Pervious PCC Compressive Strength in the Laboratory and the Field: The Effects of Aggregate Properties and Compactive Effort

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Abstract

Laboratory samples using three different gradations of crushed limestone and two different gradations of gravel were compacted at six various compactive efforts using a consistent pervious portland cement concrete (PCC) mixture design. Cores from four field demonstrations were also obtained. The effective air void content (voids accessible to water at the surface) and compressive strength of the pervious PCC samples were determined and compared, providing the following conclusions:

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, aggregate particle shape and surface texture, and aggregate uniformity coefficient. Smoother, more rounded aggregates produce lower effective void contents at the same compactive effort. Effective void content decreases with increasing aggregate uniformity coefficient.
2. 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. Compressive strength decreases with increasing effective void content. Compressive strength decreases with increasing aggregate fineness modulus.
3. The combination of low cementitious content, uniform aggregate gradation and high compactive effort in the field appears to be capable of producing pervious PCC with high permeability, greater than 142 in/hr (> 0.1 cm/sec) and high compressive strength, greater than 3000-psi (21-MPa).

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/yd^3 (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 C 33 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/yd^3 (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 entrainment are allowed.

RESEARCH OBJECTIVE

TCA saw a need for improving the workability of pervious PCC. An early step in the process was to determine the influence of aggregate properties on effective air void content and compressive strength of pervious PCC mixtures. Understanding the influence of aggregate properties would allow the research team to make proper adjustments needed to improve TCA pervious PCC mixtures' workability and compressive strength while maintaining adequate permeability.

LITERATURE REVIEW

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 and 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.

Several researchers have reported similar ranges for pervious PCC compressive strength. Meininger reported laboratory compressive strengths ranging from 1300 to 5300 psi (9 to 36.5 MPa) for air void contents ranging from 27 down to 8% respectively using AASHTO No. 8 size aggregate (*Meininger 1998, AASHTO 2004*). A laboratory study conducted by Ghafoori and Dutta using AASHTO No. 89 size aggregate reported compressive strengths between 1200 and 2800 psi (8.3 and 19.3 MPa) for void contents of 30 down to 21% respectively (*Ghafoori & Dutta, 1995*). ACI 211.3R shows compressive strengths of 1450 to 3600 psi (10 to 25 MPa) for AASHTO No. 8 size aggregate (*ACI, 2004*). Tennis, Leming, and Akers report compressive strengths ranging from 500 to 4000 psi (3.5 to 28 MPa) and state that a value of 2500 psi (17 MPa) is typical *(Tennis et al. 2004*). Crouch et al (*2003*) reported 33 field core compressive strengths ranging from 290 to 3600 (2 to 25 MPa) for effective void contents ranging from 42 to 16%, respectively from six TCA field demonstrations prior to 2004. All researchers agreed that increasing void content typically lowered the resulting compressive strength.

ACI 211.3R (*2004*), and Meininger (*1998*) showed that aggregate size influences compressive strength by using AASHTO No. 67 as the larger aggregate size and AASHTO No. 8 as the smaller aggregate size. However, it is not clear whether the compressive strength increase is due to gradation (uniformity coefficient) or particle size. Ghafoori and Dutta (*1995*) indicated the impact of increasing compactive effort was to reduce void contents and increase compressive strengths for similar specimens. Meininger (*1998*) concurred; increased compactive effort results in increased compressive strength.

LABORATORY MATERIALS AND OBTAINING SAMPLES

Laboratory materials, laboratory sample preparation procedure, and procedures for obtaining field samples are described in the NRMCA companion paper "Determining Pervious PCC Permeability with a Simple Triaxial Flexible-Wall Constant Head Permeameter." For the sake of conciseness, the sections will not be repeated in this paper.

COMPRESSIVE STRENGTH DETERMINATION

Compressive strength was determined as per ASTM C 39 (*ASTM, 2002*) using ASTM C 617 (*ASTM, 2002*) sulfur mortar capping at 28 days for laboratory samples and at various times dictated by sample arrival and prior testing requirements for field samples. However, field samples were all older than 28-days at the time of compressive strength testing. The exact time of testing was dependent on availability.

RESULTS

AASHTO T 304 Method B Voids (*AASHTO, 2004*) determinations, which gives an indication of particle shape and texture, are shown in Table 1. Laboratory results for average compressive strength and average effective void content are shown in Table 2.

Table 1. AASHTO T 304 Method B Uncompacted Voids

Size	Local Limestone	Local Creek Gravel	River Sand
12.5-mm	48.53		
9.5-mm	49.17	45.32	
6.35-mm	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 2. 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
Compressive Strength, psi (MPa)					
2	1303 (9.0)	963 (6.6)	903 (6.2)	1713 (11.8)	1133 (7.8)
5	1633 (11.3)	1563 (10.8)	1227 (8.5)	2673 (18.4)	1427 (9.8)
9	3013 (20.8)	2457 (16.9)	2017 (13.9)	3320 (22.9)	2577 (17.8)
18	3390 (23.4)	3253 (22.4)	2373 (16.4)	4257 (29.4)	2813 (19.4)
42	4820 (33.2)	3777 (26.0)	2613 (18.0)	5670 (39.1)	3103 (21.4)
78	5937 (40.9)	4630 (31.9)	2865 (19.8)	6533 (45.0)	3327 (22.9)

Field demonstration core results for average compressive strength and average effective void content are shown in Table 3.

Table 3. Field Average Effective Voids and Compressive Strength for 2005 TCA Demo Placements

Location	Number of Core Samples V/S[b]	Average Effective Voids (%)	Average Comp. Strength, psi (MPa)
Greenville, TN Parking Lot	10/5	27.8	1642 (11.3)
Williamson County, TN Ag Expo Center Sidewalk- Class C Fly Ash	10/6	25.2	2285 (15.8)
Williamson County, TN Ag Expo Center Sidewalk- Class F Fly Ash	10/0	24.4	2495[a] (17.2)
Burgess Falls - High Compaction	10/5	27.3	2790 (19.2)

[a] - cores too short for testing, average compressive strength of cylinder made at the site with similar void content shown

[b]- V/S = number of voids samples / number of compressive strength samples

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
- Aggregate particle shape and surface texture
- Uniformity coefficient

Referring to Figure 1, effective air void content decreases with increased compactive effort for all laboratory pervious PCC mixtures used in the study.

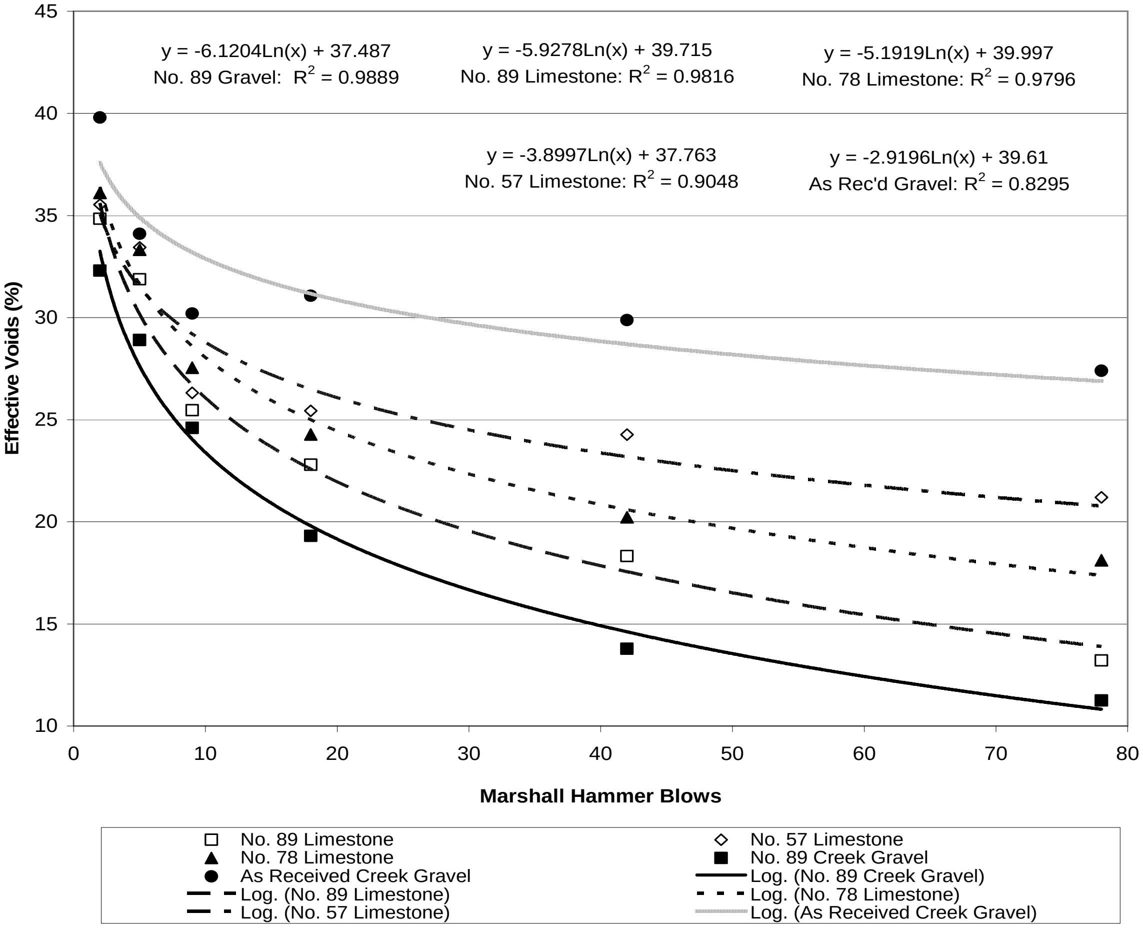

Figure 1. The Effect of Aggregate Gradation, Type and Compactive Effort on Laboratory Compacted Pervious PCC Effective Air Void Content

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. 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. Figure 2 shows effective air void content for laboratory mixtures with all aggregate types and gradations increased at compactive efforts greater than 9 blows per cylinder as the uniformity coefficient of aggregate gradation decreased.

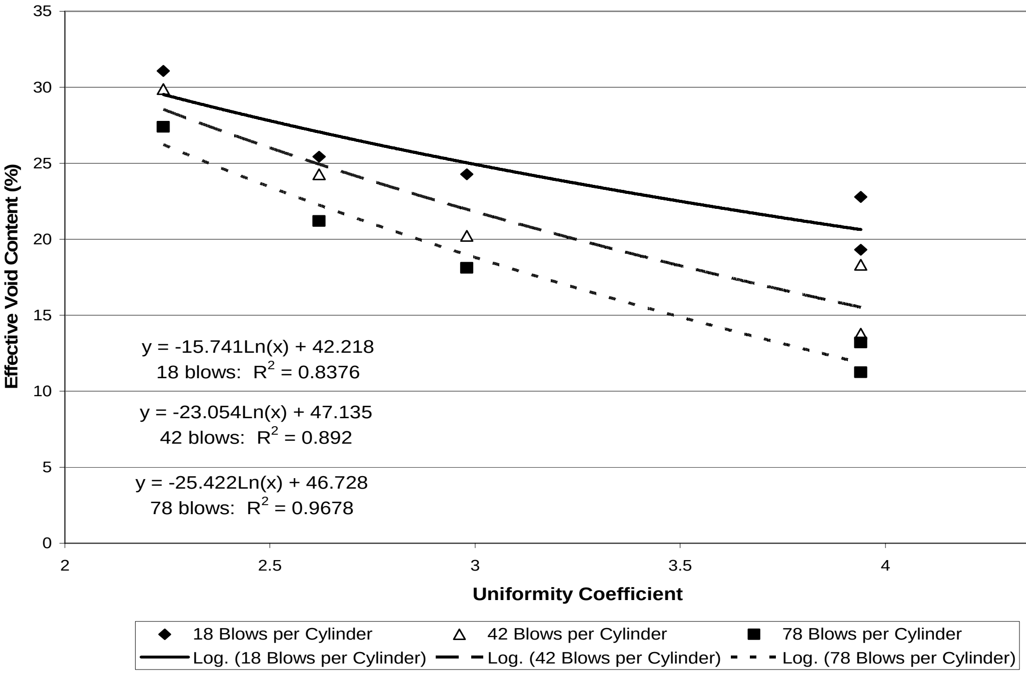

Figure 2. The Effect of Aggregate Gradation Uniformity Coefficient and Compactive Effort on Lab Compacted Pervious PCC Effective Air Void Content

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. Therefore, a more uniform gradation would have a better chance of having adequate post compaction effective voids under higher compactive efforts.

Compactive effort and mixture proportions varied at field demonstration locations. Further, detailed aggregate properties were not available for field demonstrations. Therefore, insufficient data is currently available to determine the effects of compactive effort and aggregate properties on field demonstration effective void contents.

Compressive Strength

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 Figure 3, compressive strength decreased with increased effective air void content for all laboratory aggregates used in the study except as-received gravel.

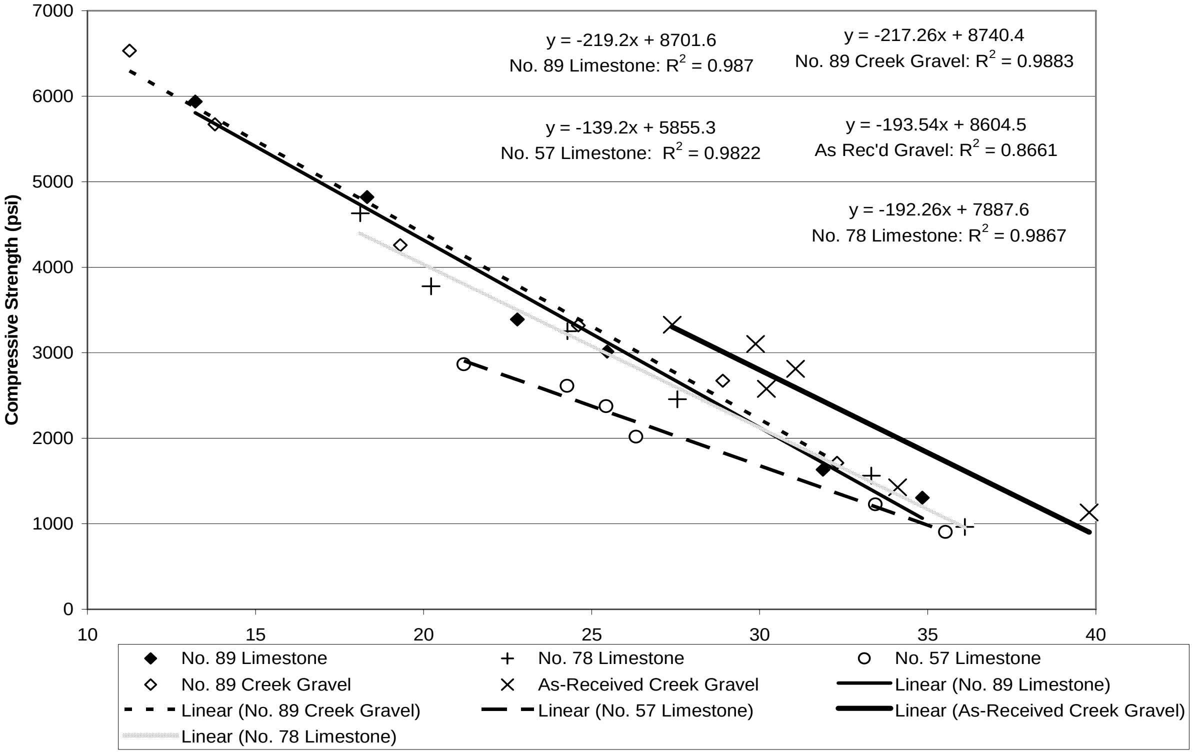

Figure 3. The Effect of Aggregate Type and Gradation and Compactive Effort on Laboratory Compacted Pervious PCC

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 (see Table 4) for laboratory samples ranged from 0.8661 to 0.9883, indicating strong to excellent relationships, respectively.

Compressive strength for limestone aggregates at all laboratory compactive efforts increased with decreasing fineness modulus. Figure 4 shows correlation coefficients for the relationship between compressive strength and fineness modulus ranged from 0.8213 to 0.9996, 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 (*2004*) indicate that the use of rounded aggregates in pervious PCC typically results in higher compressive strengths. Figure 5 supports that assertion. For similar pervious PCC mixtures (same paste amount and character and same aggregate volume and gradation), Figure 5 shows that the compressive strength of pervious PCC with rounded aggregates is greater than that for angular aggregates at all compactive efforts.

Table 4. Correlation Coefficients

Aggregate or Field Location	Number of Points for Compressive Strength	Compressive Strength – Effective Voids
Laboratory Compacted Samples		
No. 89 Limestone	6 x 3	0.9870
No. 78 Limestone	6 x 3	0.9876
No. 57 Limestone	6 x 3	0.9822
No. 89 Creek Gravel	6 x 3	0.9883
As-Received Creek Gravel	6 x 3	0.8661
Field Demonstration Cores		
Greenville	5	0.8736
Williamson County C Ash	5	0.9437
Williamson County F Ash	N/A	N/A
Burgess Falls TN State Park Sidewalk	5	0.9982

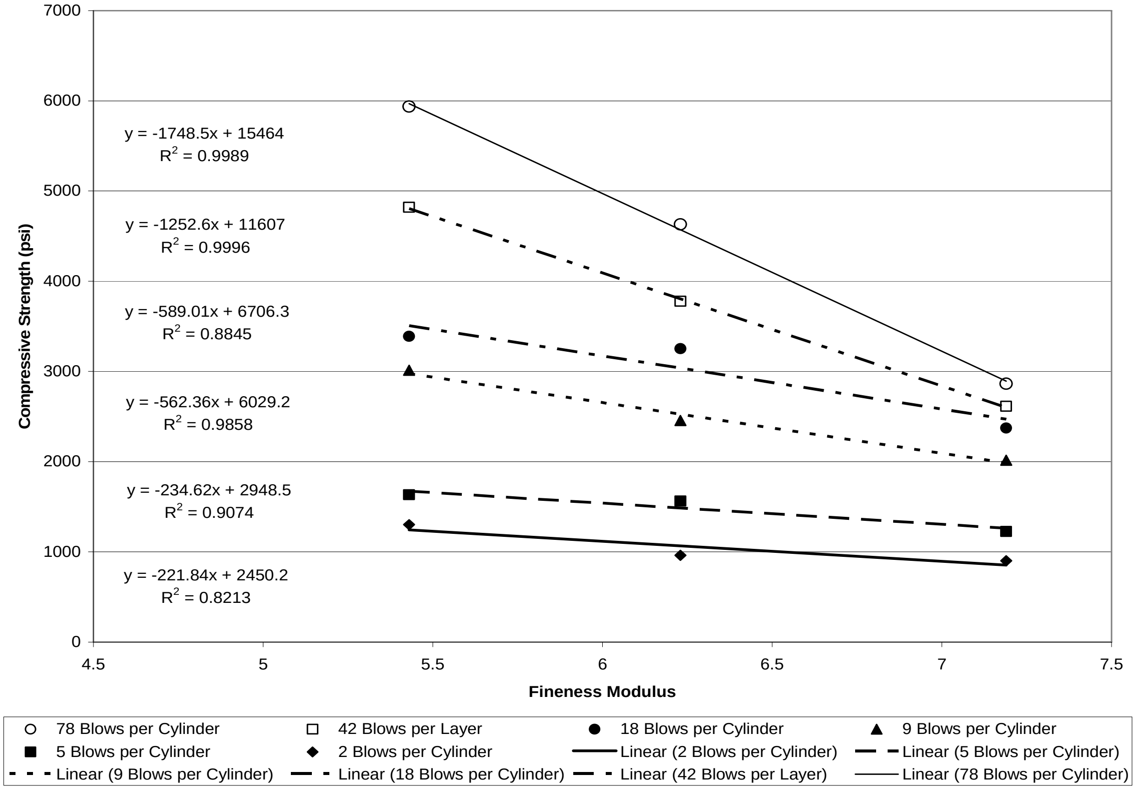

Figure 4. The Effect of Fineness Modulus and Compactive Effort on the Compressive Strength of Limestone Aggregate Pervious PCC

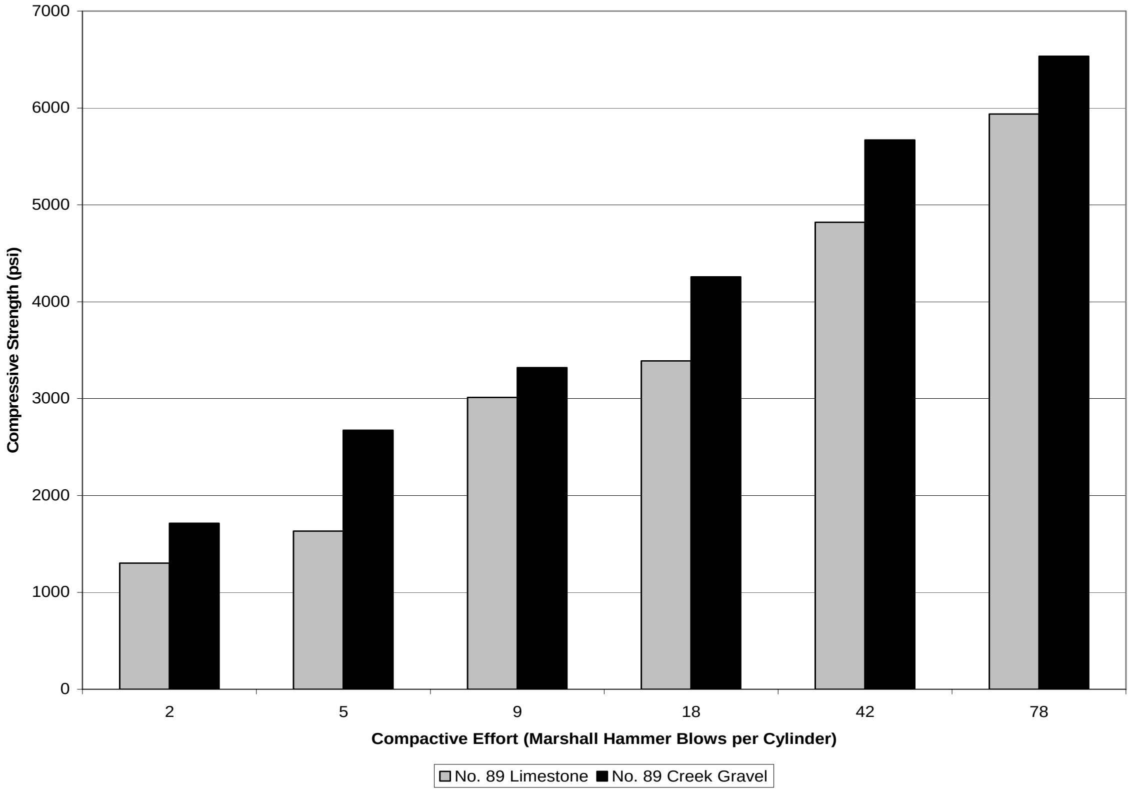

Figure 5. The Effect of Aggregate Shape, Texture and Compactive Effort on Compressive Strength of Lab Compacted Pervious PCC with No. 89 Aggregate

Initially, this seemed counterintuitive, rougher more angular aggregates would seem to enhance the paste-aggregate bond. However, Figure 6 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. Figure 7 shows compressive strength decreased with increased effective air void content for individual field demonstrations.

Correlation coefficients for the relationship between compressive strength and effective air void content (see Table 4) for individual field demonstrations ranged from 0.8736 to 0.9982, indicating strong to excellent relationships, respectively. Differences in mixture proportions and compactive effort varied among demonstrations and therefore the trend of average values of compressive strength and effective voids did not correlate well. Insufficient information was available to determine if the strong relationship between compressive strength and fineness modulus observed in the laboratory held for the field demonstrations. All aggregates used in the field demonstrations were rough, angular limestone. Therefore, no shape and texture comparisons were possible.

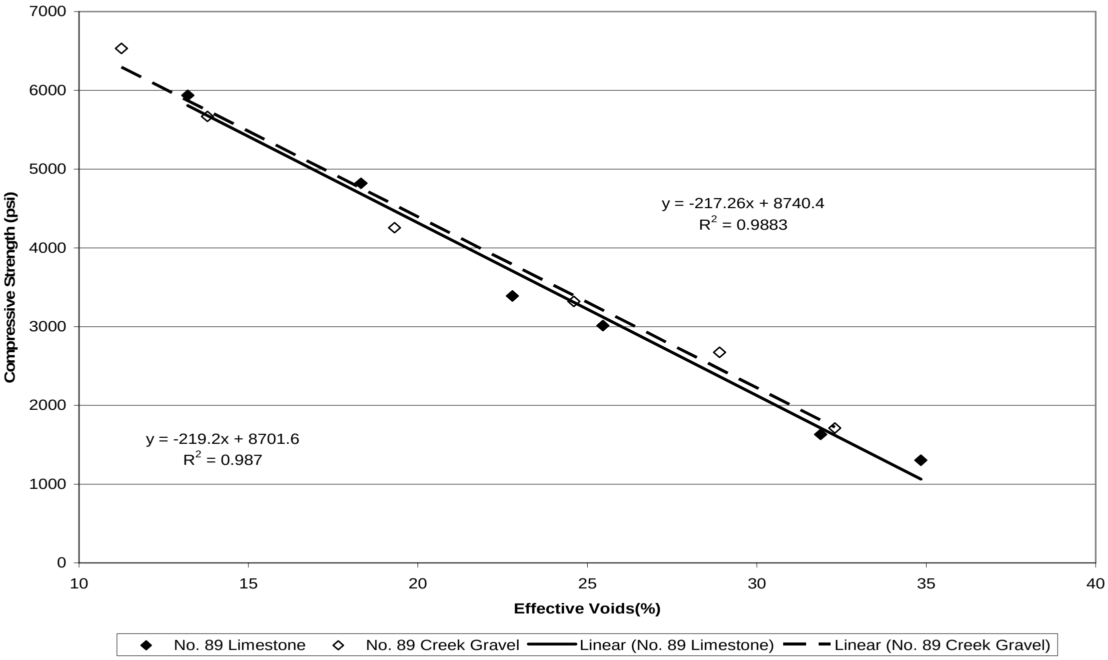

Figure 6. The Effect of Aggregate Shape, Texture and Effective Air Void Content on Pervious PCC Compressive Strength

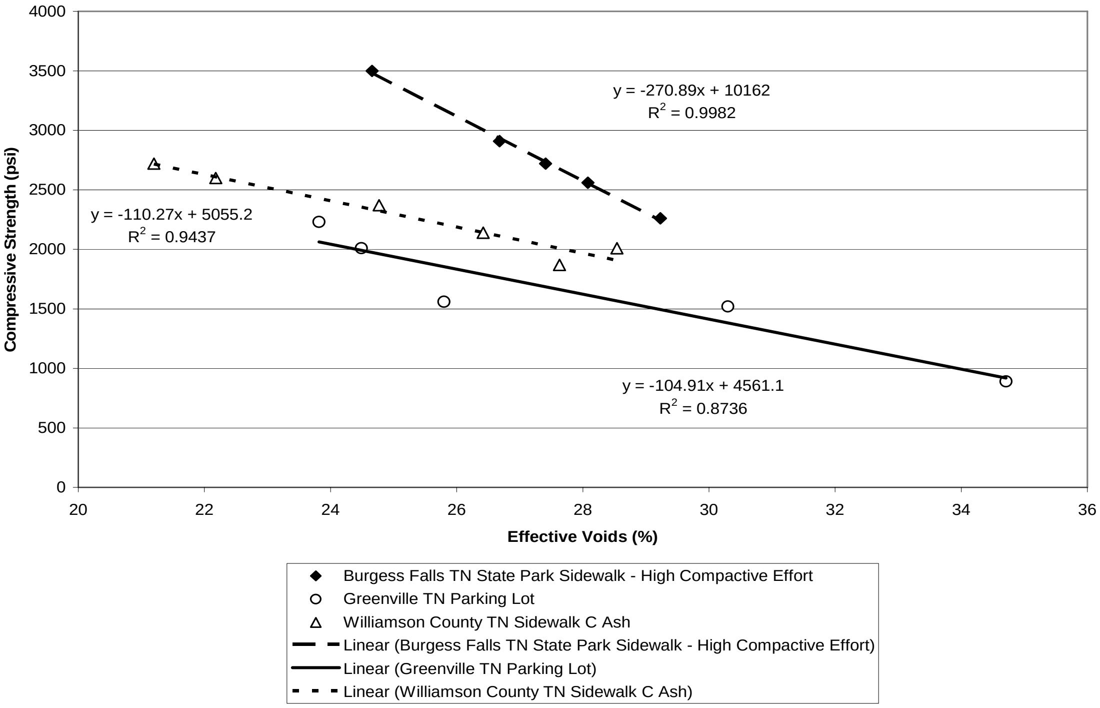

Figure 7. Compressive Strength versus Effective Air Void Content for the 2005 TCA Field Demonstrations

The pervious PCC placement at Burgess Falls State Park was compacted with a vibratory plate compactor, used a very uniform aggregate gradation and a lower cementitious materials content. The placements at the Williamson County Agricultural Expo Center and the Greenville church were compacted with a hand roller, used less uniform aggregate gradations and had a higher cementitious materials content. The equation of the Burgess Falls trend line (see Figure 7) indicates that the mixture-compaction combination would have compressive strengths of 3000 psi (21 Mpa) at 26.3% and 2000 psi (14 MPa) at 30% effective voids. The equation of the trend line also indicates that the Burgess Falls mixture-compaction combination is superior (has greater compressive strength at the same voids) to every TCA pervious PCC placement mixture-compaction combination (2 shown in Figure 7 plus 7 earlier demonstrations) in the effective void range of 15% to 30%.

Due to the success of pervious PCC mixture-compaction combination at the Burgess Falls demonstration, the authors are exploring the possibility of demonstrations with a high density paver or a small motorized roller in the near future. Perhaps the combination of a very uniform aggregate gradation and a lower cementitious content pervious PCC mixture and more compaction energy will allow the Tennessee concrete industry to obtain pervious PCC with high permeability, greater than 142 in./hr (0.1 cm/sec) and high compressive strength, more than 3000 psi (21 MPa). Permeability is covered in the NRMCA companion paper “Determining Pervious PCC Permeability with a Simple Triaxial Flexible-Wall Constant Head Permeameter.”

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, aggregate particle shape and surface texture, and aggregate uniformity coefficient. Smoother, more rounded aggregates produce lower effective void contents at the same compactive effort. Effective void content decreases with increasing aggregate uniformity coefficient.
2. 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. Compressive strength decreases with increasing effective void content. Compressive strength decreases with increasing aggregate fineness modulus.
3. The combination of low cementitious materials content, uniform aggregate gradation and high compactive effort in the field appears to be capable of producing pervious PCC with high permeability, greater than 142 in./hr (0.1 cm/sec) and high compressive strength, greater than 3000 psi (21 MPa).

REFERENCES

1. AASHTO M 43-88 (2003) "Standard Specification for Sizes of Aggregates for Road and Bridge Construction" AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C., 24th Edition 2004.
2. AASHTO T 245-97, "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus," American Association of State Highway and Transportation Officials, Standard Specifications for Transportation Materials and Methods of Sampling And Testing Part II Tests, 19th edition, 1998.
3. AASHTO T 304-96 (2000), "Standard Method of Test for Uncompacted Void Content of Fine Aggregate," American Association of State Highway and Transportation Officials, Standard Specifications for Transportation Materials and Methods of Sampling And Testing Part 2B Tests, 24th edition, 2004.
4. ACI 211.3-R02 "Guide for Selecting Proportions for No Slump Concrete," Manual of Concrete Practice 2004 CD-ROM, American Concrete Institute, Farmington Hills, MI, Appendix 6, page 25.
5. ASTM C 39-01, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04-02, October 2002, pp 21-25.
6. ASTM C 42/C42M-03, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete[1]," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04-02, 2004, pp 28-32.
7. ASTM C 136-01 "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," Annual Book of ASTM Standards, Vol. 04.02, 2004.
8. ASTM C 140-99b, "Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units," American Society for Testing and Materials, Masonry Test Methods and Specifications for the Building Industry, Fourth Edition, 2001, pp 72-82.
9. ASTM C 617-98, "Standard Practice for Capping Concrete Specimens," American Society for Testing and Materials, Annual Book of ASTM Standards, Vol. 04-02, October 2002, pp 314-318.
10. Crouch, L., Cates, M., Dotson, V., Honeycutt, K., Badoe, D., "Measuring the Effective Air Void Content of Portland Cement Pervious Pavements," Cement, Concrete, and Aggregates, Vol. 25, No. 1, West Conshohocken, PA, June, 2003.
11. Georgia Concrete and Products Association, Inc., "Recommended Specifications for Portland Cement Pervious Pavement," Georgia Concrete and Products Association, Inc., Tucker, GA, Aug. 1997, pp 1-7.
12. Ghafoori, N., Dutta, S., "Laboratory Investigation of Compacted No-Fines Concrete For Paving Materials," *Journal of Materials in Civil Engineering*, v7, No. 3, Aug., 1995, pp 183-191.
13. Gnoffo, J., Reid K., "Pervious Concrete – An Introduction for Designers, Ready-Mix Producers, and Contractors," Presentation notes, May 1997.
14. Meininger, R. C., "No-Fines Pervious Concrete for Paving," Concrete International, v10, Issue 8, Aug. 1998, pp 20-27.

15. Paine, J., “Portland Cement Pervious Pavement Construction,” *Concrete Construction*, Sept. 1992, pp 655-659.
16. Tennessee Concrete Association, “Preliminary Specifications for Portland Cement Pervious Concrete Pavement,” Tennessee Concrete Association, 7 pp.
17. Tennis, Paul D., Leming, Michael L., and Akers, David J., *Pervious Concrete Pavements*, EB302, Portland Cement Association, Skokie, Illinois, and National Ready Mixed Concrete Association, Silver Spring, Maryland, USA, 2004, 36 pages.

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