EFFECTS OF AGGREGATE TYPE AND GRADATION ON PERVIOUS PCC

L. K. CROUCH
Ph.D., P.E., Professor of Civil Engineering Tennessee Technological University
Cookeville, Tennessee, USA

NATHAN SMITH
P.E., L.I. Smith & Associates
Paris, Tennessee, USA

ADAM C. WALKER
E.I., Civil Engineer, U.S. Army Corps of Engineers
Nashville, Tennessee, USA

HEATHER J. BROWN
Ph.D., E.I., Assistant Professor Concrete Industry Management Middle Tennessee State University
Murfreesboro, Tennessee, USA

TIMOTHY R. DUNN
Research Technician 1, Center for Electric Power Tennessee Technological University
Cookeville, Tennessee, USA

ALAN SPARKMAN
Executive Director, Tennessee Concrete Association
Nashville, Tennessee, USA

ABSTRACT

Three different gradations of crushed limestone and two different gradations of gravel were substituted on an equal volume basis into a consistent pervious PCC mixture design. The effective air void content, compressive strength, and constant head permeability, of the resulting pervious PCC mixtures were determined and compared. Effective air void content of pervious PCC appears to be a function of three factors for a constant paste amount and character: compactive effort, gradation uniformity coefficient, and aggregate particle shape / surface texture. Twenty eight day compressive strength of pervious PCC appears to be a function of two factors for a constant paste amount and character: effective air void content and gradation fineness modulus. 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.

Keywords: pervious concrete; effective air voids; compressive strength; constant head permeability; coarse aggregate; gradation; particle shape and texture; compactive effort

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INTRODUCTION AND LITERATURE REVIEW

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 lighter than normal concrete. The main constituent in pervious concrete is the coarse aggregate. Typical amounts of coarse aggregate range from 2,000 to 2,500 lb/cy (0,2). The size of aggregate used in pervious applications has been shown to vary, but the most widely accepted size is a nominal maximum of 3/8-inch (0). One reason for this smaller size aggregate is to provide a smoother riding surface (3). 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 (2,4).

Water and Portland cement combine to make the paste in pervious concrete. Portland cement is typically Type I or Type II with a minimum cement content of 600 lbs/cy (4). 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 (2,4). The use of admixtures such as water reducers, set retardanters, and air entrainment are allowed.

The 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 (5). Meinenger reported that a minimum air void content of 15 percent is needed for water percolation (6). 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. Furthermore, studies at Tennessee Technological University of air void content in field samples have shown that pervious pavements may often times exceed the values prescribed to be necessary for compressive strength (15 – 25 percent) with occasional measurements above 35 percent (3).

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 (fewer than 10,000 pounds gross vehicle weight (7)) are generally limited to areas of either low speed or infrequent use. Therefore, strength is a secondary property of the pavement behind its air void content, and normal compressive strengths above 3,000 psi, while attainable, are generally not required. For parking lots, a design compressive strength of 2,000 psi is desired, and even lower strengths may be acceptable when the concrete will not receive vehicular loads such as pedestrian trails and sidewalks.

Permeability is the ability of a porous media to allow the passage of a fluid (8). The permeability of pervious pavements is of utmost concern to design professionals seeking solutions for storm water runoff. As stated earlier, 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 11 cm/sec with void ranges between 13 and 35 percent (6,9).

RESEARCH OBJECTIVE

The Tennessee Concrete Association (TCA) saw a need for improving the workability of pervious PCC. As a first step in the process, the influence of aggregate properties on pervious PCC effective air void content, compressive strength, and constant head permeability were determined. Understanding the influence of aggregate properties would allow the research team to make proper adjustments to TCA pervious PCC mixtures needed to improve workability and compressive strength while maintaining adequate permeability.

MATERIALS

Limestone coarse aggregate was obtained locally in two gradations: “3/8-inch” and AASHTO No. 57 (10). 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 1-inch 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. Aggregate gradations are shown in Figure 1. Table 1 shows D_{10} (effective void size), fineness modulus (11), and uniformity coefficient values for the selected aggregate gradations. Table 2 shows specific gravities and absorptions (12, 13) for the aggregates. AASHTO T304 Method B Voids (14) which gave an indication of particle shape and texture are shown in Table 3. Type 1 Portland cement from bulk storage was obtained from a local PCC producer. Local tap water was used for all mixtures.

PROCEDURE

The approximate mixture proportions used for all mixtures are shown in Table 4. 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 three-cubic-foot nominal capacity laboratory electric mixer. One cubic foot batches were used. In each case, fifteen 4 by 8-inch cylinders were cast from each batch, five at three different compactive effort levels. Compactive effort was achieved using a 10-lb Marshall Hammer with an 18-inch drop and rodding in some cases. 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 (15) blows
- 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 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. 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 compressive strength and constant head permeability testing. Effective air void determination was performed as per Crouch et al (3) 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, the cylinders used for this procedure were not used for any other testing. Concrete block testing (16) uses a similar procedure to determine volumetric properties on some units and assume they are representative of other units in the lot.

Permeability testing was performed using a triaxial flexible wall constant head permeability apparatus developed specifically for the project. A complete description of the apparatus is beyond the scope of this paper and a technical article is planned in the near future. Permeability tests were typically conducted about 21 days after casting on 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. Compressive strength was determined as per ASTM C 39 (17) using ASTM C 617 (18) sulfur mortar capping at 28 days.

RESULTS

Figure 2 shows the results of the effective air voids determination. Figures 3 and 4 show compressive strength results. Table 5 shows the results of constant head permeability testing.

ANALYSIS OF RESULTS

Effective Air Void Content

Effective air void content of pervious PCC appears to be a function of three factors for a constant paste amount and character:

- Compactive effort
- Uniformity coefficient
- Aggregate particle shape and surface texture

Referring to Figure 2, effective air void content decreases with increased compactive effort for all aggregates used in the study. Correlation coefficients for the relationship between effective air voids and compactive effort ranged from 0.8295 to 0.9889, indicating strong to excellent relationships, respectively. Effective air void content for all aggregate types and gradations increased at compactive efforts greater than 9 blows per cylinder as the uniformity coefficient of aggregate gradation decreased. The effect was more pronounced as compactive effort increased. For compactive efforts of 9 blows per cylinder or less, the effect of uniformity coefficient on effective air void content was small. For aggregates with the same gradation, lower AASHTO T 304 Method B Uncompacted Void Contents (a measure of particle shape and texture) resulted in lower effective air void contents for all compactive efforts. The effect became more pronounced with increasing compactive effort. It is not surprising that rounder, smoother aggregates are easier to force into a denser configuration than more angular, rougher aggregates.

Compressive Strength

Twenty eight day compressive strength of pervious PCC appears to be a function of two factors for a constant paste amount and character:

- Effective air void content
- Gradation fineness modulus

Referring to Figures 3 and 4, compressive strength decreased with increased effective air void content for all aggregates used in the study except as-received gravel. Three points near thirty percent effective air voids for the as-received gravel gradation are the only exception to the trend. Correlation coefficients for the relationship between compressive strength and effective air void content ranged from 0.8661 to 0.987, indicating strong to excellent relationships, respectively.

Compressive strength for limestone aggregates at all compactive efforts increased with decreasing fineness modulus. Figure 5 shows correlation coefficients for the relationship between compressive strength and fineness modulus ranged from 0.8213 to 0.9989, indicating strong to excellent relationships, respectively. The effect was more pronounced as compactive effort increased. The effect may be due to increased aggregate contact points in finer gradations resulting in increased compressive strengths. The effect of fineness modulus on compressive strength of gravel gradations was not clear. Only two different gravel gradations were used in the study with a total fineness modulus range less than 0.6.

Tennis, Leming, and Akers (19) indicate that the use of rounded aggregates in pervious PCC typically results in higher compressive strengths. Figure 6 supports that assertion. For similar pervious PCC mixtures (same paste amount and character and same aggregate volume and gradation), Figure 6 shows that the compressive strength of pervious PCC with rounded aggregates is greater than that for angular aggregates at all compactive efforts. Initially, this seemed counterintuitive, rougher more angular aggregates would seem to enhance the paste-aggregate bond. However, Figure 7 shows a plot of compressive strength versus effective air void content, indicating no appreciable compressive strength difference. These two seemingly conflicting views can be resolved by considering the true effect of round, smooth aggregates – lowering the effective air void content at the same compactive effort when compared to angular, rough aggregates. Thus, rounded, smoother aggregates increase compressive strength at a particular compactive effort by decreasing effective air void content of the mixture, not by improving paste-aggregate bond strength.

Permeability

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

Referring to Table 5 and Figure 8, constant head permeability usually increased with increased effective air void content. Number 57 limestone and as-received gravel provide a few exceptions to the trend. Correlation coefficients for the relationship between constant head permeability and effective air void content ranged from 0.8657 to 0.9988, indicating strong to excellent relationships, respectively.

Figure 9 shows that permeability for 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. Figure 10 shows the effect of effective void size and compactive efforts on the permeability of gravel aggregate pervious PCC. In four of the six cases the permeability of the as-received gravel, which had effective void size approximately twice that of the No. 89 gravel, was six times greater than that of the No. 89 gravel.

Drain down is a result of too much paste 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 and increased compactive effort.

CONCLUSIONS

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

1. Effective air void content of pervious PCC appears to be a function of three factors for a constant paste amount and character: compactive effort, gradation uniformity coefficient, and aggregate particle shape / surface texture.
2. Twenty eight day compressive strength of pervious PCC appears to be a function of two factors for a constant paste amount and character: effective air void content and gradation fineness modulus.
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.

EPILOG

The lessons enumerated in this article were subsequently used to develop two new pervious PCC mixture designs for TCA.

1. TCA low compactive effort mixture containing round, smooth No. 89 aggregate, chemical admixtures, and supplementary cementing materials for improved workability and ease of compaction.
2. TCA high compactive effort mixture containing angular, rough crushed stone in a very uniform gradation, chemical admixtures, and a lower cementing materials content to increase resistance to compaction and maintain permeability.

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Disclaimer

The opinions, findings, and conclusions expressed here are those of the authors and not necessarily those of the Tennessee Concrete Association.

The opinions and assertions contained herein are the private ones of the authors and are not to be construed as reflecting the official views of the Department of Defense or the United States Army Corps of Engineers.

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Table 1. Aggregate Properties

Property	No. 89 Limestone	No. 78 Limestone	No. 57 Limestone	Local Pea 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

Table 2. Aggregate Specific Gravities and Absorptions

Aggregate	BSG_{OD}	BSG_{SSD}	ASG	Absorption (%)
No. 89 Limestone	2.631	2.664	2.720	1.243
No. 78 Limestone	2.624	2.658	2.717	1.302
No. 57 Limestone	2.627	2.660	2.716	1.240
Local Pea Gravel	2.281	2.408	2.613	5.581
River Sand*	2.583	2.607	2.646	0.927

* - used to provide the finer parts of some gradations (Nos. 8, 16, 50)

Table 3. AASHTO T 304 Method B Uncompacted Voids

Size	Local Limestone	Local Pea Gravel	River Sand
12.5-mm (0.5-inch)	48.53		
9.5-mm (0.375-inch)	49.17	45.32	
6.35-mm (0.25-inch)	50.01	44.56	
4.75-mm (No. 4)	50.78	43.46	
2.36-mm (No. 8)	50.96	44.03	40.84
1.18-mm (No. 16)			42.32

Table 4. Pervious PCC Mixture Proportions

Component	Proportions
Type 1 Portland Cement	600 lbs/CY
Aggregate (SSD)	2337-2578 lbs/CY (15.6 cubic feet solid volume)
Water	180 lbs/CY
Water / cement ratio	0.3

Table 5. Permeability (cm/sec) for Each Mixture and Compactive Effort

Compactive Effort (blows/cylinder)	No. 89 Limestone	No. 78 Limestone	No. 57 Limestone	No. 89 Gravel	As-received Gravel
2	1.2	3.32	6.03	0.43	3.1
5	0.73	1.15	1.88	0.13	1.8
9	0.15	0.17	0.44	0.04	0.01
18	0.08	0*	0.07**	0.01	0.06
42	0.01	0*	0.07**	0	0.07
78	0.003	0*	0.01**	0	0.03

* - drain down clogged samples

** - ends cut to reduce drain down effect

Figure 1. Particle Size Distribution

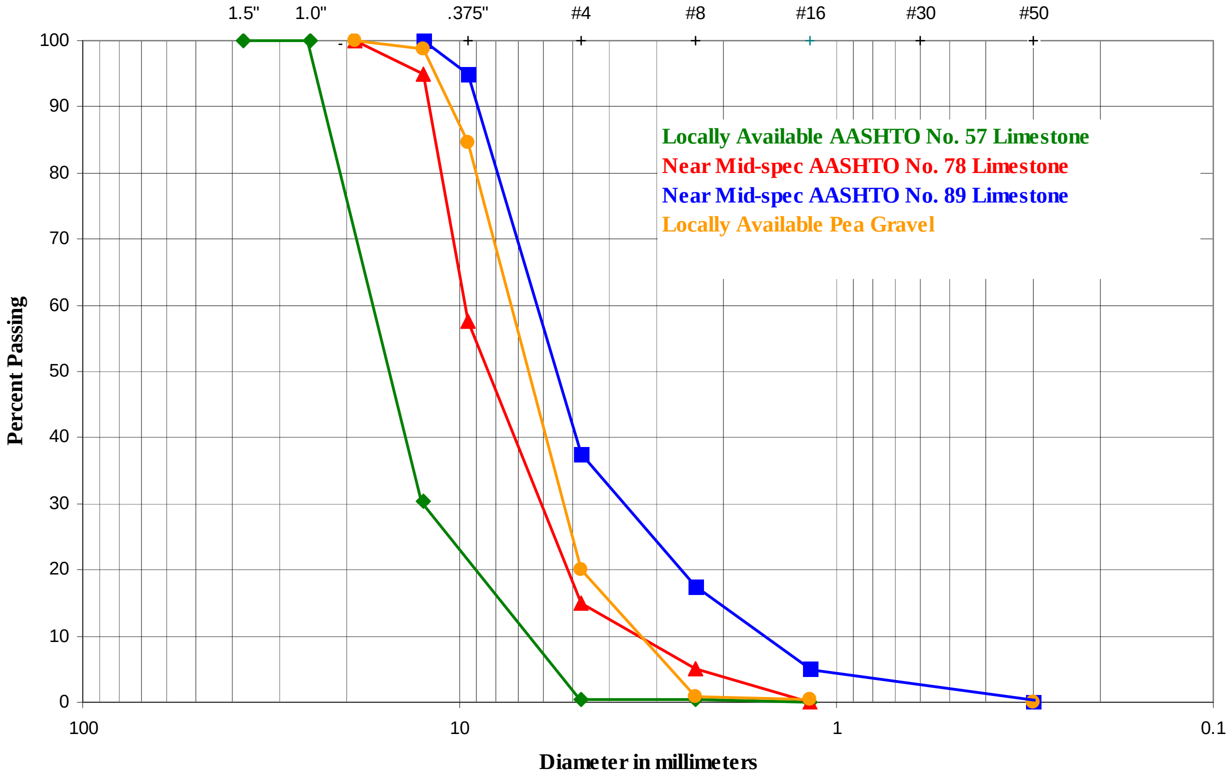

Figure 2. The Effect of Aggregate Gradation, Type and Compactive Effort on Pervious PCC Effective Air Voids

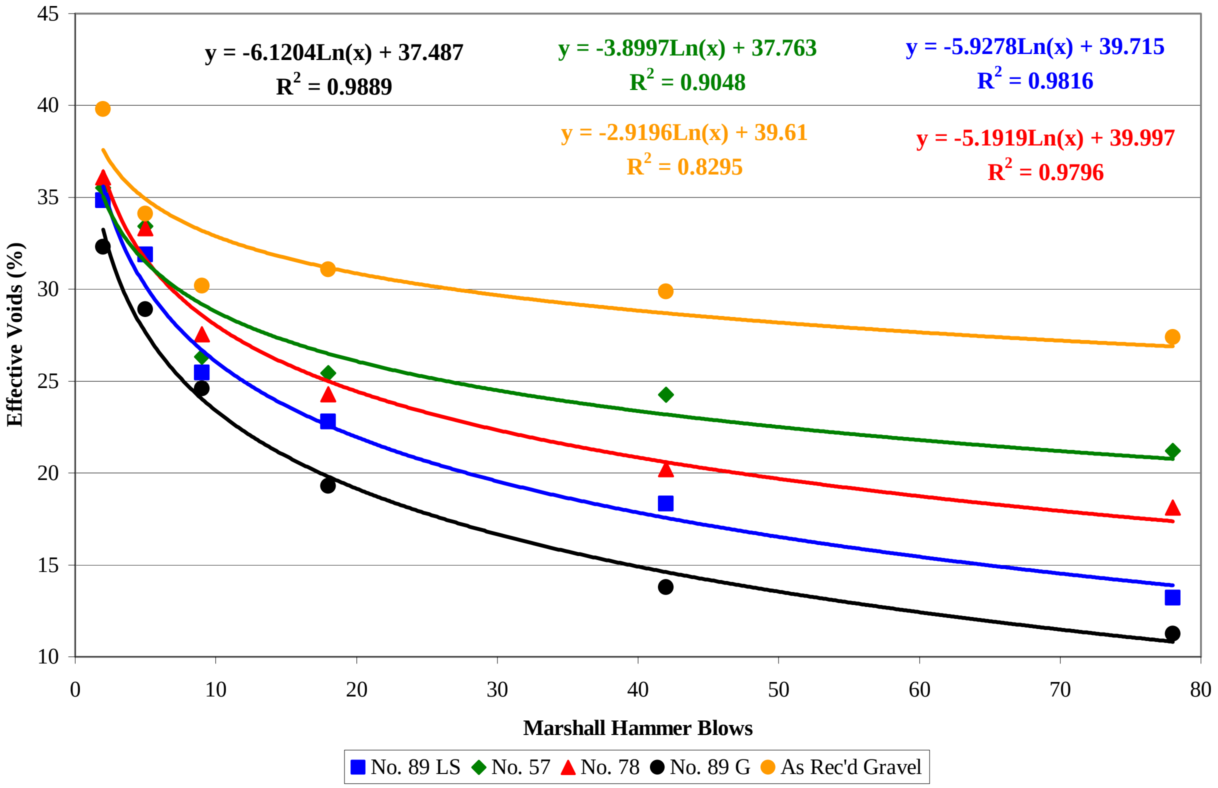

Figure 3. The Effect of Limestone Gradation and Compactive Effort on Effective Air Void Content of Pervious PCC

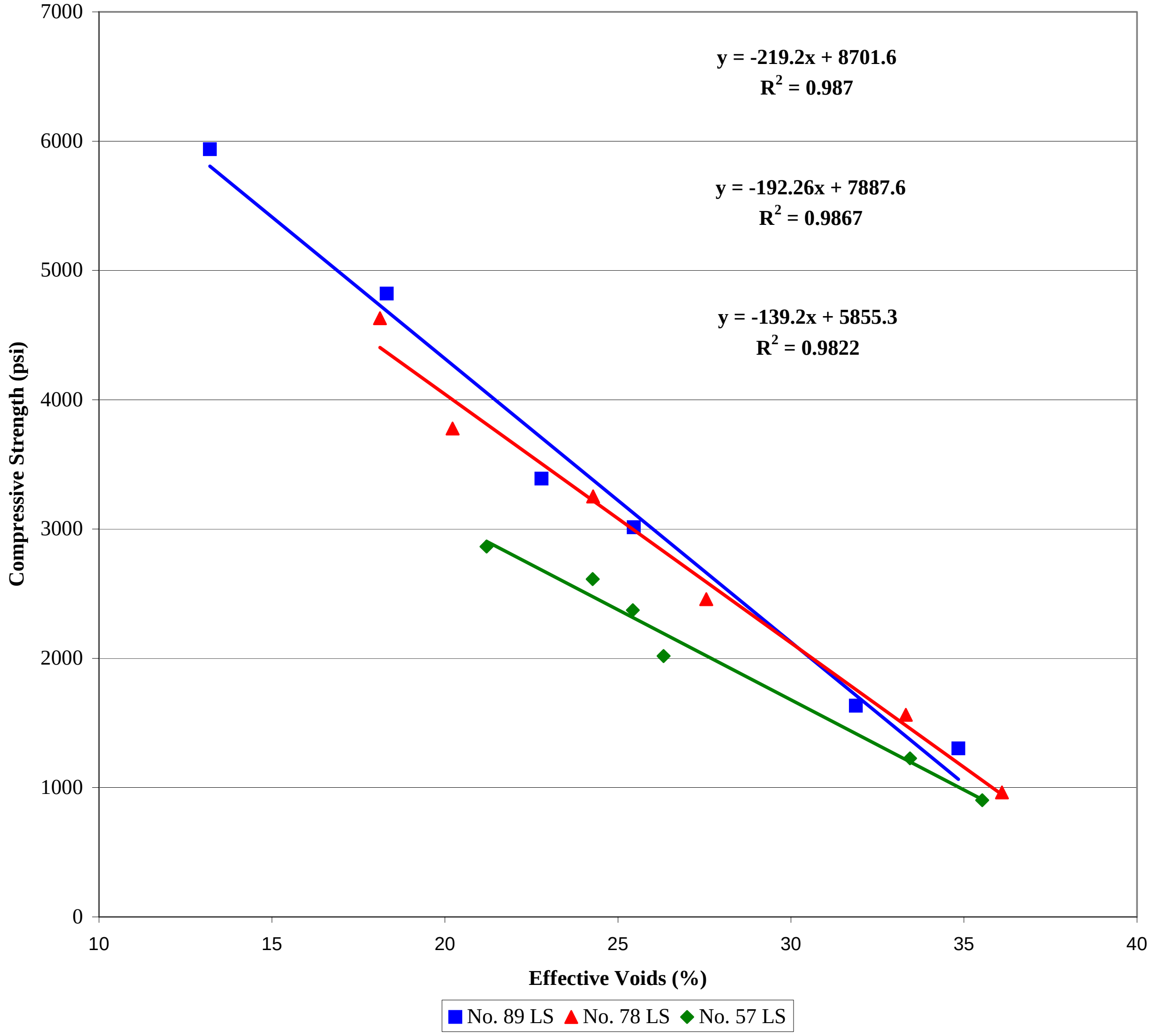

Figure 4. Effect of Gravel Gradation and Effective Air Void Content on Compressive Strength of Pervious PCC

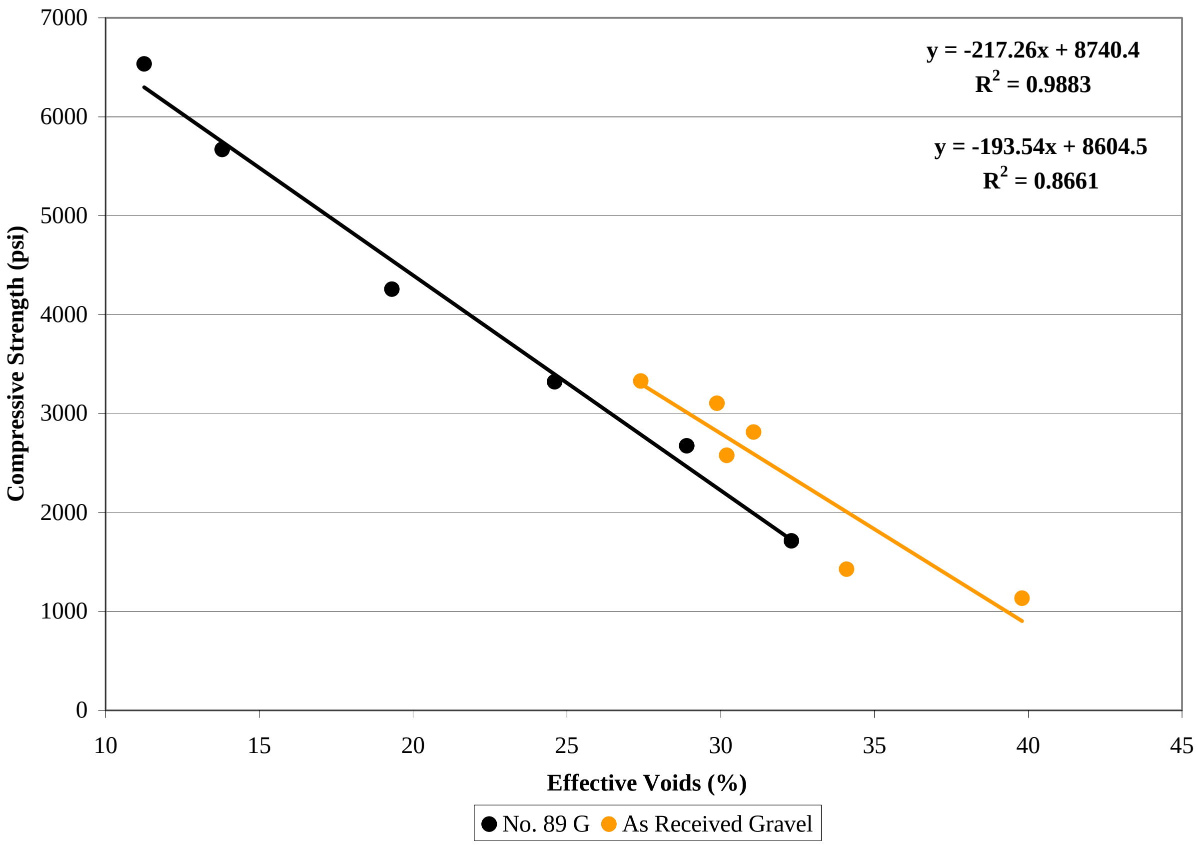

Figure 5. The Effect of Fineness Modulus and Compactive Effort on the Compressive Strength of Limestone Aggregate Pervious PCC

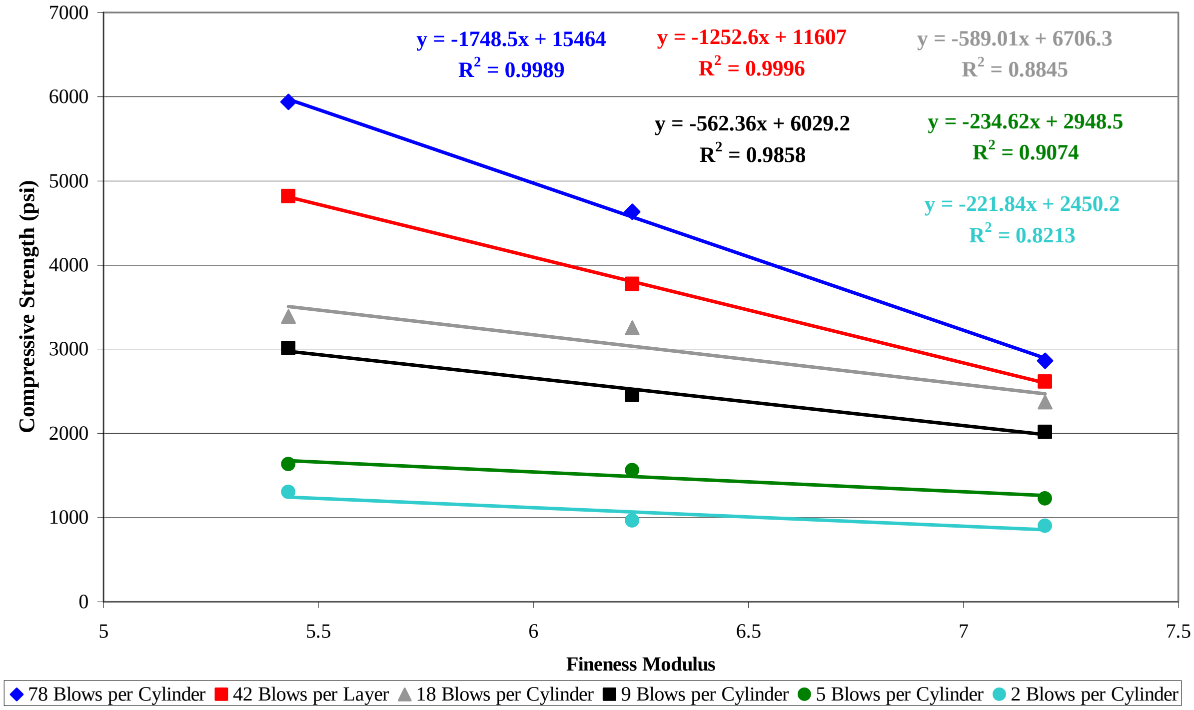

Figure 6. Effect of Aggregate Shape, Texture and Compactive Effort on Compressive Strength

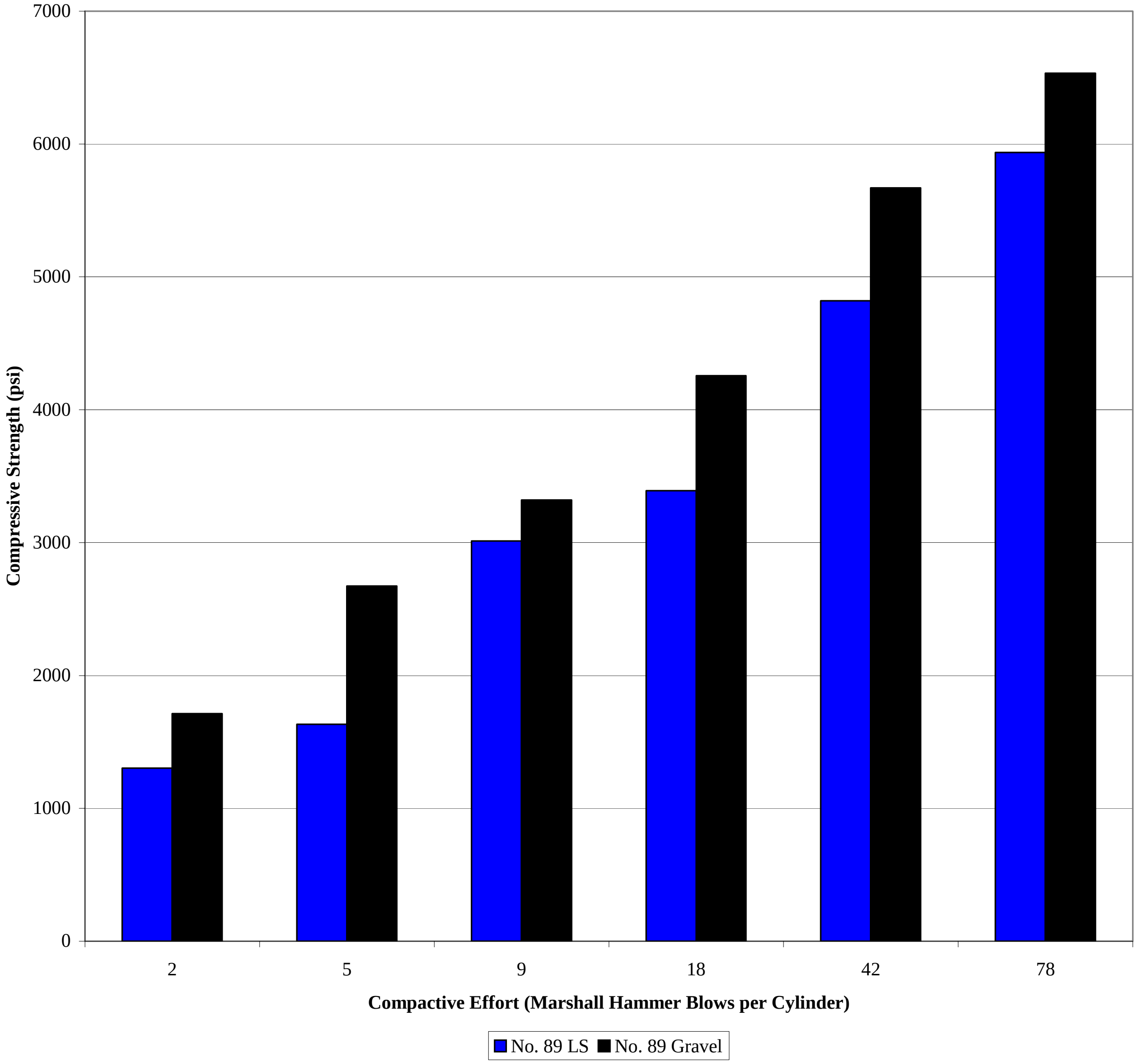

Figure 7. Effect of Aggregate Shape, Texture and Effective Air Void Content on Pervious PCC Compressive Strength

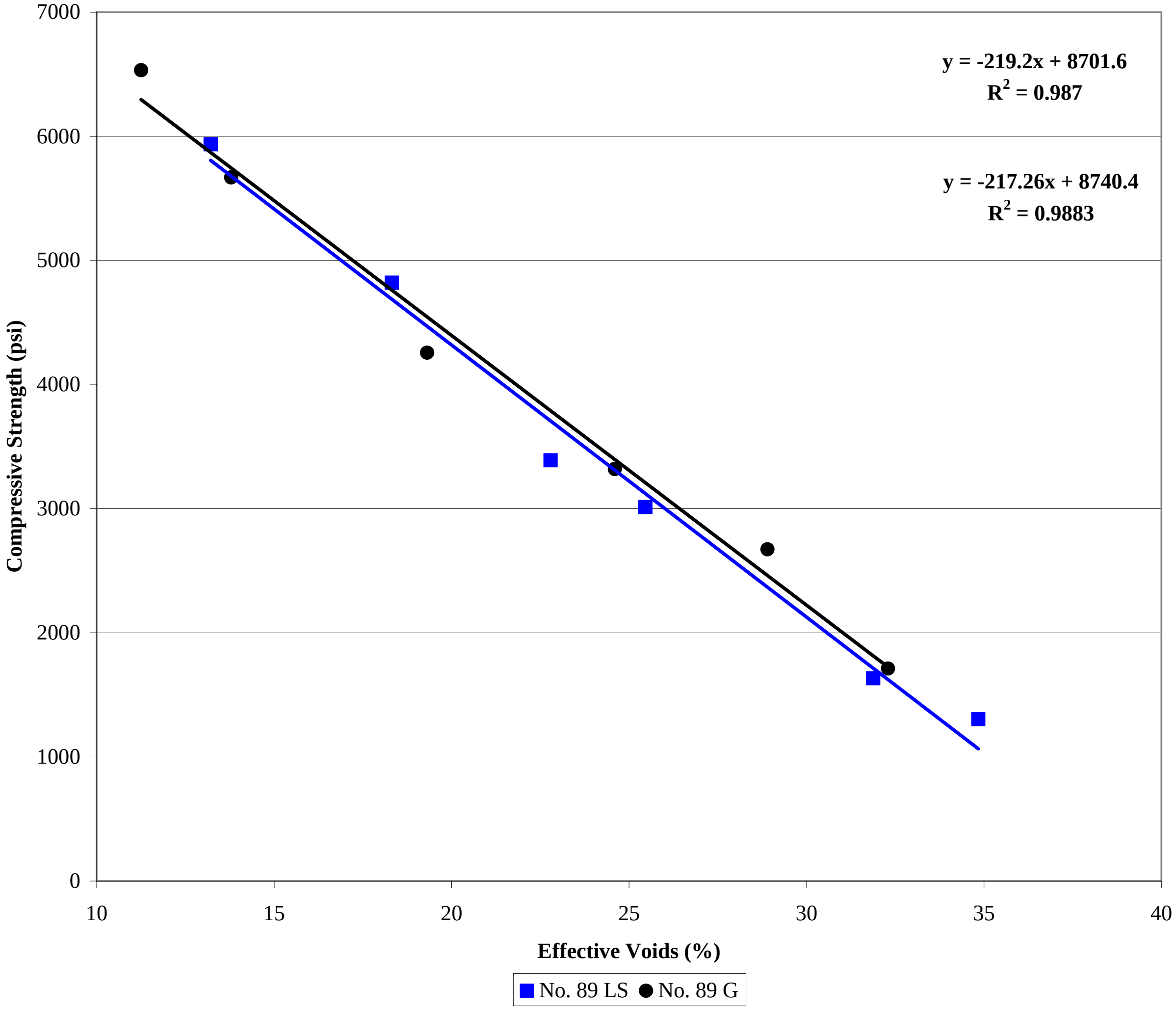

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Figure 8. The Effect of Aggregate Gradation and Effective Air Void Content on Pervious PCC Permeability

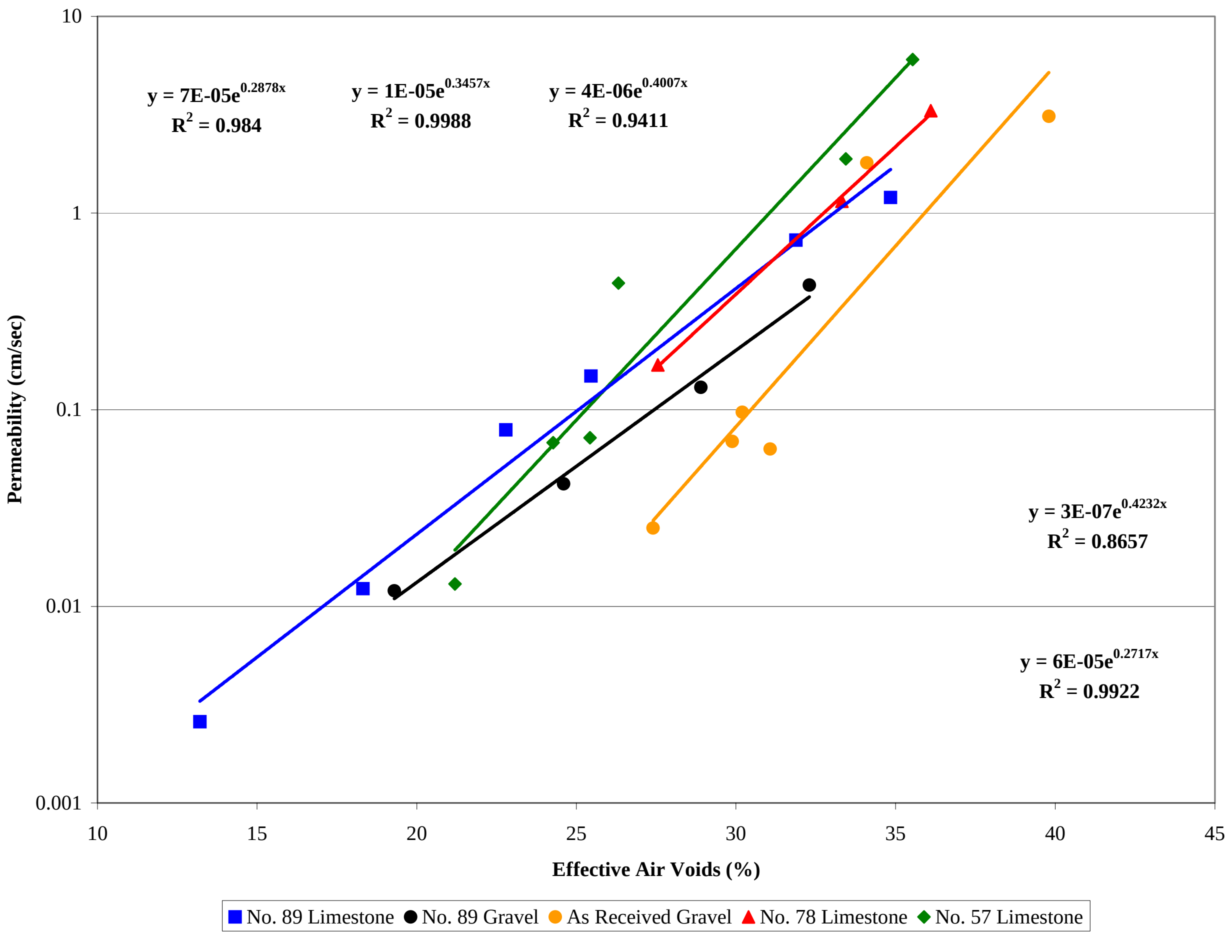

Figure 9. The Effect of Effective Void Size on the Permeability of Lightly Compacted Limestone Aggregate Pervious PCC Specimens

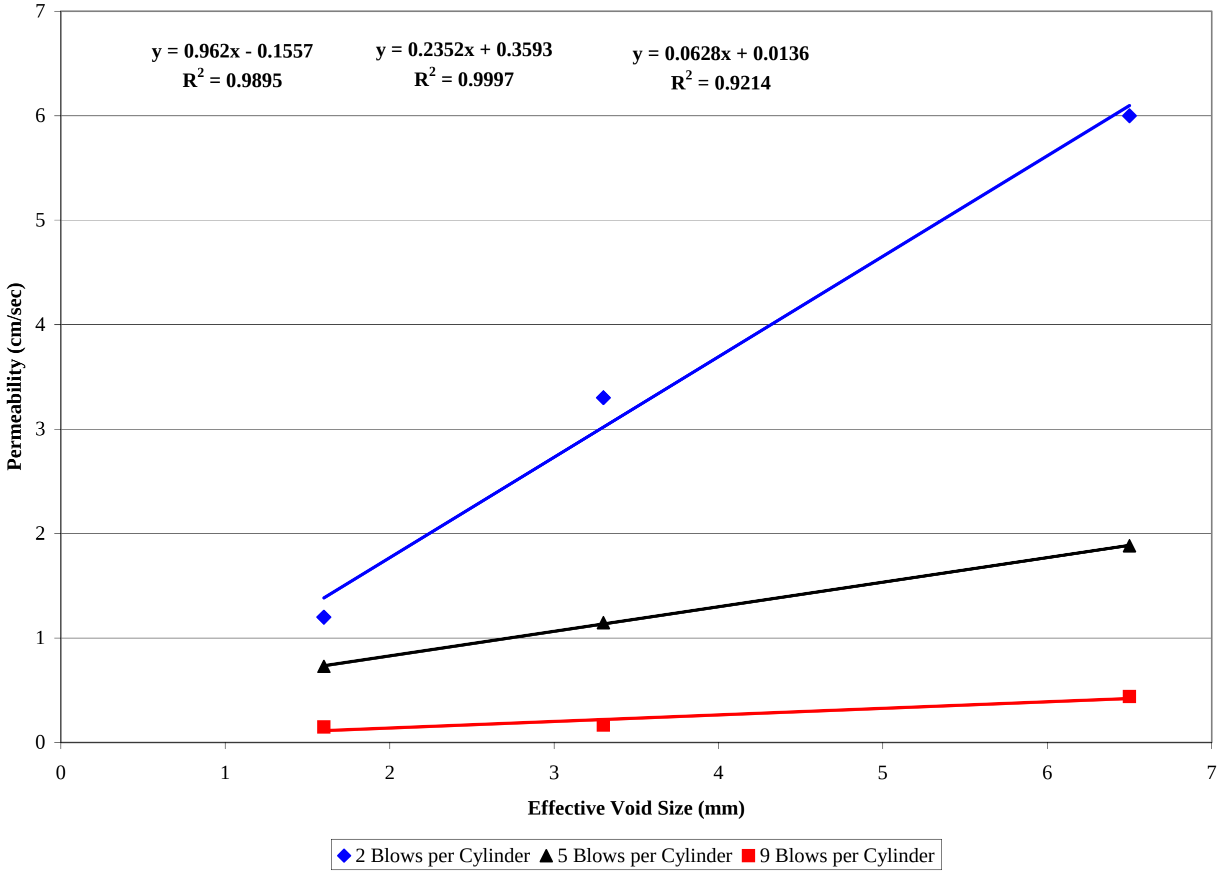

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Figure 10. The Effect of Effective Void Size and Compactive Effort on Permeability of Gravel Aggregate Pervious PCC Samples