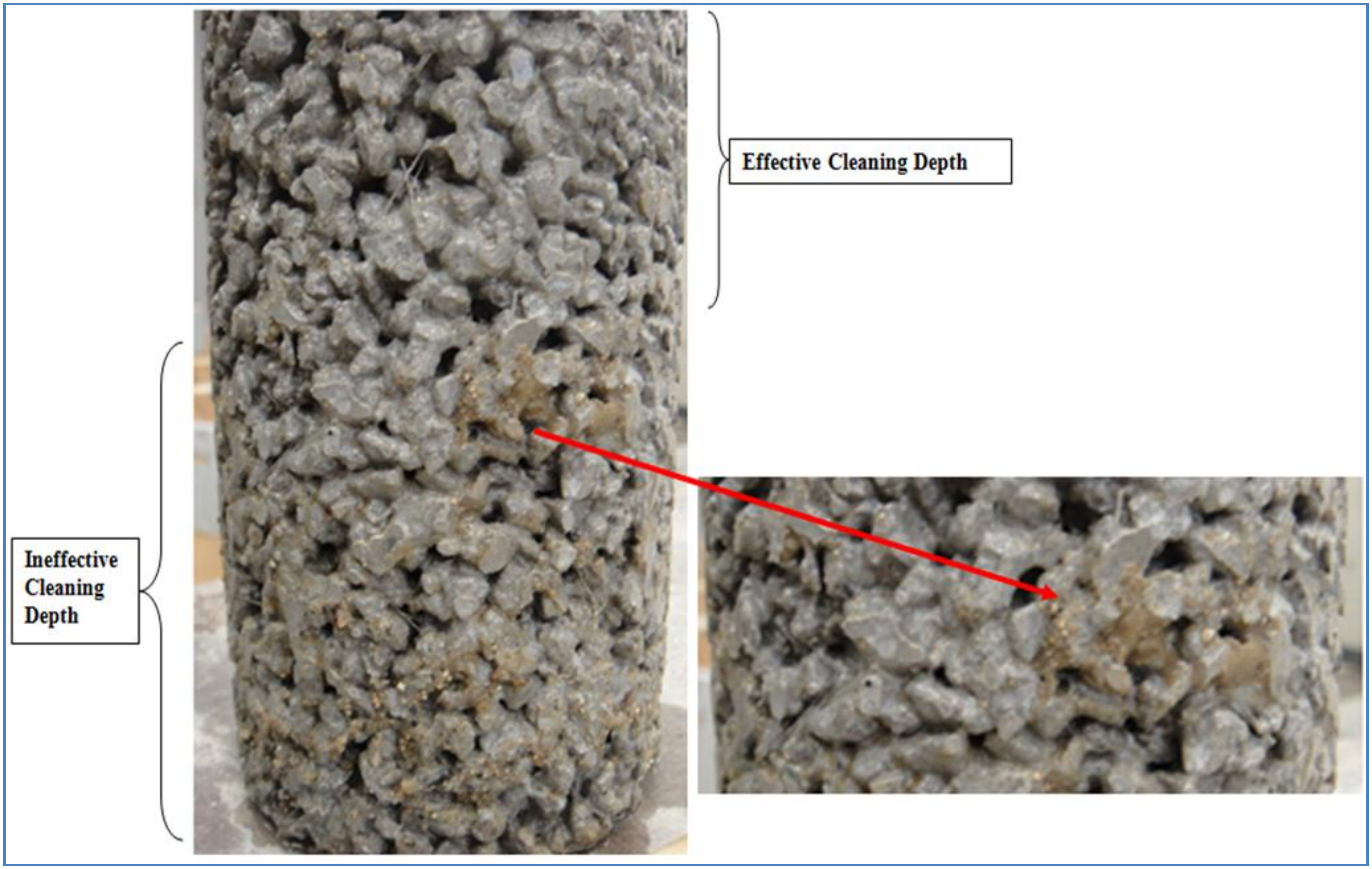


Figure 4-18. Cylinder Specimens Subjected to Clay Silty Sand Sedimentation and Cleaned by Vacuuming

### 4.3.3 The Combination of Pressure Washing and Vacuuming

#### 4.3.3.1 Sand

The changes in permeability of specimens subjected to sand and cleaned by the combination of pressurized washing and vacuuming over 20 clogging cycles are shown in Figure 4-19. All specimens in the three groups lost at least 70% of the initial permeability after 20 clogging cycles while Group 1; lost the most permeability about 75% due to its low void ratio about 15%. The residual permeability is 121 in/hr, 305 in/hr and 449 in/hr for Groups 1, 2 and 3, respectively.

Pressure washing followed by vacuuming showed the most improvement in specimens in Group 3 that received about 25% and the other two groups, Group 1 and Group 2 that received the equivalent permeability recovery about 11% of the initial value. The similar results were observed that the specimens with the high initial void ratios and permeability coefficients achieve the greatest permeability coefficients.

It should be noted that residual permeability for each group tends to achieve a constant value, and this constant remaining permeability value is lowest for Group 1 and highest but approximately equivalent for both Group 2 and 3. Regarding to the permeability recovery, the average value is lowest for Group 1 and highest for Group 3 and Group 2 is in the middle, which may indicate that the permeability recoveries increase directly with the initial void ratios of specimens.

The similar phenomenon of the deposited materials on the top of specimens after sedimentation was observed as described in Section 4.3.1.1 (See Figure 4-9). This material was completely removed from the top by pressure washing followed by vacuum sweeping.

**Table 4-14. Specimens Subjected to Sand Sedimentation and Cleaned by Pressure Washing and Vacuuming**

| Group ID Void Ratio | Permeability Recovery Mean (%) | Std. Dev. | Upper 95% Mean | Lower 95% Mean | Average Initial Permeability (in/hr) | Average Residual Permeability (In/hr) |
|---|---|---|---|---|---|---|
| Group 1 (15%) | 11.0 | 3.9 | 9.2 | 12.9 | 457.6 | 121.5 |
| Group 2 (20%) | 11.8 | 4.5 | 9.6 | 13.9 | 956.4 | 305.6 |
| Group 3 (25%) | 25.2 | 4.7 | 23 | 27.5 | 1428.4 | 449.1 |

As expected, the highest residual permeability coefficient and average permeability recoveries were achieved comparing to Section 4.3.1.1, specimens subjected to sand sediments and cleaned pressure washing and Section 4.3.2.1, specimens subjected to sand sediments and cleaned by vacuuming. This finding also confirms the conclusion in the literature that the combined pressure washing and vacuuming can provide the best cleaning efficiency comparing to only applying pressure washing or vacuuming along [38, 41]. Surface-retained particles were completely cleaned off and some of the retained particles within the top zone of specimens were also loosened by vibration caused pressure washing, and the most of surface pores would open and available for water infiltration again. After pressure washing, vacuuming can pick up the loosed particles within the few inches near the top of specimen, and further increase the infiltration rate. According to Table 4-14 and Figure 4-19 the permeability recoveries achieved by either pressure washing and vacuuming is approximately equivalent.

The effective cleaning depth also increased approximately from one third depth to one half depth of specimen height (See Figure 4-21) due to the removal of extra sedimentation particles that were retained within the top zone but loosened by the vibration of pressure washing applied on the specimen surface. This phenomenon may lead to a best cleaning efficiency of pressure washing followed by vacuuming. Also, the pore structure characteristics of specimen at void ratios are important to permeability recovery as presented in Section 4.4.2.1.

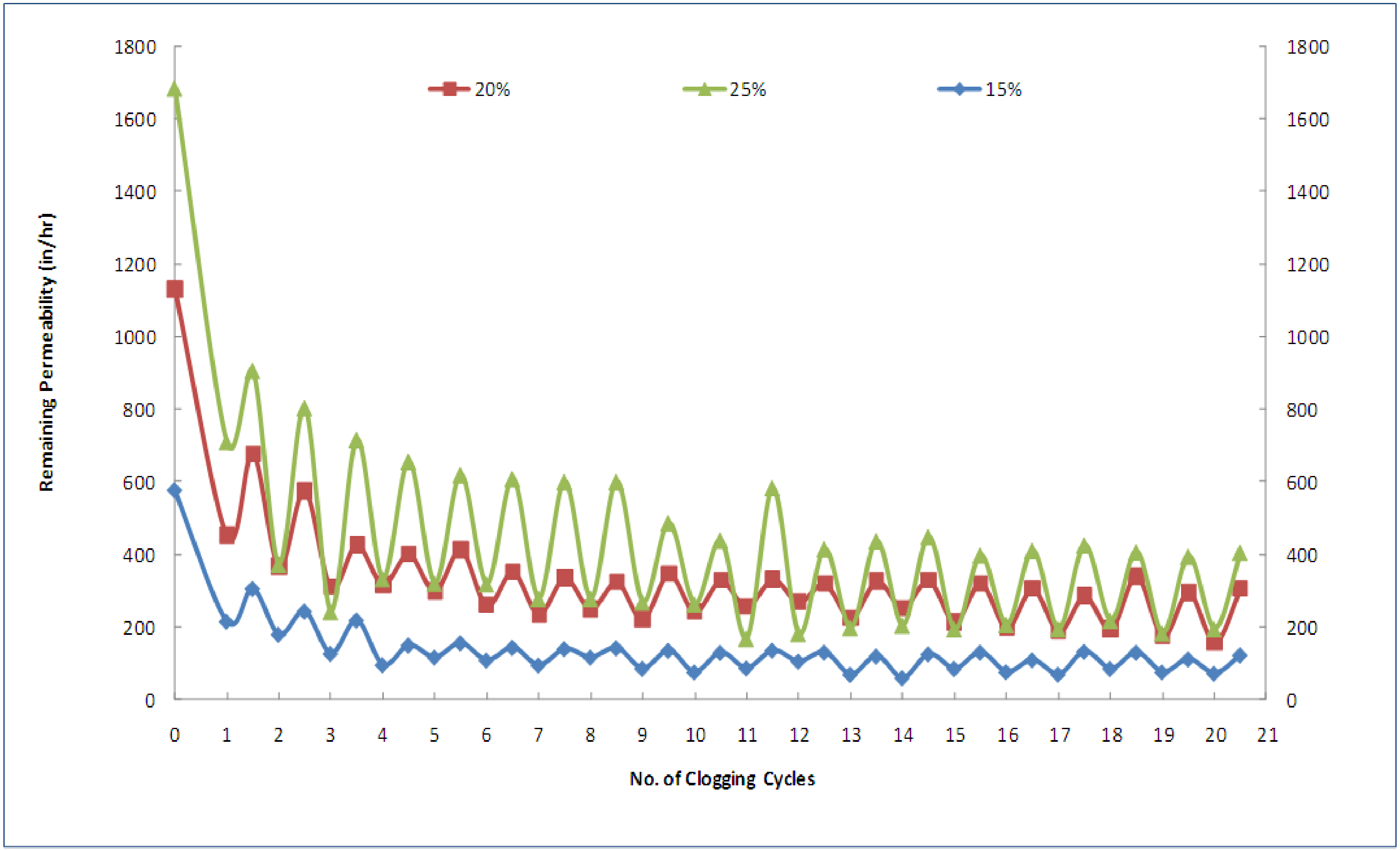
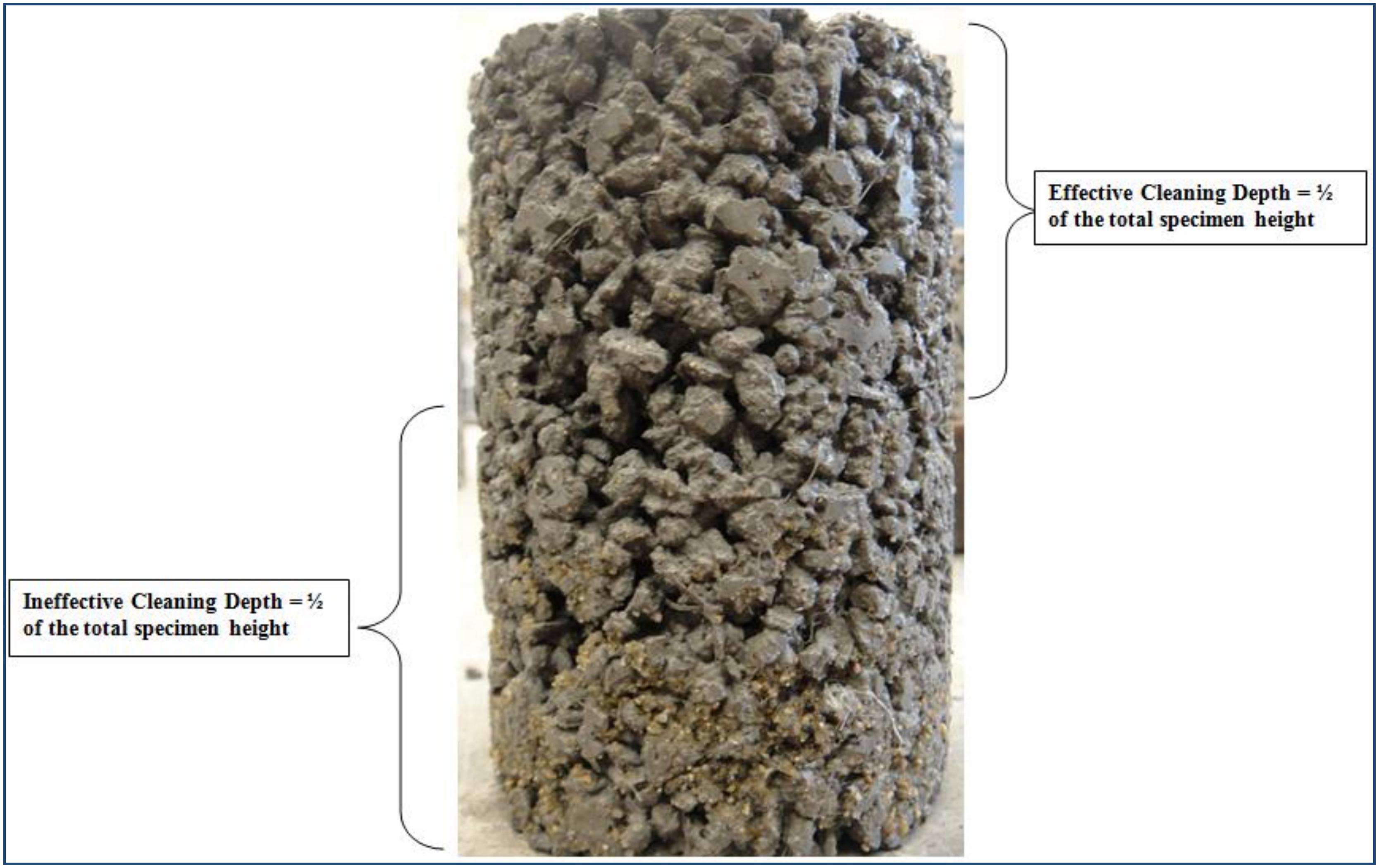


Figure 4-19. Permeability Coefficient of Permeability of Specimens Subjected to Sand Sediments and Cleaned by Pressure Washing and Vacuuming



Effective Cleaning Depth = ½ of the total specimen height

Ineffective Cleaning Depth = ½ of the total specimen height

**Figure 4-20. Cylinder Specimens Subjected to Sand Sedimentation and Cleaned by Pressue Washing and Vacuuming**

### 4.3.3.2 Clayey Silty Sand

The changes in permeability of specimens subjected to clayey silty sand sediments and the combination of pressure washing and vacuuming as cleaning method with 20 clogging cycles of the test procedure are shown in Figure 4-21. Testing specimens lost more than 75% of initial permeability after the test while Group 1, lost the most permeability at about 80% of the initial permeability due to the low porosity. The residual permeability is 144 in/hr, 268.1 in/hr and 364.1 in/hr for Group 1, 2 and 3 (See Table 4-16). As previously discussed, the same phenomenon was observed that the residual permeability increases directly with the initial permeability and/or void ratio.

Group 3 showed the best average permeability recovery at about 20% among three groups. However, it is not statistically higher than Group 1 and 2 based on the statistical analysis with 95% confidence interval (See Table 4-16). Under clayey silty sand sedimentation, the effect of void ratio of specimens on cleaning efficiency by the combination of vacuuming and pressure washing are small, and proved to be statistically insignificant.

As observed in Figure 4-22, the effective cleaning depth by vacuuming and pressure washing is at most one third of the total height of the specimen, because a significant amount of sedimentation materials were found within the bottom two thirds of the specimens. The similar phenomenon of the deposited materials on the top of specimens after sedimentation was observed as described in Section 4.3.1.2 (See Figure 4-15). This material was completely removed from the top by pressure washing followed by vacuum sweeping. Under clayey silty sand sedimentation, the specimens can at least achieve the residual permeability of approximately 140 in/hr after 20 clogging cycles and even 2 times of higher for specimens at 25% void ratios. This is more than sufficient to satisfy the hydraulic performance of pervious concrete. This is established based on the annual maintenance by performing pressure washing followed by vacuuming. As recommended by EPA [43], performing annual maintenance on pervious concrete pavement was preferred, which may be overdone based on this finding.  The effective cleaning depth as observed in this section decreases comparing to the value observed in Section 4.3.3.1, which could explain the lower cleaning efficiency and residual permeability coefficients. The similar interpretation regarding to the effective cleaning depth used in Section 4.3.2.2 still applied in this section. However, a difference should be noted, comparing the effective cleaning depths as observed in Section 4.3.2.1 and Section 4.3.3.1, the effective cleaning depth increased from one third to approximate one half of the total specimen height when using the combination of pressure washing and vacuuming instead of vacuuming only. However, this difference is not found when comparing observations from Section 4.3.2.2 and Section 4.3.3.2, which may be explained by the effect of clayey silt acting as cementitious materials bonding the sand sediments and concrete in the pores and reduce the effective cleaning efficiency.

**Table 4-15. Specimens Subjected to Clayey Silty Sand Sedimentation and Cleaned by Pressure Washing and Vacuuming**

| Group ID (Void Ratio) | Permeability Recovery Mean (%) | Std Dev | Upper 95% Mean | Lower 95% Mean | Average Initial Permeability (in/hr) | Average Residual Permeability In/hr |
|---|---|---|---|---|---|---|
| Group 1 (15%) | 14.2 | 4.8 | 13.5 | 15.3 | 613.5 | 143.5 |
| Group 2 (20%) | 13.1 | 9.7 | 11.7 | 15.6 | 1119.2 | 268.1 |
| Group 3 (25%) | 20 | 8.2 | 16 | 26.7 | 1359.4 | 364.1 |

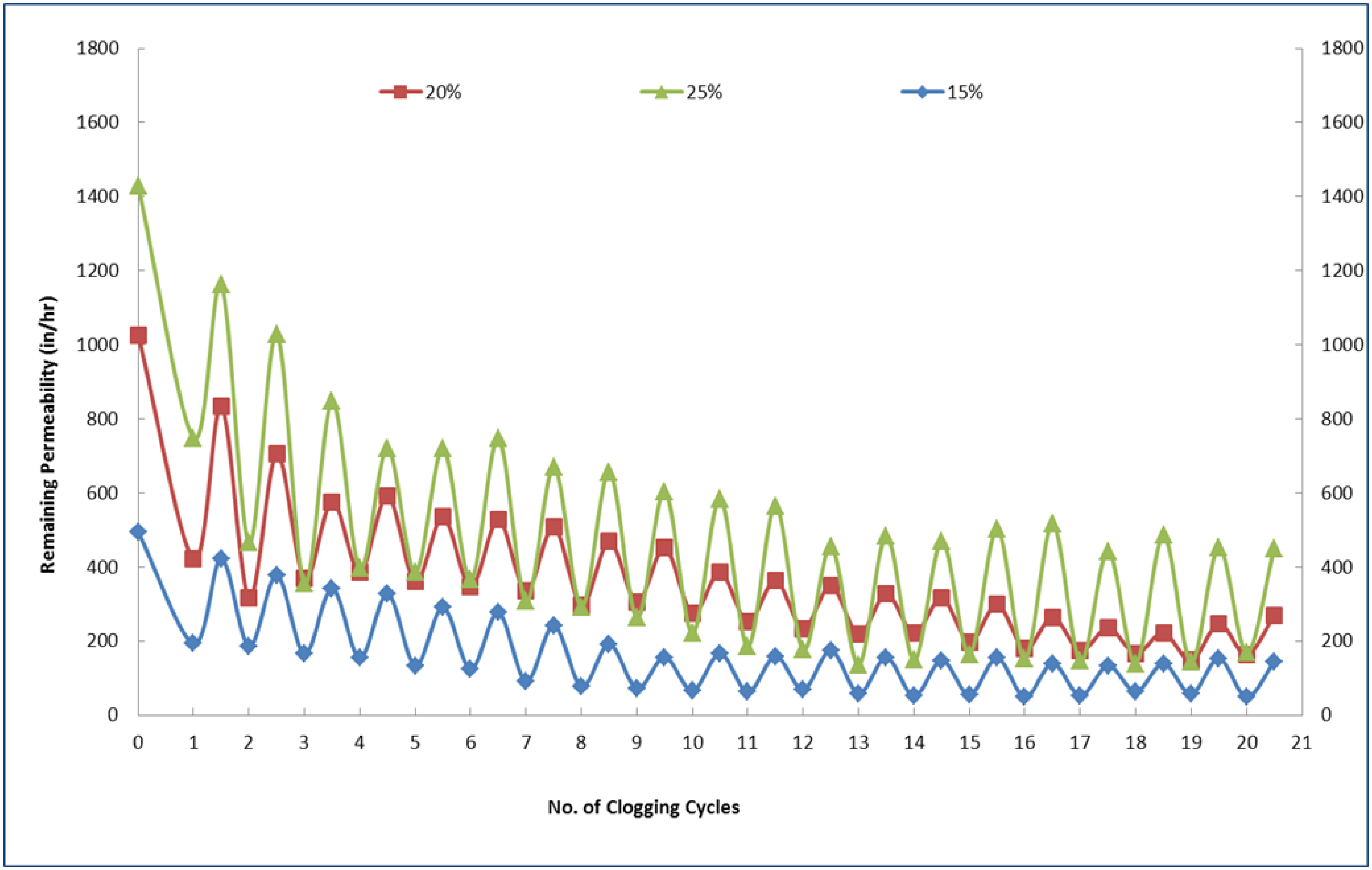


Figure 4-21. Cylinder Specimens Subjected to Clay Silty Sand Sedimentation and Cleaned by Pressue Washing and Vacuuming

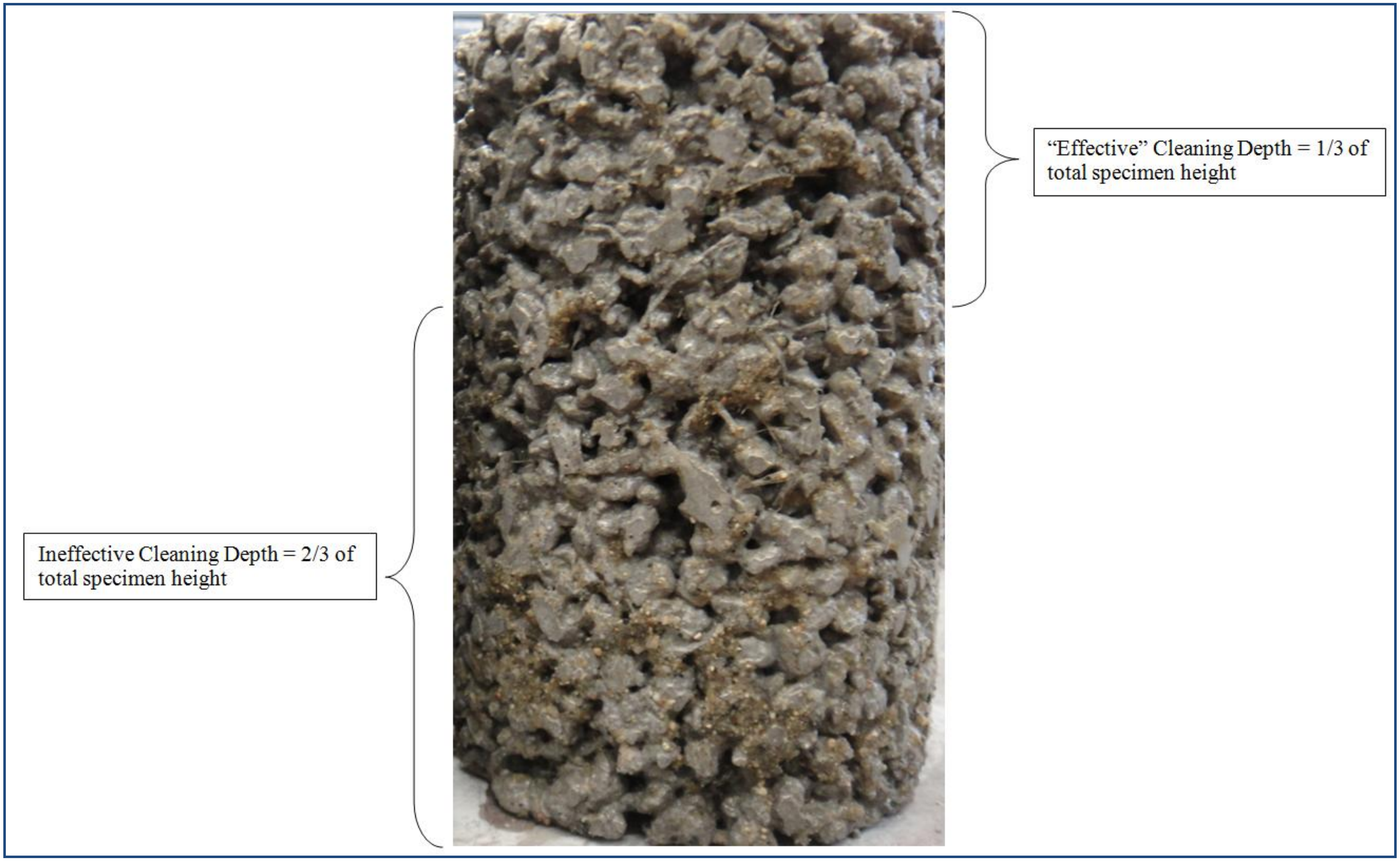


Figure 4-22. Cylinder Specimens Subjected to Clay Silty Sand Sedimentation and Cleaned by Pressue Washing and Vacuuming

### 4.3.4 Implications of Sedimentation Effects on PCPC

In this section, a “big picture” is provided. The clogging testing in described Section 4.2 and 4.3 on cylindrical specimens showed the reasonably similar results of permeability changing trends, they are, zigzag curves. The differences in these multiple zigzag curves were found and interpreted from the three perspectives of void ratios of PCPC, characteristics sedimentation materials, and rehabilitation methods.

In clogging test, the water with sediments has a one direction flow through the specimen. The water with sediments flows through a confined space tended to push the sediments deeper into the specimens. The initial high head of the water (18 in) may have contributed to this effect, and also, due to the great variability of infiltration rate and density of in-place pervious concrete pavement, the testing results in this study based simulated clogging test may not truly indicate the “real” case, but more importantly is to provide a guide of considering and preventing the clogging effect of pervious concrete from occurring in terms of three perspectives as mentioned above, which would be helpful to establish the quantitative and accurate study on clogging effect of pervious concrete pavement.

In general, this section is organized into three parts: 1) the effect of void ratios of PCPC, 2) sedimentation materials and 3) rehabilitation methods on sedimentation effects of pervious concrete**.**

#### 4.3.4.1 Effects of Sedimentation Materials

All the sedimentations tests confirmed that sand sediments will most likely be trapped on the surface or near the top zone within the specimen (See Figure 4-4 and Figure 4-10); clayey silt will be deposited within the concrete or travel through the concrete, and then retained between the space between the concrete and filter fabric or underlying soil (See Figure 4-1 and Figure 4-2). Based on the observation of clayey silty sand material, clayey silt also tends to adhere to sand particles surface due to its cohesion property (See Figure 4-6, 4-7 and Figure 4-14). The presence of coarser particles in sedimentation materials may change the deposition pattern of clayey silty material. The dense, less permeability surface acted like a coarse filter, passing the small particles most likely the clay grains but trapping larger ones as sand particles. The observations in this study confirmed these findings results from previous studies.

By conducting the laboratory clogging sedimentation test on cylindrical specimens, some conclusions are found that clay would cause the negligible permeability reduction of the pervious concrete itself (See Table 4-6); sand would cause significant permeability reduction (See Figure 4-5), which can be recovered to an acceptable residual permeability by using proper cleaning method (See Figure 4-9, 4-16 and 4-19), and may still satisfy the minimum requirements of hydraulic performance of pervious concrete pavement; clayey silty sand as sedimentation material cause the most significant permeability reduction, lowest residual permeability and permeability recoveries (See Figure 4-8). Current available rehabilitation methods showed the limited cleaning efficiency (See Figure 4-13, 4-17 and 4-21), and the initial design of pervious concrete pavement should take clogging into consideration.

However, the cleaning efficiency depends on the void ratios of pervious concrete pavement. Due to the great variability of infiltration rate, uniformity of density and void ratios of in-place pervious concrete, the actual clogging effect may not be predicted accurately based on the results obtained in this study.

#### 4.3.4.2 Effect of Void Ratios of PCPC

According to Section 4.2, the test results show that the higher void ratios achieved the higher residual permeability coefficients of the clogged specimens subjected to the same sedimentation loads without rehabilitation methods applied (See Figure 4-8 and 4-9 ). A proper maintenance schedule may be established based on the trends of permeability with repeated clogging experiments. The test results showed that the pavement with low void ratios at around 15% requires earlier and more frequent maintenances than those with higher void ratios at 20% or above. However, more research is recommended to be further confirm this finding.

According to Section 4.3, the similar test results were also obtained. The specimens with greater void ratios always achieve the higher residual permeability and permeability recoveries by cleaning. This conclusion is based on conducting a series of laboratory clogging tests on cylindrical specimens involving three sedimentation materials and rehabilitation methods on cylindrical specimens with 15%, 20% and 25% designed void ratios.

Based on the test results in Case A and Case B, it is recommended to using 20% of void ratios as the minimum design void ratio of pervious concrete pavement in terms of the clogging consideration. For 15% as design porosity, there is a possibility of failure of hydraulic performance, that is, the residual permeability is lower than 5% of the initial value and about 20 in/hr, when pavement subjected to clayey silty sand while the cleaning methods may not be effective. For 25% as design void ratios, the hydraulic performance may be overdesigned and cause the strength failure due to this high void ratio. However, further researches are recommended to confirm this finding.

#### 4.3.4.3 Effect of Rehabilitation Methods

According to the test results presented in Section 4.3, the combined pressure washing and vacuuming as the cleaning method is regarded as the best rehabilitation method. However, the cleaning efficiencies depend on the pervious concrete void ratios and the characteristics of sedimentation materials. In Figures 4-23 to 4-28, the vertical axis is the remaining percent of permeability, and the horizontal axis is the clogging cycles conducted. As observed, vacuuming and pressure washing always show approximately the equivalent remaining percentage, and the V+P (pressure washing and vacuuming indicates for the green bar) always shows the highest remaining permeability percentage. It should be noted that under sand sediments with the increase of void ratios, the difference in three bar heights tend to decrease.

Under sand sedimentation (See Figures 4-22, 4-23, 4-24), the residual permeability of clogged specimens, cleaned by V+P, kept a fairly constant value at 30% of initial permeability with conducting more clogging cycles. By contrast, applying pressure washing and vacuuming kept approximate 20% of initial permeability for specimens containing 20% and 25% of void ratios but only 10% for those containing 15% of void ratios. Under clayey silty sand sedimentation (See Figures 4-26, 4-27 and 4-28), V+P kept a fairly constant value at 20% of initial permeability with conducting more clogging cycles. By contrast, applying pressure washing and vacuuming only can keep 10-20% of initial permeability for specimens containing 20% and 25% of void ratios but less than 10% for those containing 15% of void ratios.

This finding may indicate that pressure washing followed by vacuuming always keep the remaining permeability highest under same sedimentation type and loading, Number of clogging cycles and initial void ratios of pervious concrete comparing to those only using pressure washing or vacuuming. Further researches are recommended to conduct similar clogging tests on pervious concrete slab instead of core sample in order to better simulate the real case.

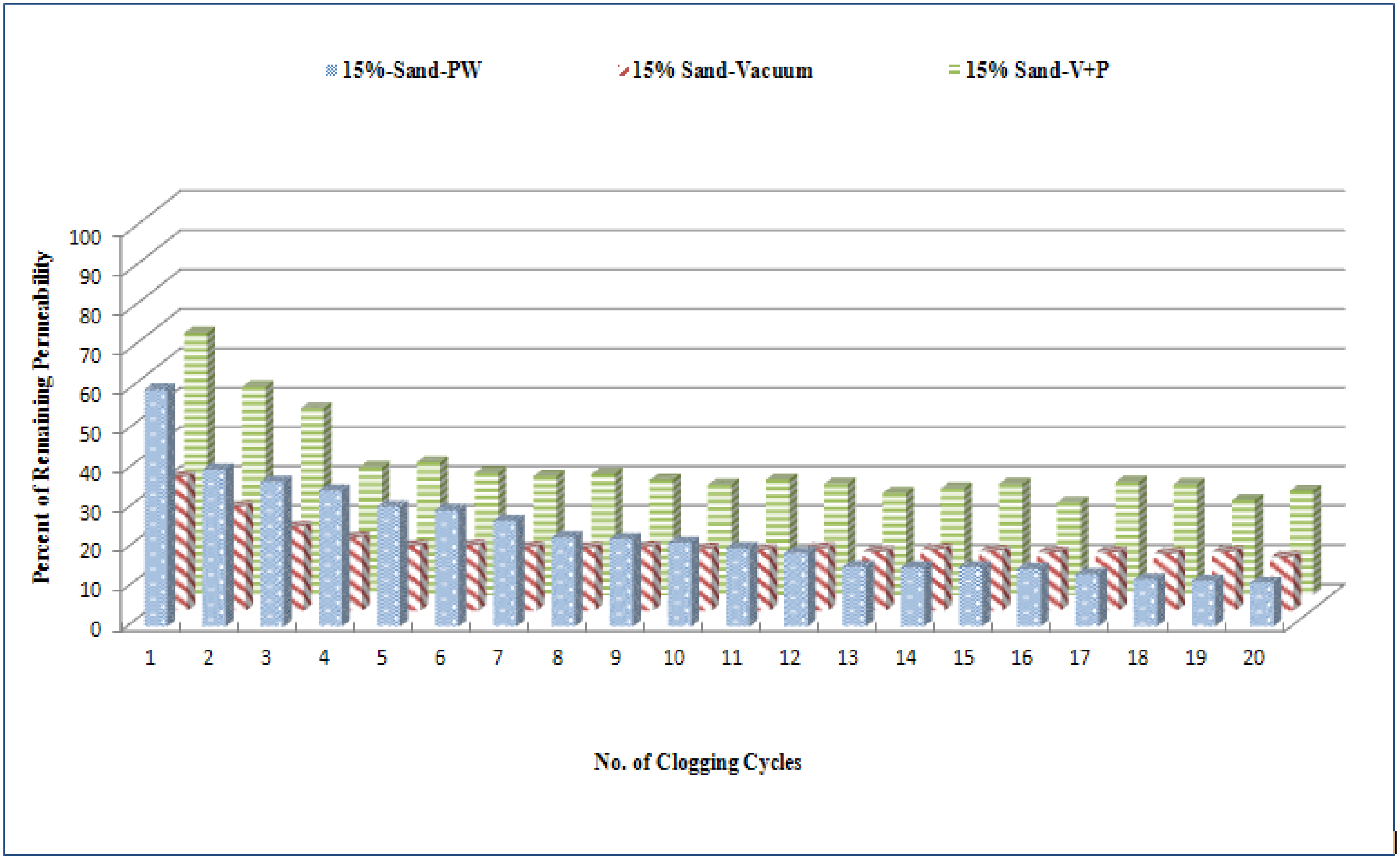


Figure 4-23. Specimens with 15% Void Ratio Subjected to Sand and Cleaned by Three Rehabilitation Methods

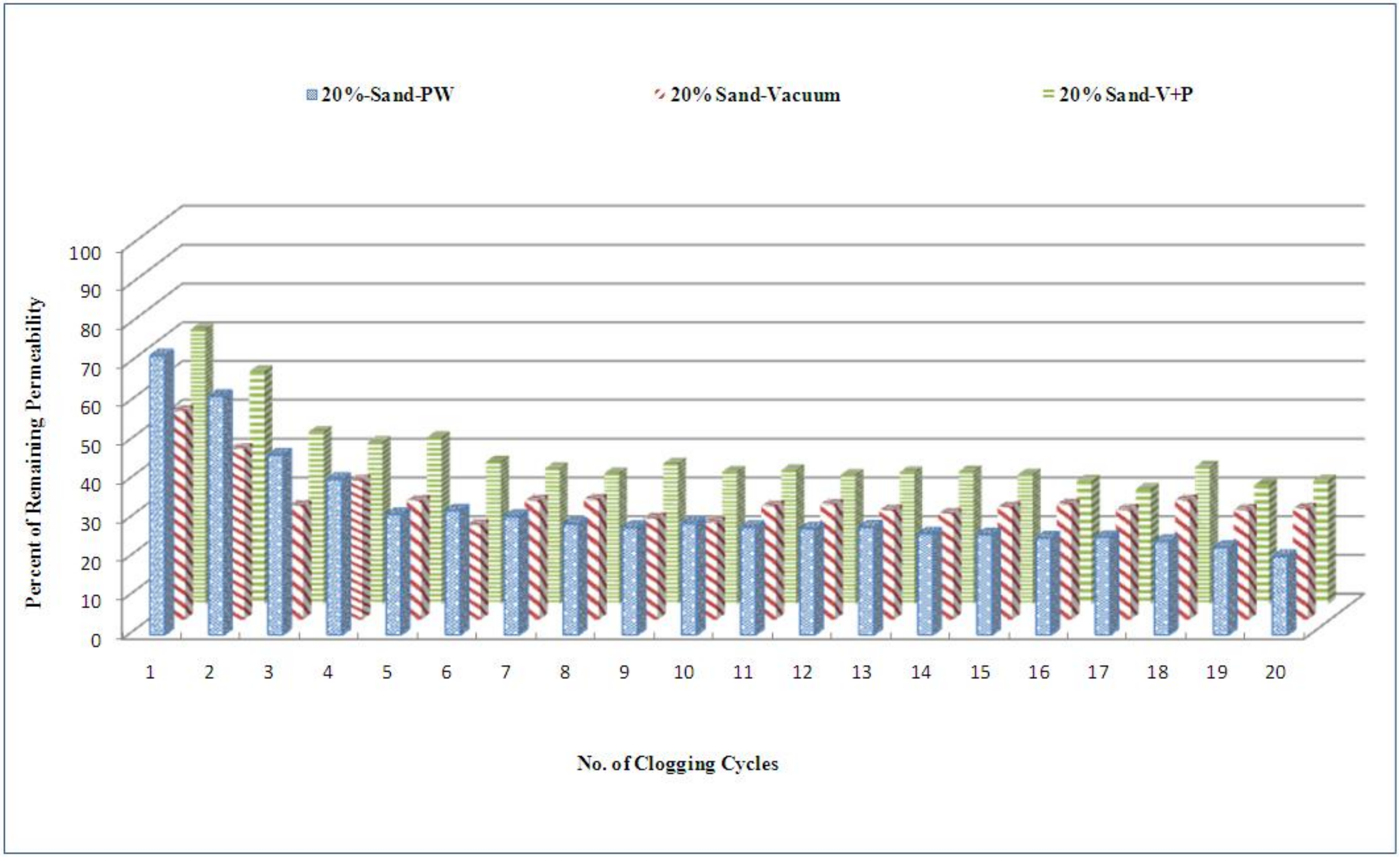


**Figure 4-24. Specimens with 20% Void Ratio Subjected to Sand and Cleaned by Three Rehabilitation Methods**

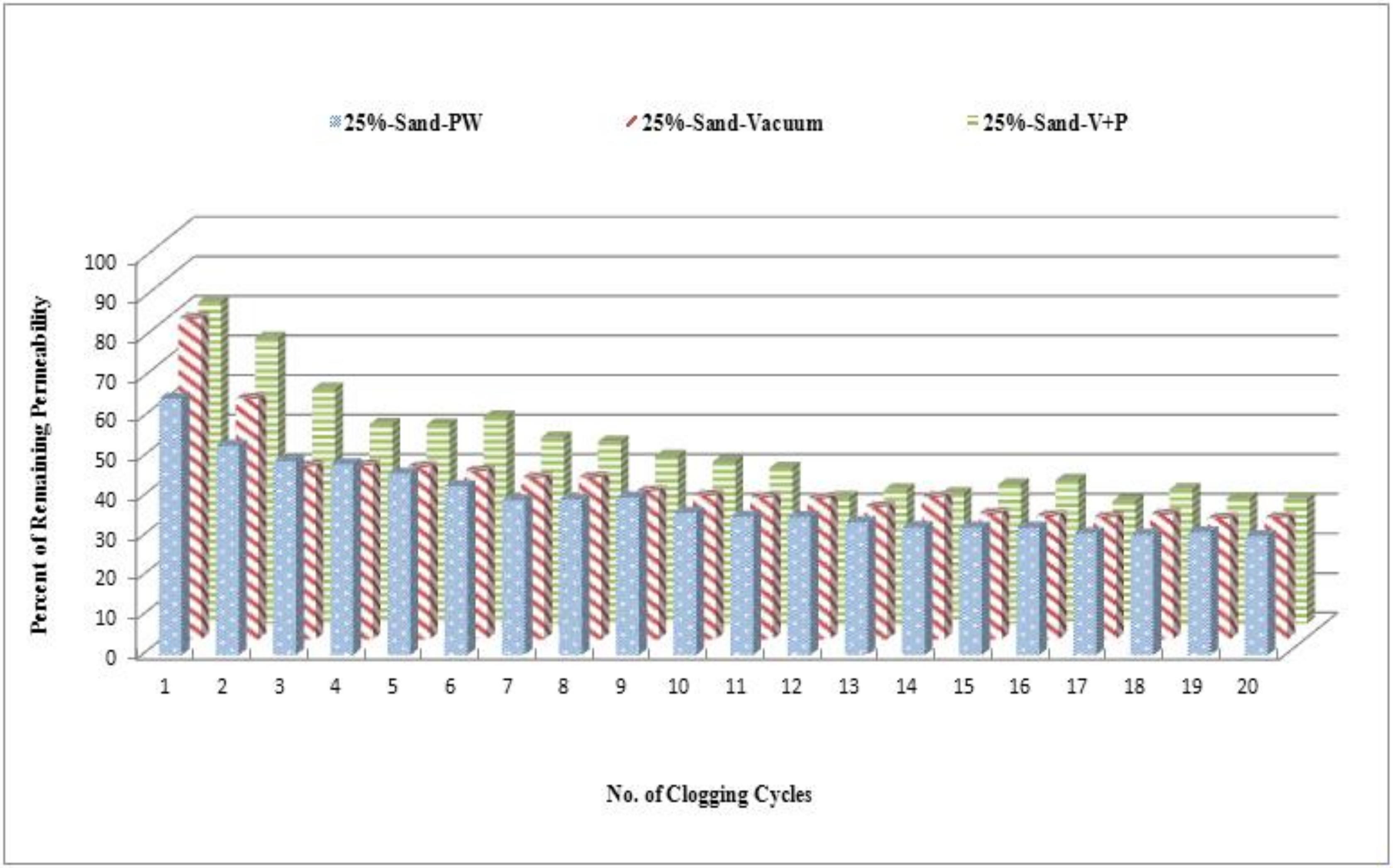


Figure 4-25. Specimens with 25% Void Ratio Subjected to Sand and Cleaned by Three Rehabilitation Methods

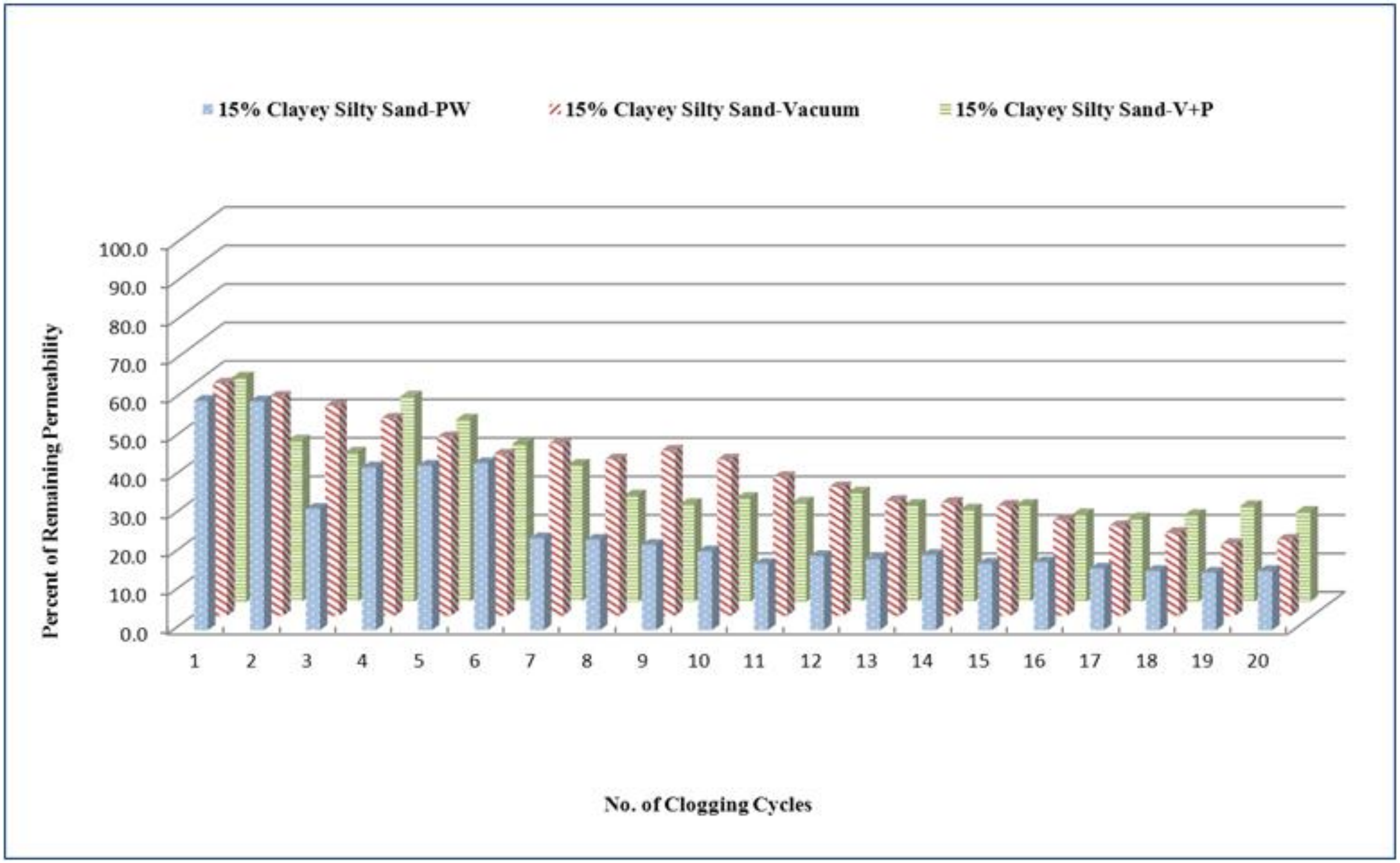


Figure 4-26. Specimens with 15% Void Ratio Subjected to Clayey Silty Sand and Cleaned by Three Rehabilitation Methods

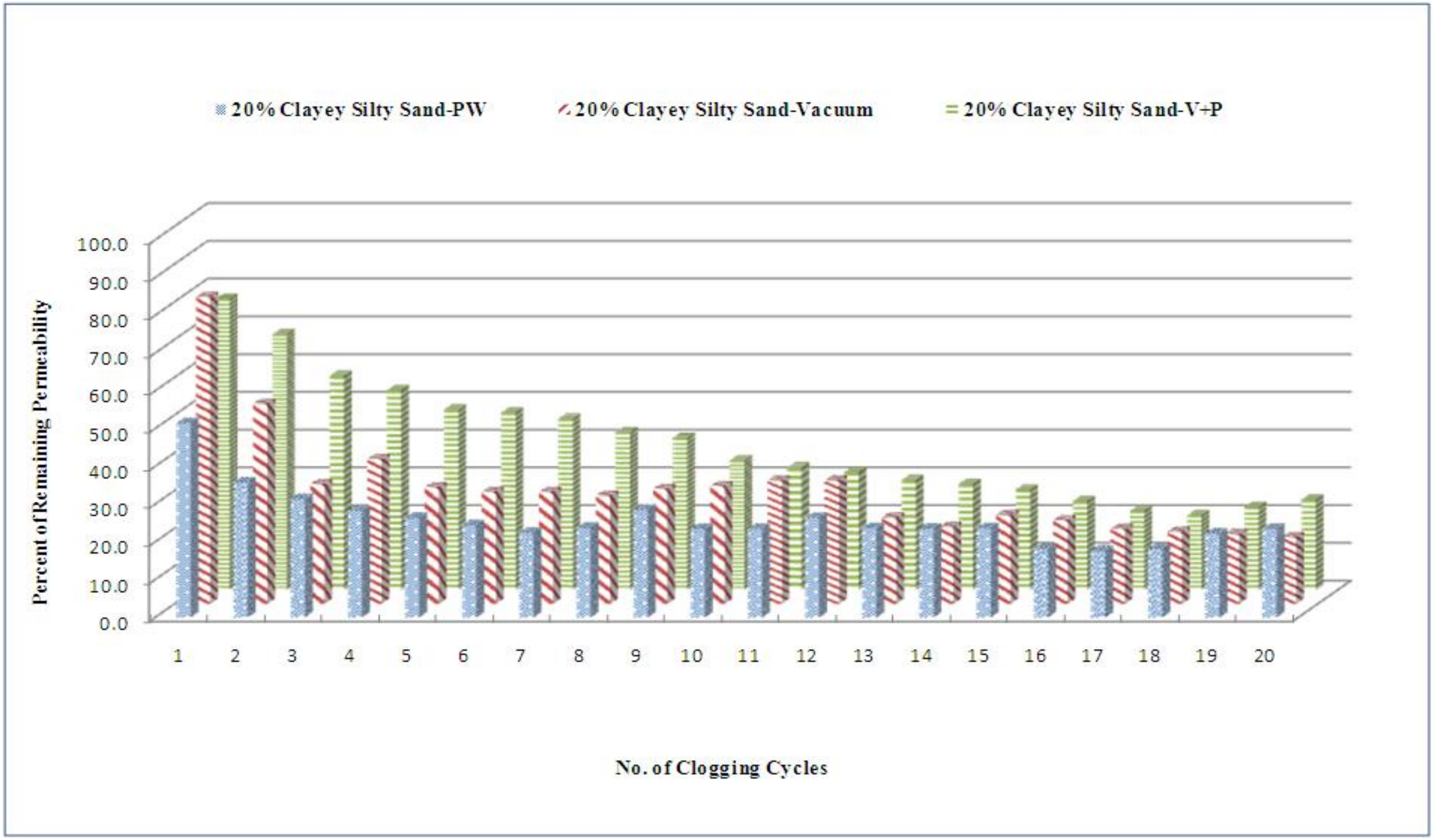


**Figure 4-27. Specimens with 20% Void Ratio Subjected to Clayey Silty Sand and Cleaned by Three Rehabilitation Methods**

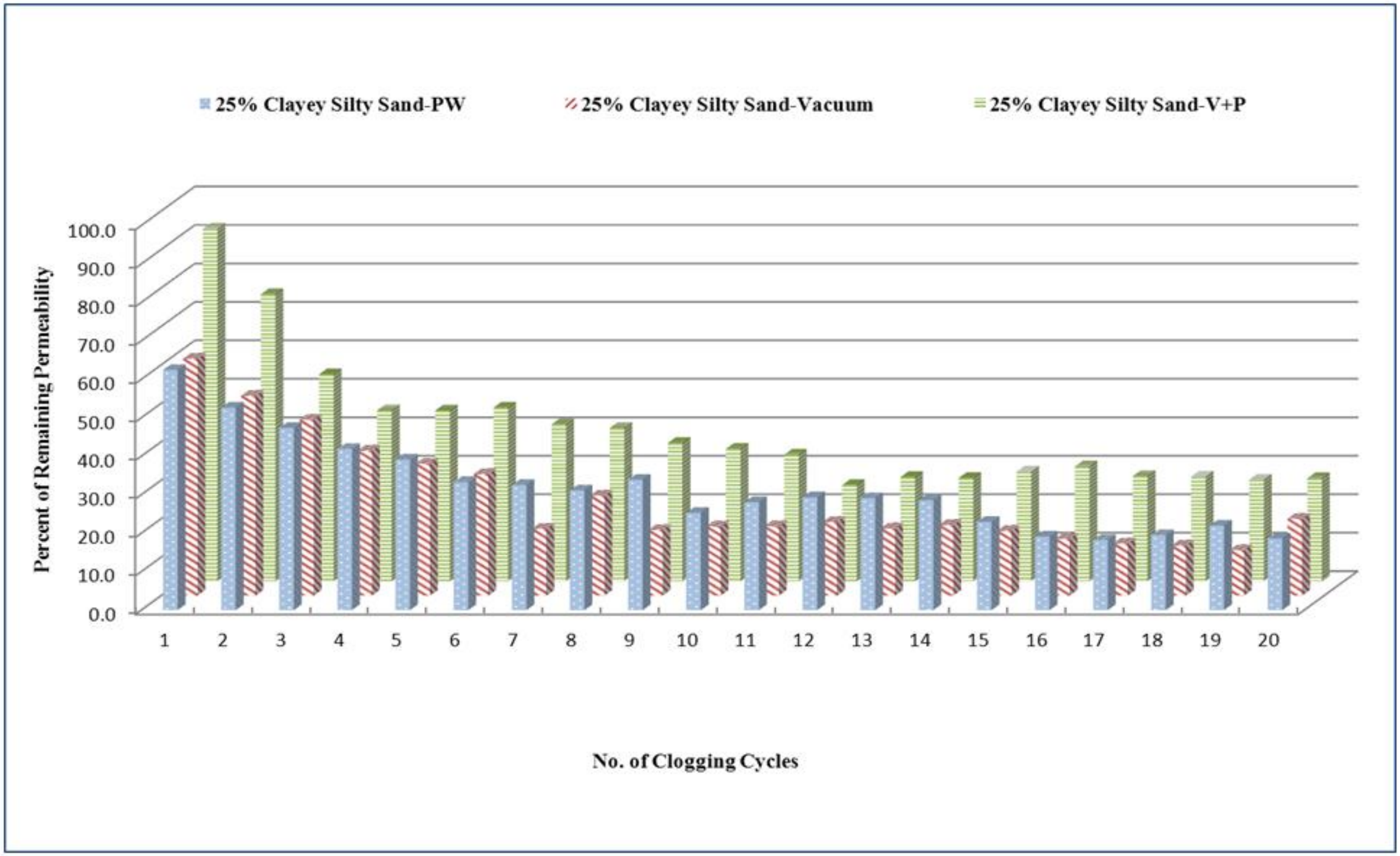


**Figure 4-28. Specimens with 25% Void Ratio Subjected to Clayey Silty Sand and Cleaned by Three Rehabilitation Methods**

## 4.4 Design Considerations and Maintenance Strategy for PCPC Pavement Subjected to Clogging Issues

The implications of the design considerations include several common situations for PCPC pavement overlying different subgrades, therefore, the various sedimentation conditions, were investigated in this section. Also, the preferred cleaning methods and procedures are discussed corresponding with each sedimentation condition. A detailed discussion about the design of PCPC pavement subjected to clogging conditions can be found in literature [28].

In general, four steps are involved in design procedure:

1) Conduct the conventional hydrologic analysis including the determination of Curve Numbers, surrounding area and localized soil characteristics;
2) Determination of the localized soil characteristics including soil type, gradation and composition; determine the initial exfiltration rate of subgrade layer;
3) Predict the total sediment load and the sediment load in mass per unit area of PCPC pavement based on 20 years of service life;
4) Conduct clogging test to determine the hydrologic behavior in terms of permeability change and the residual permeability;

Mata [28] provides the minimum on-situ permeability on the order of 200-800 cm/h (78.8-315 in.hr.), therefore, permeability lower than this rate during a clogging test may indicate the pervious concrete needs maintenance or initial design porosity may be adjusted to achieve the higher permeability rate. However, the specific value of in situ permeability of pervious pavement is normally determined based on local precipitation, surrounding area and pervious pavement site design.

Based on the testing results, design recommendations developed in this study are summarized as below based on different clogging conditions. This may provide a reference for in-situ pervious concrete construction. The composition, soil properties, and gradation of subgrade materials should be determined, and taken into the consideration of pavement design and maintenance. A comprehensive summary of residual permeabilities and cleaning efficiencies in different clogging conditions are shown in Table 4-16.

### 4.4.1. Sand

Depending on the subgrade materials' characteristics, when the localized subgrade soil and potential clogging material are mostly cohesionless, the hydraulic performance of PCPC layer may end up with different levels based on different initial porosities. The experimentally determined residual permeability can still reach more than 30 in/hr. for 15% of initial porosity, 200 in/hr. for 20% of initial porosity, and 570 in/hr. for 25% of initial porosity. These values were obtained without applying maintenance. Under this case, a high initial porosity of pervious pavements around 25% is preferred to achieve the higher residual permeability and cleaning efficiency if it is necessary.

### 4.4.2. Cohesive Materials

When the localized subgrade soil and potential clogging material are mostly cohesive, the clogging effect on hydraulic performance of PCPC layer is negligible and independent with the design initial porosity. An appropriate initial porosity may be selected to achieve the hydraulic performance based on local precipitation amount, stomwater runoff, site characteristics and surrounding areas. However, the accumulation of clay layer within the space between concrete layer and filter fabric may reduce the system permeability. Under this sedimentation case, based on the properties of cohesive material, the maintenance operation is preferred to be conducted in the wet condition, and pre-wetting is recommended prior to conducting maintenance. Pressure washing followed by vacuuming is preferred. Also, the opening size of filter fabric used in PCPC construction should at least No.200 sieve size (75μm) to allow the passing of fine particles.

### 4.4.3. Blended Materials

When the localized subgrade soil and potential clogging material are mostly blended material, the clogging effect on hydraulic performance of PCPC layer is the most significant. Greater permeability reductions were obtained in this case. Independent with the initial porosity, the residual permeability for all specimens is approximate 30 in/hr. without the application of maintenance. With the maintenance in this case, residual permeabilities are depended on the initial porosities of PCPC specimens. Overall, specimens containing 25% of initial porosity and cleaned by annual pressure washing followed by vacuuming show the highest residual permeability around 430 in/hr. Therefore, under this sedimentation case, the greater initial porosity and the combined pressure washing and vacuuming are preferred. Due to the large amount of cohesive materials, pre-wetting activity is recommended before conducting the maintenance.

## Table 4-16. Residual Permeabilities and Cleaning Efficiencies in Different Clogging Conditions

| Group | | No Maintenance | With Maintenance | | | | | | | | | Sediment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Porosity | | Pressure Washing | | | Vacuuming | | | PW+V | | | |
| | | Residual K | Initial K | Residual K | Efficiency | Initial K | Residual K | Efficiency | Initial K | Residual K | Efficiency | |
| | | (In/hr.) | (In/hr.) | (In/hr.) | (%) | (In/hr.) | (In/hr.) | (%) | (In/hr.) | (In/hr.) | (%) | |
| **1** | **15%** | 411 | 422 | 416 | 98 | - | - | - | - | - | - | **Cohesive** |
| **2** | **20%** | 600 | 1065 | 1046 | 99 | - | - | - | - | - | - | |
| **3** | **25%** | - | 1465 | 1454 | 98 | - | - | - | - | - | - | |
| **1** | **15%** | 119 | 405 | 54 | 4 | 593 | 87 | 2.4 | 458 | 121.5 | 11 | **Sand** |
| **2** | **20%** | 118 | 900 | 182 | 7.8 | 739 | 232 | 7.1 | 956 | 372 | 11.8 | |
| **3** | **25%** | 143 | 1407 | 588 | 9.4 | 1506 | 497 | 9.6 | 1428 | 449 | 25.2 | |
| **1** | **15%** | 35 | 600 | 70 | 9.4 | 455 | 48 | 11.8 | 614 | 80 | 14.2 | **Blended** |
| **2** | **20%** | 37 | 1041 | 232 | 9.8 | 655 | 174 | 10.27 | 1120 | 229 | 13.1 | |
| **3** | **25%** | 53 | 1277 | 285 | 15 | 1580 | 216 | 12.54 | 1359 | 364 | 20 | |

# Chapter 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Study Summary

Portland Cement Pervious Concrete (PCPC) is regarded as an “environmental friendly” construction pavement material. It has a few advantages over conventional pavement including reducing or eliminating stormwater runoff and treatment of pollutants, the low long term cost and better pavement surface condition during snow or rain storm. Great progress has been made in the past few years in developing the freeze-thaw durable pervious concrete pavement, increasing hydraulic and strength properties, and maintenance strategy.

However, there is a concern that the pores in the pervious concrete might clog due to long term deposition of fine focuses on the extreme events due to the catastrophic event(s) or flooding close to unpaved area. The objective of this research is to provide a quantitative evaluation of clogging effect of pervious concrete by considering three variables; characteristic of sedimentation materials, void ratios of pervious concrete and rehabilitation methods. A laboratory procedure was conducted to mimic a series of pervious clogging cycles with various clogging materials.

The testing matrix was divided into Case A and B. Case A simulates the more realistic clogging condition, which involving a small sedimentation load. Case B simulates the reasonable but worst scenario, which involving a large sedimentation loads. The definition of clogging cycle, as introduced in Section 3.4.3, was introduced to simulate the clogging and cleaning that occurs to PCPC pavement in reality. In Case A, each specimen was exposure up to 20 clogging repetitions without cleaning to predict the residual pavement performance as well as the permeability changing with simulated service time. In Case B, each specimen was exposure up to 20 clogging cycles to simulate the effective service life time. Three types of sediments, which are pure sand, clayey silt and clayey silty sand, are used to simulate the realistic clogging condition of PCPC pavement. Testing specimens at 15%, 20% and 25% of void ratios are used to determine the effect of pervious concrete properties on clogging. Three rehabilitation methods, which are pressure washing, vacuum sweeping and the combined of these two, are employed and applied on the testing specimens in Case B, and the cleaning efficiency of each method is compared.

Overall, testing results of Case A confirm fairly well with Case B. It is predicted that the fine materials (cohesive materials) usually cause the negligible effect on hydraulic performance of PCPC with void ratios from 15% to 25%. However, fine particles may be trapped within the space between the concrete pavement layer and filter fabric layer, and cause the reduction of pavement system permeability. The traditional cleaning method show limited cleaning efficiency in this condition. Therefore, the minimum opening size of filter fabric used in PCPC pavement is greater than No. 200 sieve size, which to allow the passing of fine grains particles and prevent the accumulation of fine grain layer from occurring with clogging.

Coarse materials (cohesiveless materials) normally cause the significant reduction on hydraulic performance of PCPC, but the design goals for hydrological purpose can be still maintained. The cleaning recovery and permeability reduction inversely related with designed void ratio of PCPC. The combined vacuuming and pressure washing show the best cleaning efficiency under this case.

The blended sediments normally lead to the most significant reduction on hydraulic performance of PCPC, and the residual permeability and permeability recoveries are fairly lowest compared to the case only using fine or coarse sediments alone. However, the higher initial porosity of PCPC pavement may “retard” the occurring of serious clogging as seen in Figure 4-7, and there is a risk of clogging failures occurring at the end of service time in this case. This clogging phenomenon can be explained by using “critical pore radius theory”.

However, as previously noted, the testing results in this study may not be able to be directly used to predict the actual permeability results in actual condition due to the high nonuniformity of density, void distribution, and permeability coefficients of in place PCPC pavement layer. The spread of surface water flow as well as the distribution of sediments on pervious pavement are also complicated to be mimicked in laboratory condition. The very high water level from 20 inches to 4 inches above the specimen top applied in clogging test may violate the realistic condition as well. The 20 inch of water pressure may increase the amount of clogging materials trapped in pervious concrete specimen, and overestimate the permeability reduction.  Further efforts on developing a more “simulated” clogging test should be spend to solve these problems.

## 5.2 Conclusions

### 5.2.1 Case A: Typical (Small) Sedimentation Test

Sedimentation tests in Case A indicate that:

1) Initial void ratios affect the residual permeability of pervious concrete under clayey silt and sand sedimentation. The specimens with higher void ratios (20% or above) could achieve the higher residual permeability than those with lower void ratios (15% or lower). However, under the sedimentation of clayey silty sand, the residual permeability is constantly low for all testing specimens.
2) Clayey silty sand as blended clogging materials cause the most significant permeability reduction, and more than 90% of the initial permeability was reduced at the end of clogging test. The specimens with different void ratios all reach a constant residual permeability coefficient about 20 in/hr.
3) For clay sediments, there is no significant permeability reduction for concrete itself as found in Section 4.2.1, but the simulation of deposited clay clayey between pavement and filter fabric is critical, and should be taken into design consideration in terms of the selection of filter fabric openings.
4) Clayey silty sand causes the rapidest permeability reduction, and easily deposit within the pervious concrete in a short period. Based on the simulated clogging test, the permeability coefficients of testing specimens decrease to 10% of the initial value in 3-5 years after construction. Cohesive clayey silt acts like cementing materials forms the bonding between concrete and sedimentation material particles in the pores.

5) The maintenance of pervious concrete may be established according to sedimentation material types and pervious concrete pavement property.

### 5.2.2 Case B: Worst (Large) Sedimentation Test

Sedimentation tests in Case B partially confirmed the findings obtained in Case A, and further concluded that:

1) Residual permeability and permeability recoveries by rehabilitation methods increase directly with the initial permeability and/or initial void ratio of pervious concrete.
2) As expected, clayey silty sand sediments segregated with larger size particles, that is, sand, trapped on or in the surface of pervious concrete and finer grained seize washing through the specimens. Also, partial fine grains adhered to sand particles surface within the specimens, and further reduce the permeability.
3) Pressure washing followed by vacuuming is confirmed as the best rehabilitation method. Pressure washing and vacuum sweeping typically result an equivalent increase in permeability, and the use of both methods of maintenance resulted in the greatest increase in filtration rates.

### 5.2.3 Clogging-Resistant PCPC Pavement Design Recommendation

Designing the clogging-resistant pervious concrete pavement is the ultimate objective by taking the clogging issue into the design consideration of PCPC pavement. This design includes the considerations on pervious pavement and construction site characteristics. The pervious pavement characteristics include mixtures, mixed materials properties, design porosity, initial infiltration rate; the local environment includes surrounding impermeable area, precipitation amount, surface water runoff, geological environment, subgrade soil characteristics. 25% of initial design porosity or higher is recommended for the pervious pavement located in areas where the localized soils are most cohesiveless or blended materials. The high initial infiltration rate is preferred. 15% of initial porosity is recommended where the localized soil are most cohesive materials. Also, it is recommended using the minimum opening size of filter fabric of 75 µm for pervious pavement constructions.

## 5.3 Recommendations

1. Additional studies are recommended to establish the mathematical relationship between the porosity and pore structures parameters including pore size, distribution, tortuosity and permeability.
2. Additional study of the relationships between void size distribution, porosity and sediment characteristics is recommended.
3. Based on the finding in Case A, additional studies are recommended to establish the proper maintenance schedule and confirm the current empirical-based maintenance regulation
4. Additional studies on the microstructure of pervious concrete are recommended. The better understanding of pore structure characteristics including total porosity, effective porosity, pore geometry and tortuosity is benefit for predicting the hydraulic and strength performance of pervious concrete.

5. Most of the previous clogging tests were conducted on cylindrical specimens, and the results based on this setup may be different from the actual condition. It is recommended to conduct the clogging test on casted PCPC slabs (See Figure 5-1), which is to better simulate the actual water runoff spread, flow distance and clogging materials distribution on pavement surface. More accurate evaluation of permeability reduction might be obtained by using ASTM C 1701 “Standard Test Method for Infiltration Rate in Place Pervious Concrete”

**Figure 5-1. Laboratory Clogging Testing by Using ASTM C 1701 Standard “Standard Test Method for Infiltration Rate in Place Pervious Concrete”**

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