Determining Pervious PCC Permeability with a Simple Triaxial Flexible-Wall Constant Head Permeameter

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Abstract

A simple triaxial flexible-wall constant head permeameter was constructed for determining the permeability of pervious PCC in the range of 1 to 14,000 inches/hour (0.001 to 10 cm/sec). Laboratory samples using three different gradations of crushed limestone and two different gradations of creek gravel were compacted at six different compactive efforts using a consistent pervious PCC mixture design. Cores from four field demonstrations were also obtained. The effective air void content and constant head permeability of both the field and laboratory pervious PCC mixtures were determined and compared, providing the following conclusions:

1. Effective void content of similar pervious PCC decreases with increasing compactive effort.
2. Constant head permeability of pervious PCC appears to be a function of three factors for a constant paste amount and character: effective air void content, effective void size, and drain down.
3. Average constant head permeability values of laboratory compacted specimens showed good agreement with two of three published values at low voids and fair agreement at high voids values.
4. Average constant head permeability of laboratory compacted and field cored specimens agreed reasonably well (within 50%) for similar effective void contents.

INTRODUCTION

Pervious concrete is a mixture of coarse aggregate, water, Portland cement, and possibly admixtures. Unlike traditional Portland cement concrete, pervious concrete contains little or no fine aggregate, and has been called “no-fines” concrete for many years. This lack of fine aggregate gives the pavement its open void structure and produces a permeable concrete. Typical amounts of coarse aggregate range from 2000 to 2500 lbs/CY (1,186 to 1,483 kg/m^3), (*Paine 1992, Georgia 1997*). Current specifications for pervious pavements in Georgia as well as preliminary specifications by the Tennessee Concrete Association (TCA) recommend an ASTM C33 No. 8 or No. 89 size aggregate gradation (*Paine 1992, TCA*) to provide a smoother riding surface. Portland cement is typically Type I or Type II with a cement content of 600 lbs/CY (396 kg/m^3)(*TCA*). The water-cement ratio varies according to factors such as aggregate size, desired void content, and temperature, and may range from 0.25 to 0.45. Current Georgia and Tennessee specifications do not define a standard water-cement ratio but rather prescribe a moisture condition that produces a metallic sheen in the paste without causing the paste to flow (*Georgia 1997, TCA*). The use of admixtures such as water reducers, set retarders, and air entrainers are allowed.

RESEARCH OBJECTIVE

TCA saw a need for improving the workability of pervious PCC. As a first step in the process a technique for determining constant head permeability was developed. Maintaining adequate permeability is essential for pervious PCC performance.

LITERATURE REVIEW

Permeability Background

Permeability is the ability of a porous media to allow the passage of a fluid. Work published by Darcy in 1856 provides the fundamental theory behind fluid flow in porous media. Traditional soil mechanics states Darcy’s Law in the following manner (*Head 1994*):

$$Q = A * k * i * t$$

where

Q = volume of fluid
A = cross-sectional area
k = coefficient of permeability
i = hydraulic gradient
t = time of measurement.

The hydraulic gradient is defined as the change in head, or head loss, on either side of a sample divided by the sample length, or

$$i = \frac{\Delta h}{L}$$

It therefore is a dimensionless number. The coefficient of permeability may be defined as the mean discharge velocity of flow under the action of a unit hydraulic gradient

(*Head 1994*). The coefficient of permeability will often be stated simply as permeability throughout this paper for convenience.

The term Q in the first equation may be ambiguous to some readers since it typically represents the flow rate, or discharge per unit time, of a fluid in hydraulics. However, in permeability calculations, the flow rate is denoted by q, and Darcy's Law may be restated as

$$q = A * k * i$$

The discharge velocity, sometimes known as the Darcy velocity, is not the actual velocity of water flowing within the void spaces of the sample column. Instead, it refers to the flow rate divided by the entire cross-sectional area of the sample. The discharge velocity can be determined from the following equation:

$$v = \frac{q}{A}$$

Substituting yields Darcy's Law in the simplest form:

$$v = k * i$$

Darcy's Law only holds for laminar flow of fluids with low velocities. The coefficient of permeability, k, is a constant of proportionality for porous media subjected to fluids with low velocities. For liquids at high velocities, Darcy's Law becomes invalid (*Scheidegger 1960*). The coefficient of permeability is not a constant for flows in the turbulent regime.

For fluid flow in circular conduits, the normal method for determining the flow regime is first to calculate the Reynolds number which is a dimensionless number calculated from the velocity of flow, inside diameter of pipe, and the kinematic viscosity as shown in the following equation:

$$\mathrm{Re} = \frac{V * D}{\nu}$$

The transition from laminar to turbulent flow occurs at a Reynolds number around 2100. For porous media, the Reynolds number is a function of grain size, Darcy velocity, and the kinematic viscosity as shown in the following equation:

$$\mathrm{Re} = \frac{v_{DARCY} * d_{10}}{\nu}$$

Laminar flow exists for Reynolds numbers less than 1.0, and for Re between 1.0 and 10, there is no serious departure from laminar flow (*Gupta 1995*).

Prior Pervious PCC Studies

A major difference in pervious concrete from normal Portland cement concrete is the amount of air voids in the hardened state. The air voids are interconnected which allow water to drain through the concrete to subsequent layers. Values for air voids in pervious concrete typically range from 15 to 35 percent (*NRMCA*). Meinenger reported that a minimum air void content of 15 percent is needed for water percolation (*Meininger*

1998). However, it should be noted that with a high water-cement ratio or too much compaction, even pavements with a void content above 15 percent may experience reduced water infiltration due to either drain down of the paste that clogs the lower levels of the concrete or clogging of the surface.

The applications of pervious pavement include parking lots, pedestrian and bicycle trails, and minor roads. The required strength of pervious pavements will therefore vary for the design purpose. Pervious pavements exposed to normal vehicular loads (less than 10,000 lbs (44.5 kN) gross vehicle weight (*Gnoffo & Reid 1997*)) are generally limited to areas of either low speed or infrequent use. Therefore, strength is a secondary property of the pavement. For parking lots, a design compressive strength of 2000-psi (13.8-MPa) is desired, and even lower strengths may be acceptable when the concrete will not receive vehicular loads such as pedestrian trails and sidewalks.

The permeability of pervious pavements is of utmost concern to design professionals seeking solutions for storm water runoff. Permeability increases as the amount of air voids increase. At void contents below 15 percent, the paste begins to isolate voids, and the pavement becomes impermeable. Current studies show coefficient of permeability values between 0 and 15590 in/hr (11 cm/sec) with void ranges between 13 and 35 percent (*Meininger 1998, Ghafoori & Dutta 1995*). Pervious concrete pavements have been in use for many years in southern states, especially Florida. The utilization of pervious pavement has grown in other states as awareness of the technology has spread. With increasing land development, the strain on urban watersheds continues to grow, and consequently, the need for new storm water control devices is paramount. Pervious concrete offers government agencies and developers another tool to handle the problem of water runoff in developing integrated storm water best management practices. The benefits of pervious pavements are two fold: first, the detention of storm water runoff to levels at or above predevelopment levels, and secondly, the removal of pollutants in the pavement surface and stone base before release into the ground water.

A laboratory study of no-fines concrete was conducted by Meininger and the results were published in 1998 (*Meininger 1998*). Permeability of the cylinders was measured using a falling head approach. The cylinders were covered with mastic and a cylinder mold was placed over the top half of the cylinders. After conditioning the specimens by running water through the samples and allowing it to reach a certain level above the concrete, the time required for the water level to fall 4 inches (102-mm) was measured. The percolation was reported in inches per minute. At air void contents around 15%, the permeability in the cylinders approached zero and at air void contents of 35%, a permeability value near 4960 in/hr (3.5 cm/sec) was reported.

The Florida Concrete and Products Association published a report entitled "Field Performance Investigation Portland Cement Pervious Pavement" in 1989 (*Wingerter & Paine 1989*). The report investigates five different placement procedures and the permeability of the pavements during use. This study did not report the air content of the pavements. Permeability tests of the pavements were conducted in a manner similar to that used by Meininger.

A study conducted by Ghafoori and Dutta published in 1995 included permeability testing of "no-fines" concrete (*Ghafoori & Dutta 1995*). The authors constructed a device similar to that of Meininger, but used a constant head approach for permeability determination on cylinders made in the laboratory. After establishing a head of 1 inch (25-mm), the volume of outflow in a certain amount of time was recorded. The results of this study show that permeability increases from 850 in/hr (0.6 cm/sec) at an air void content of 13% to 17008 in/hr (12.0 cm/sec) at an air void around 30%.

Zouaghi, et al. measured permeability using both a constant head and falling permeameter in Japan in 1998. Results of that study found permeability to range from around 5669 in/hr (4 cm/sec) at an air void content of 35% decreasing toward zero at a void content of 15% (*Zouaghi et al. 1998*).

LABORATORY MATERIALS

Limestone coarse aggregate was obtained locally in two gradations: "9.5-mm" and AASHTO No. 57 (*AASHTO, 2004*). The aggregates were sieved and recombined to produce a near mid-specification AASHTO No. 89 and No. 78. No attempt was made to alter the No. 57 to near mid-specification due to the shortage of 25-mm material. Local pea gravel was obtained, sieved, and recombined to obtain a No. 89 gradation identical to the near mid-specification No. 89 limestone. In order to reduce the amount of sieving required, a local river sand was obtained, sieved, and used to provide the finer portions, passing No. 4 sieve and retained on the No. 50 sieve, of all coarse aggregate gradations. Table 1 shows D_{10} (effective void size), fineness modulus (*ASTM, 2004*), and uniformity coefficient values for the selected aggregate gradations.

Table 1. Aggregate Properties

Property	No. 89 Limestone	No. 78 Limestone	No. 57 Limestone	As-received Gravel
D_{10} (mm)	1.6	3.3	6.5	3.3
Fineness Modulus	5.43	6.23	7.19	5.94
Uniformity Coefficient	3.94	2.98	2.62	2.24

Type 1 Portland cement from bulk storage was obtained from a local PCC producer. Local tap water was used for all laboratory mixtures.

LABORATORY SAMPLE PREPARATION PROCEDURE

The approximate mixture proportions used for all laboratory mixtures are shown in Table 2. Aggregates were substituted into the mixture on a volume basis to determine their effect on pervious PCC properties. All test batches were mixed in a 3 cubic foot (0.085 m^3) nominal capacity laboratory electric mixer. 1 cubic foot (0.028 m^3) batches were used. In each case, fifteen 4 by 8 inch (102 by 203-mm) cylinders were cast from each batch, five at three different compactive effort levels.

Compactive effort was achieved using a 10-lb (44.5 N) Marshall Hammer with a 18 inch (457-mm) drop and rodding in some cases.

Table 2. Pervious PCC Mixture Proportions

Component	Laboratory	Burgess Falls, TN	Greenville TN	Williamson Co.- C Ash	Williamson Co. - F Ash
Type 1 PC, lbs/CY (kg/m^3)	600 (396)	484 (287)	435 (258)	450 (267)	450 (267)
Class F Fly Ash, lbs/CY (kg/m^3)	0	0	100 (59)	0	110 (65)
Class C Fly Ash, lbs/CY (kg/m^3)	0	0	0	131 (78)	0
Aggregate SSD, lbs/CY (kg/m^3)	2338– 2578 (1386-1529)[a]	2681 (1591) Uniform 0.5-in (12.5-mm)	2382 (1413) ASTM No. 7	2338 (1387) No. 89	2338 (1387) No.7 or No. 8
Water, lbs/CY (kg/m^3)	180 (107)	147 (87)	175 (104)	177 (105)	177 (105)
Retarder, oz/cwt (liters/m^3)	0	3 (0.56)	0	0	0
Water Reducer, oz/cwt (liters/m^3)	0	0	22 (4.56) Mid range	5 (1.1) High range	5 (1.08) High range
Viscosity Modifier oz/cwt (liters/m^3)	0	10 (1.87)	0	2 (0.45)	2 (0.43)
Hydration Stabilizer oz/cwt (liters/m^3)	0	5 (0.94)	0	0	0

[a] – 15.56 ft^3/CY (0.58 m^3/m^3) of solid volume

The following compactive effort levels were chosen to attempt to encompass the entire range of field compactive efforts:

- 1 layer, no rodding, 2 Marshall Hammer blows (*AASHTO 1998*)
- 1 layer, no rodding, 5 Marshall Hammer blows
- 3 layers, rodded 25 times per layer, 3 Marshall Hammer blows per layer
- 3 layers, rodded 25 times per layer, 6 Marshall Hammer blows per layer
- 3 layers, rodded 25 times per layer, 14 Marshall Hammer blows per layer
- 3 layers, rodded 25 times per layer, 26 Marshall Hammer blows per layer

Since only 17 steel 4 by 8 inch (102 by 203-mm) molds were available, multiple batches were required for each mixture. On the day after casting, all cylinders were de-molded, labeled, and placed in a lime-water immersion at 73±3°F (22.9 ± 1.7°C). Two of the five cylinders cast for each mixture at each compactive effort level were used to determine the effective air void content. The remaining three cylinders were used for constant head permeability testing. Effective air void (voids which can be penetrated by water from the surface) determination was performed as per Crouch et al (*2003*) with the exception that the cylinders remained in the water bath 24 hours prior to determination of submerged weights. Since effective air void determination required oven drying at 212°F (100°C), the cylinders used for this procedure were not used for any other testing. Concrete block testing (*ASTM, 2001*) uses a similar procedure to determine volumetric properties on some units and assume they are representative of other units in the lot.

FIELD SAMPLES

Field samples were obtained by coring as per ASTM C 42 (*ASTM, 2004*) from the locations of TCA pervious concrete placements in Tennessee in 2005. Unlike laboratory samples, field samples were oven-dried at 125°F (51.7°C) to essentially constant mass for effective void content determination (*Crouch et al. 2003*). Drying the samples at a lower temperature allowed them to be used for subsequent testing without alteration of the sample properties. Available information on field mixture proportions is shown in Table 2.

PERMEABILITY APPARATUS AND PROCEDURE

Permeability testing was performed using a triaxial flexible wall constant head permeability apparatus developed specifically for the project. The apparatus and procedure are similar to ASTM D 5084 (*ASTM, 1993*). The chamber was constructed from an 11.75 inch (298.45 mm) diameter, 0.375 inch (10 mm) wall thickness PVC pipe and an acrylic insert for viewing the sample. The flexible hoses and fittings were 1 inch (25 mm) to allow for the increased flow rate. A sketch of the apparatus is shown in Figure 1.

Photographs and a detailed description of the apparatus can be found in Smith (*Smith 2004*). Flow was confined to the sample by placing a flexible latex membrane around the sample which was collapsed onto the cylinder by water pressure. The cell pressure was created from filling the outer chamber with water up to a constant height in the cell pressure reservoir. The cell pressure reservoir was maintained at least 12 inch (30-cm) above the inflow reservoir. The inflow reservoir was mounted on tracks which allowed for adjustment of the height, enabling the permeameter to test pervious samples with different effective void contents by changing the hydraulic gradient. As long as the inflow reservoir was below the cell pressure reservoir, the pressure in the sample was less than the pressure in the chamber which kept the membrane collapsed.

Permeability tests were typically conducted about 21 days after casting on laboratory specimens taken directly from the curing tank. After permeability testing, the specimens were returned to the lime-water curing tank until 28 days after casting for compressive strength testing. Timing of the testing of field specimens varied and was based on availability.

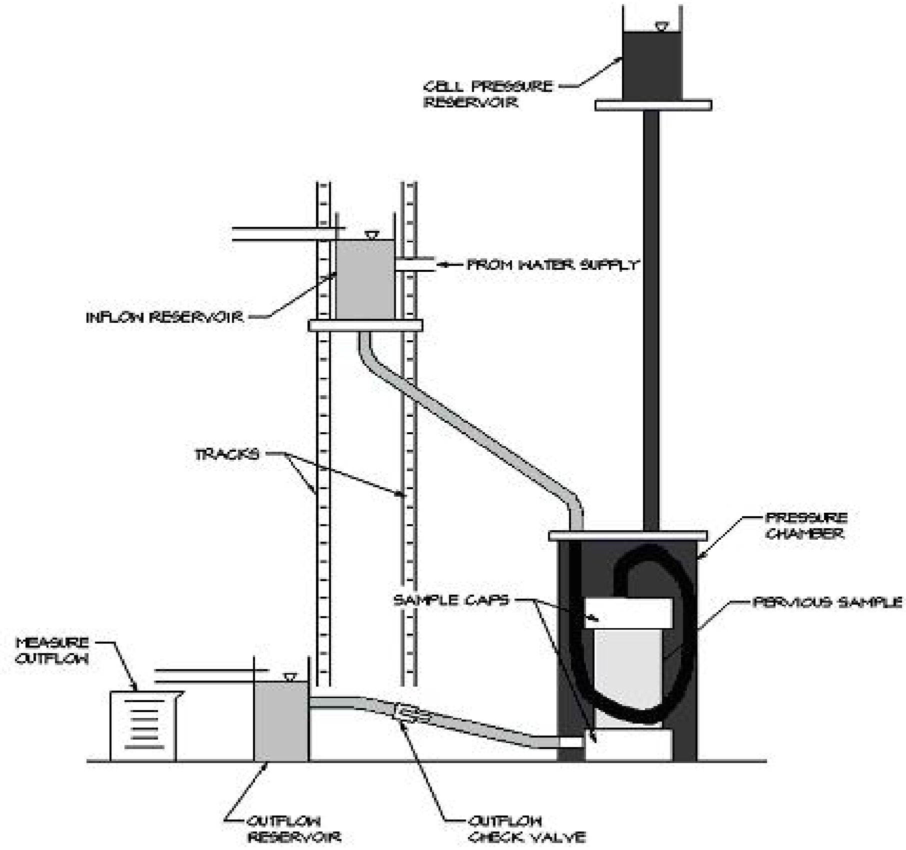

Figure 1. Sketch of Simple Constant Head Triaxial Flexible-wall Permeameter

Permeability samples were kept immersed following effective void determination until the time of testing. The following is a summary of the procedure. A detailed account of the procedure can be found in Smith (*2004*). In summary, a sample was installed in the apparatus in a flexible latex membrane. The membrane was collapsed with cell pressure and the sample was vacuum saturated. The differential head was established and three flow tests were conducted. Outflow temperature was measured for each flow test. Afterwards, the sample was removed from the apparatus and measured.

Permeability was calculated using the following equation.

$$Q = A * k * i * t$$

Since the permeability assembly is enclosed within the pressure chamber, the hydraulic head at the beginning and end of the sample cannot directly be obtained. Instead, the hydraulic gradient must be corrected for head losses in the system, and is calculated using the following equation

$$i = \left(\frac{\Delta h - h_L}{L} \right)$$

where h_L is the head loss in the system.

To calculate the head loss in the system, an 8 inch (203 mm) long dummy sample of 4 inch (100 mm) diameter PVC pipe was employed using the same procedure as was used for the pervious concrete cylinders. The head loss in the PVC dummy sample was assumed to be negligible. A detailed account of the procedure for correcting for system head loss and dynamic viscosity can be found in Smith (*2004*). Smith *(2004)* also shows that Darcy's Law remained valid for permeability calculations.

RESULTS

Laboratory results for permeability and effective void content are shown in Table 3 and Figure 2. Field demonstration core results for permeability and effective void content are shown in Table 4 and Figure 3. Due to paper length constraints, compressive strength results will be discussed in a companion paper.

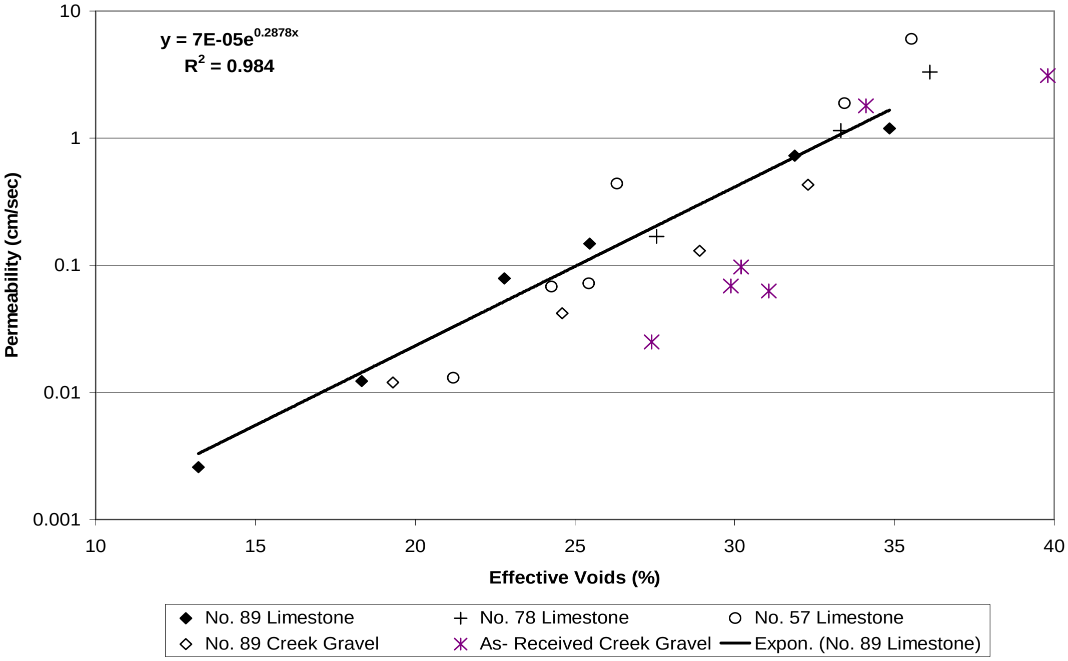

Figure 2. Permeability vs. Effective Void Content for Lab Compacted Samples

ANALYSIS OF RESULTS

Constant head permeability of pervious PCC appears to be a function of three factors for a constant paste amount and character:

- Effective air void content
- Effective void size
- Drain down

Table 3. Laboratory Results for Each Aggregate and Compactive Effort

Compactive Effort (blows/cylinder)	No. 89 Limestone	No. 78 Limestone	No. 57 Limestone	No. 89 Creek Gravel	As-received Creek Gravel
Effective Voids (%)					
2	34.8	36.1	35.5	32.3	39.8
5	31.9	33.3	33.4	28.9	34.1
9	25.5	27.6	26.3	24.6	30.2
18	22.8	24.3	25.4	19.3	31.1
42	18.3	20.2	24.3	13.8	29.9
78	13.2	18.1	21.2	11.3	27.4
Permeability in/hr (cm/sec)					
2	1700 (1.20)	4706 (3.32)	8546 (6.03)	609 (0.43)	4394 (3.10)
5	1035 (0.73)	1630 (1.15)	2665 (1.88)	184 (0.13)	2551 (1.80)
9	213 (0.15)	241 (0.17)	624 (0.44)	57 (0.04)	14 (0.01)
18	113 (0.08)	0[a]	99 (0.07)[b]	14 (0.01)	85 (0.06)
42	14 (0.01)	0[a]	99 (0.07)[b]	0	99 (0.07)
78	4 (0.003)	0[a]	14 (0.01)[b]	0	43 (0.03)

[a] - drain down clogged samples

[b] - ends cut to reduce drain down effect

Table 4. Field Average Effective Voids and Permeability for 2005 TCA Demo Placements

Location	Number of Core Samples V/ P	Average Effective Voids (%)	Average Permeability in/hr (cm/sec)
Greenville	10/10	27.8	652 (0.46)
Williamson County C Ash	10/9	25.2	198 (0.14)
Williamson County F Ash	10/10	24.4	99 (0.07)
Burgess Falls	10/10	27.3	425 (0.30)

Referring to Table 3 and Figure 2, constant head permeability usually increased with increased effective air void content for laboratory samples. Number 57 limestone and as-received creek gravel provide a few exceptions to the trend. Correlation coefficients for the relationship between constant head permeability and effective air void content (see Table 5) ranged from 0.8657 to 0.9988 for laboratory samples, indicating strong to excellent relationships, respectively.

Figure 4 shows that permeability for laboratory limestone aggregate pervious PCC at compactive efforts of 2, 5, and 9 blows per cylinders increased with increased aggregate effective void size (D_{10}). The effect was most pronounced at the lowest level of compactive effort and diminished as compactive effort increased. Data for No. 78 limestone was not available at compactive efforts greater than 9 blows per cylinder. Referring to Tables 1 and 3, in four of the six cases the permeability of the as-received creek gravel, which had effective void size approximately twice that of the No. 89 creek gravel, was six times greater than that of the No. 89 creek gravel.

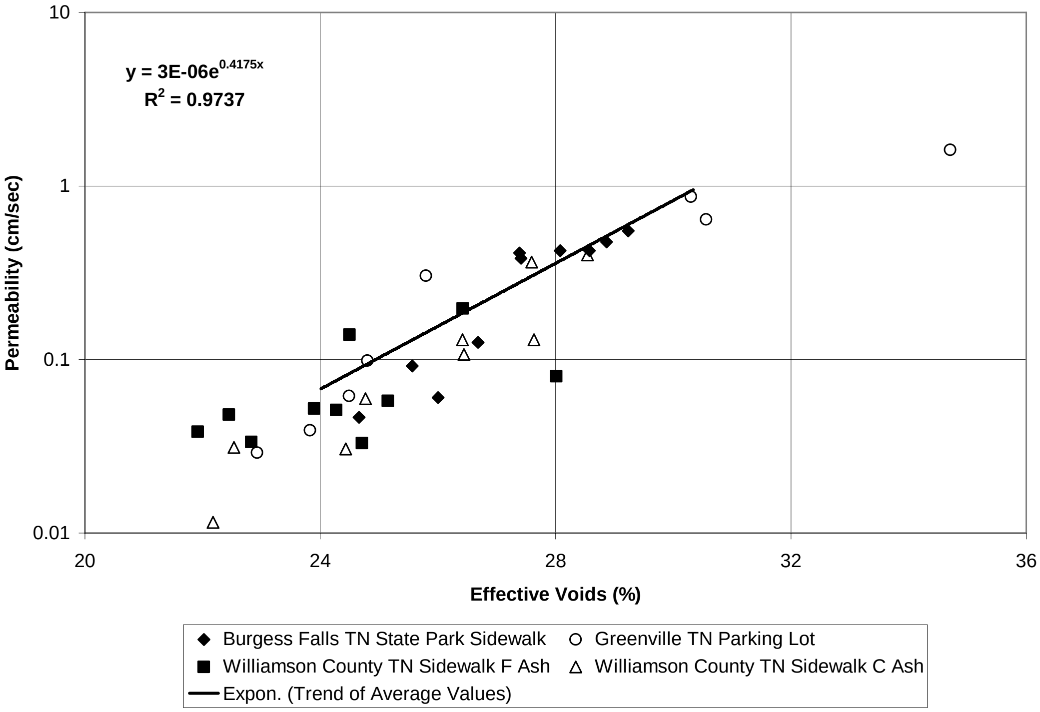

Figure 3. Permeability vs. Effective Void Content for Cores from 2005 TCA Field Demonstrations

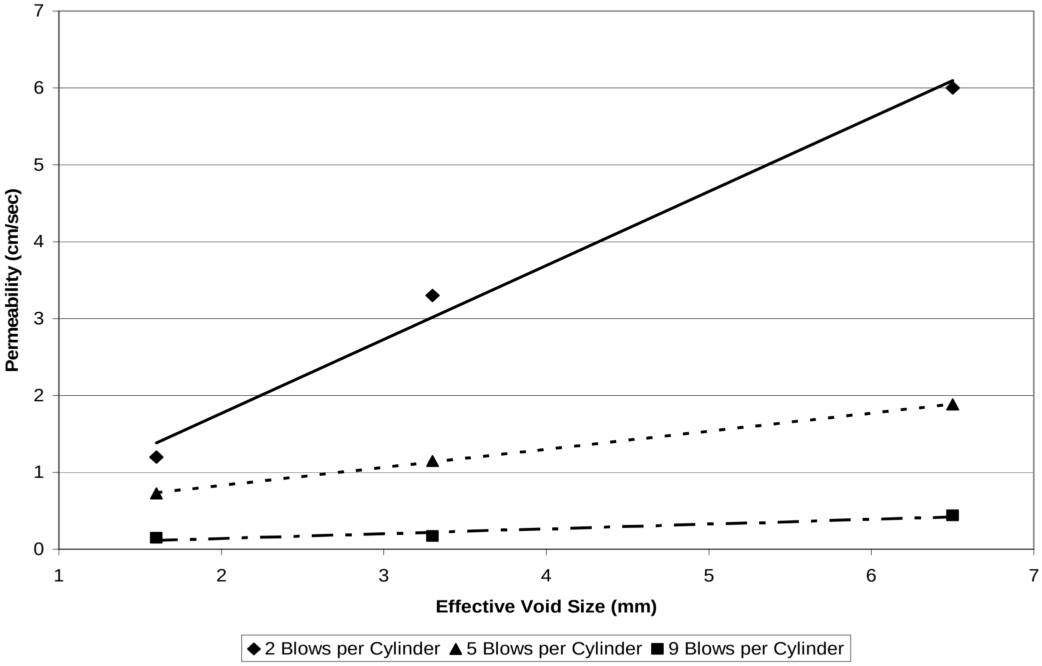

Figure 4. The Effect of Void Size on the Permeability of Lightly Compacted Laboratory Limestone Aggregate Pervious PCC

Table 5. Correlation Coefficients

Aggregate or Field Location	Number of Points for Permeability	Permeability vs. Effective Voids
Laboratory Compacted Samples		
No. 89 Limestone	6	0.9840
No. 78 Limestone	3	0.9988
No. 57 Limestone	6	0.9411
No. 89 Creek Gravel	4	0.9922
As-Received Creek Gravel	6	0.8657
Field Demonstration Cores		
Greenville	8	0.8951
Williamson County C Ash	9	0.8965
Williamson County F Ash	10	0.3533
Burgess Falls - High Compaction	10	0.8745
Trend of Field Average Values for each Location	4	0.9737

Drain down is a result of too much paste for the applied compactive effort or the paste being too fluid. Drain down can seal the lower surface of pervious PCC and render it virtually impermeable. The possibility of drain down increased with increased fineness modulus due to decreased aggregate surface area. The possibility of drain down also increases with increased compactive effort due lower effective void content. Referring to Table 4 and Figure 3, constant head permeability generally increased with increased effective air void content for field samples. However, all field demo locations exhibited exceptions to the trend. Correlation coefficients for the relationship between constant head permeability and effective air void content (see Table 5) ranged from 0.3533 to 0.8965 for field demonstrations, indicating non-existent to strong relationships, respectively. When the permeability values for each demonstration location were averaged and the trend of averages was plotted versus effective void content, the correlation coefficient was 0.9737.

Linear interpolations of laboratory No. 89 limestone pervious PCC mixture results yielded permeability values of 468, 198, and 170 in/hr (0.33, 0.14, and 0.12 cm/sec) for effective void contents of 27.5, 25.5, and 24.4 percent. Field demonstration core permeability values averaged 652, 425, 198, and 99 in/hr (0.46, 0.3, 0.14, and 0.07 cm/sec) at average effective void contents of 27.8, 27.3, 25.2, and 24.4 percent, respectively. Although the amount of data is very limited, a maximum difference of 227 in/hr (0.16 cm/sec) (approximately 50%) seemed to be reasonable agreement.

Table 6 shows comparisons between linear interpolations from laboratory measured permeabilities and values provided in the literature at fifteen and thirty percent air void contents. Agreement of laboratory data with Meininger (*1998*) and Zouaghi, et al (*1998*) was good at fifteen percent voids and fair at thirty percent air voids. However, agreement with Ghafoori and Dutta (*1995*) was poor at both air void contents. Insufficient data was available to determine if field core permeability results agreed with literature values.

Table 6. Interpolations from Measured Permeability Values Compared to Values from the Literature.

Source	Permeability at Two Air Void Contents (cm/sec)	
	15% Voids	30% Voids
Lab No. 89 Limestone	≈ 7 (0.005)	≈ 666 (0.47)
Lab No. 78 Limestone	0	≈ 822 (0.58)
Lab No. 57 Limestone	Not Available	≈ 369 (0.26)
Lab No. 89 Creek Gravel	< 14 (0.01)	≈ 326 (0.23)
As-Received Creek Gravel	Not Available	≈ 14 (0.01)
Meininger (*8*)	≈ 0	≈ 2551 (1.8)
Ghafoori & Dutta (*10*)	1290 (0.91)	17009 (12)
Zouaghi, et al (*12*)	≈ 0	≈ 2976 (2.1)

CONCLUSIONS

Based on the limited data available, the following preliminary conclusions can be drawn.

1. A new simple constant head triaxial flexible wall permeameter was developed with the capability to measure permeabilities in the range of 0.001 to 10 cm/sec for both field cores and laboratory compacted samples.
2. Effective void content of similar pervious PCC decreases with increasing compactive effort.
3. Constant head permeability of pervious PCC appears to be a function of three factors for a constant paste amount and character: effective air void content, effective void size, and drain down.
4. Average permeability values of laboratory compacted specimens showed good agreement with two of three published values at low voids and fair agreement at high voids values.
5. Average permeability of laboratory compacted and field cored specimens agreed reasonably well (within 50%) for similar effective void contents.

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