STATE OF TENNESSEE
DEPARTMENT OF TRANSPORTATION

COMPARISON OF AASHTO PCC AIR DETERMINATION TECHNIQUES

FINAL REPORT

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16. Abstract

A field investigation of the four current AASHTO Standard Test Methods for determining air content of plastic PCC was conducted. The four methods are:

1. Air Content of Freshly Mixed Concrete by the Pressure Method. AASHTO T 152-97.
2. Air Content of Freshly Mixed Concrete by the Volumetric Method, AASHTO T 196-96.
3. Mass per Cubic Meter (Cubic Foot), Yield, and Air Content (Gravimetric) of Concrete, AASHTO T 121-97.
4. Air Content of Freshly Mixed Concrete by the Chace Indicator, AASHTO T 199-00

Duplicate air tests were conducted on thirty-two three-cubic-yard field batches of TDOT Class A PCC using all four currently available AASHTO plastic PCC air determination techniques. Methods were compared statistically using the range of the duplicate tests. Further, the research team analyzed method mechanics, applicability, logistics and costs.

The research team recommends that the Tennessee Department of Transportation continue using the pressure method for normal weight aggregate concrete and the volumetric method for lightweight aggregate concrete. The two methods had similar precision and accuracy for TDOT Class A PCC. In the vast majority of cases, the true air content of TDOT Class A PCC appears to below the observed value produced by the pressure method and above the observed value produced by the volumetric method. The gravimetric method and Chace Air Indicator were found to have several disadvantages when compared to current TDOT methods. The recommendations are based primarily on mechanics and applicability and are summarized in the following table.

Parameter	Advantage
Precision	No Advantage
Accuracy	No Advantage
Initial Cost	No Advantage
Physical Effort Required	Pressure Method
Time to Perform a Test	Pressure Method
Applicability to Lightweight Aggregate PCC Mixtures	Volumetric Method
Applicability to High PC Content Mixtures	Pressure Method
Applicability to Sticky PCC Mixtures (i.e. mixtures containing Micro Silica)	Pressure Method

17. Key Words

Air content, Concrete, Volumetric method, Pressure method, Gravimetric method, Chace Indicator, Unit weight, Compressive strength

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INTRODUCTION

Portland cement concrete (PCC) requires both strength and durability to perform adequately in-service. Until recently, PCC strength received much more attention from designers than durability. Unfortunately, most structures that fail in-service fail by loss of durability rather than by a catastrophic strength failure. In the past, PCC durability received less attention because:

1. PCC strength, specifically compressive strength, is much easier to measure than PCC durability;
2. PCC strength failures, although very rare, are catastrophic usually leading to loss of life or significant property damage, while PCC durability failures are typically characterized by a relatively slow deterioration of structural components;
3. Increasing PCC strength is probably easier than increasing PCC durability.

Many designers still pay careful attention to strength and assume that entrained air will provide adequate durability. Entraining tiny air bubbles in the paste has been found to be very effective in enhancing PCC durability. Specifically, entrained air in PCC:

1. Enhances freeze-thaw resistance - millions of tiny bubbles that act as expansion reservoirs to relieve the expansion pressure;
2. Enhances deicer attack resistance - bubbles relieve osmotic pressure;
3. Enhances sulfate attack resistance - relieves expansion pressure;
4. Reduces scaling of PCC surfaces;
5. Enhances workability - bubbles act like ball bearings or lubricants (water and possibly sand can be reduced);

6. Reduces segregation and bleeding - makes concrete more cohesive through the action of surface tension at the air-water interface;
7. Reduces compressive strength, flexural strength, and modulus of elasticity due to loss of section.

The vast majority of the effects of entraining air are clearly beneficial to PCC. Some strength reduction due to entraining air is expected and compensated for by designers to achieve the benefits of the first six effects. However, an excessive amount of entrained air seriously reduces the strength and stiffness of PCC. The Portland Cement Association (1) estimates that compressive strength is reduced by two to six percent, flexural strength two to four percent, and modulus of elasticity is reduced 105,000 to 200,000-psi, per percent increase in air content. Obviously, accurate measurement of air content is essential in producing PCC with adequate durability and strength.

There are four current AASHTO Standard Test Methods for determining air content of plastic PCC:

1. Air Content of Freshly Mixed Concrete by the Pressure Method, AASHTO T 152-97 (2)
2. Air Content of Freshly Mixed Concrete by the Volumetric Method, AASHTO T 196-96 (3)
3. Mass per Cubic Meter (Cubic Foot), Yield, and Air Content (Gravimetric) of Concrete, AASHTO T 121-97 (4)
4. Air Content of Freshly Mixed Concrete by the Chace Indicator, AASHTO T 199-00 (5)

Each method has it's own particular advantages and disadvantages.

A detailed approach to the project can be found in the Project Protocol Section of the report. However, in general, the research team will conduct duplicate air tests on thirty-two three-cubic-yard field batches of TDOT Class A PCC using all four currently available AASHTO plastic PCC air determination techniques. The compressive strength of all thirty-two mixtures will also be evaluated using both 6-by-12-inch and 4-by-8-inch cylinders.

The objective of this study is to recommend the most suitable currently available AASHTO method for determining plastic PCC air content. Information such as method average range of results, statistical difference from other available methods, and logistical factors were used to formulate recommendations on which method is most suitable for TDOT use. The most important anticipated result is the determination of the method that produces the most consistent and reliable results for TDOT PCC mixtures. When implemented, the results obtained will generate a higher level of confidence in PCC air content determination. A reliable technique to determine the air content of plastic PCC will allow TDOT to maximize the durability benefits of entraining air in PCC while avoiding the serious strength and stiffness reductions associated with excessive entrained air content.

LITERATURE REVIEW

The results of a survey of the AASHTO member states conducted to determine the primary air content determination methods for normal weight and lightweight PCC are summarized in figures 1 and 2. The results showed a clear trend for both inquiries. Approximately 78% of the states responding indicated the pressure method was their primary method for determining the air content of normal weight PCC. In addition, approximately 94% of the states responding that allowed the use of lightweight aggregate PCC stated that their primary air determination for these mixtures was the volumetric method. Figure 3a and 3b shows the allowable specification range of air contents for normal weight PCC mixtures. A copy of the questionnaire and cover letter are provided in the appendix.

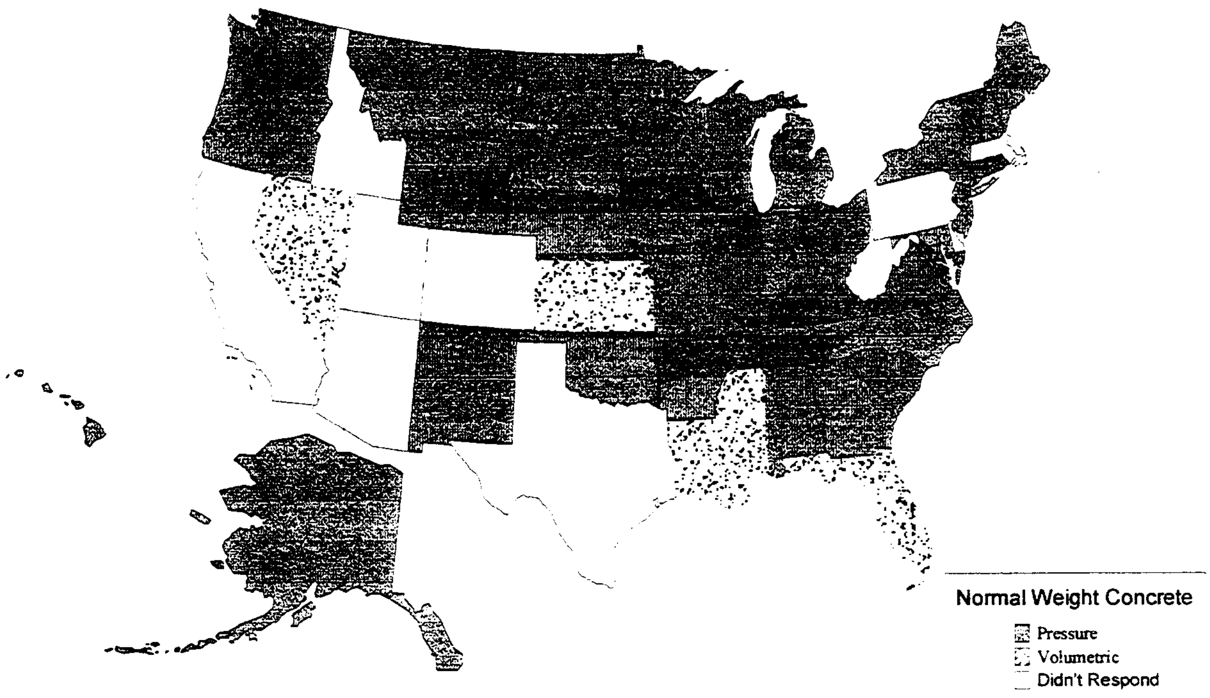

Figure 1. Primary Air Content Measurement Method for Normal Weight PCC

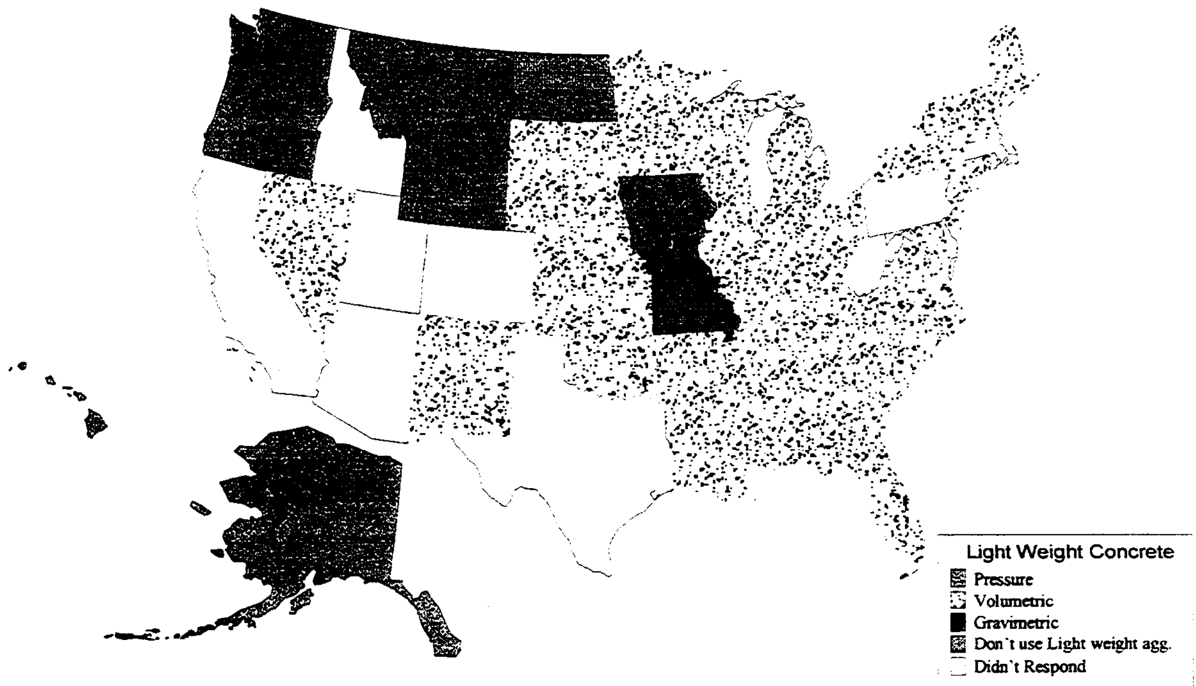

Figure 2. Primary Air Content Measurement Method for Light Weight PCC

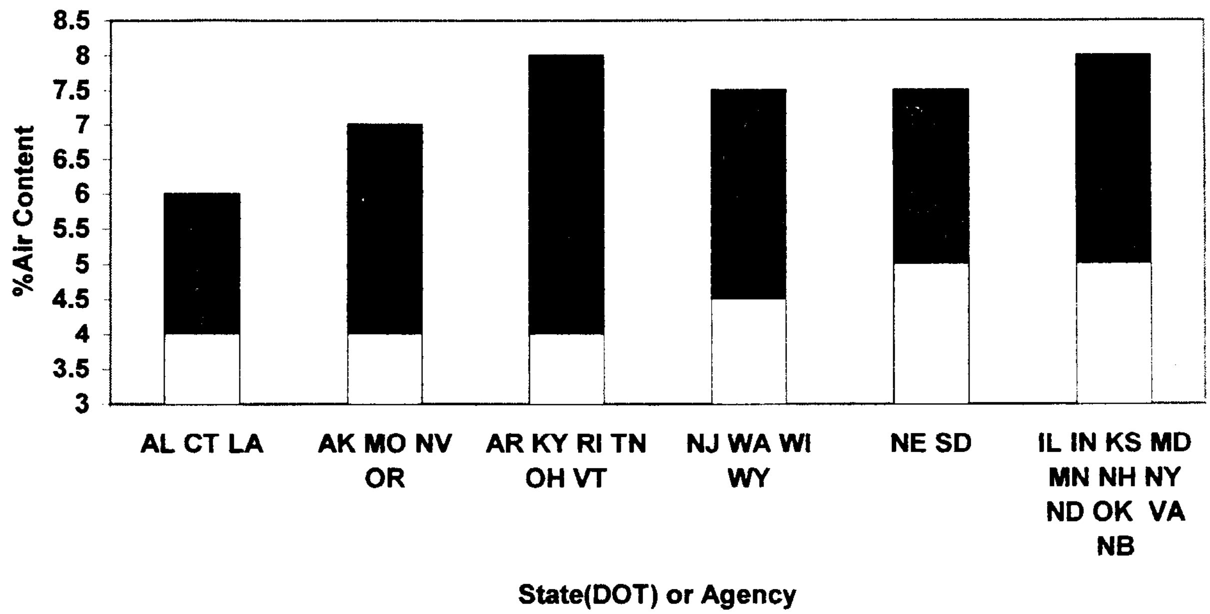

Figure 3a. Allowable Air Content Range for Normal Weight PCC

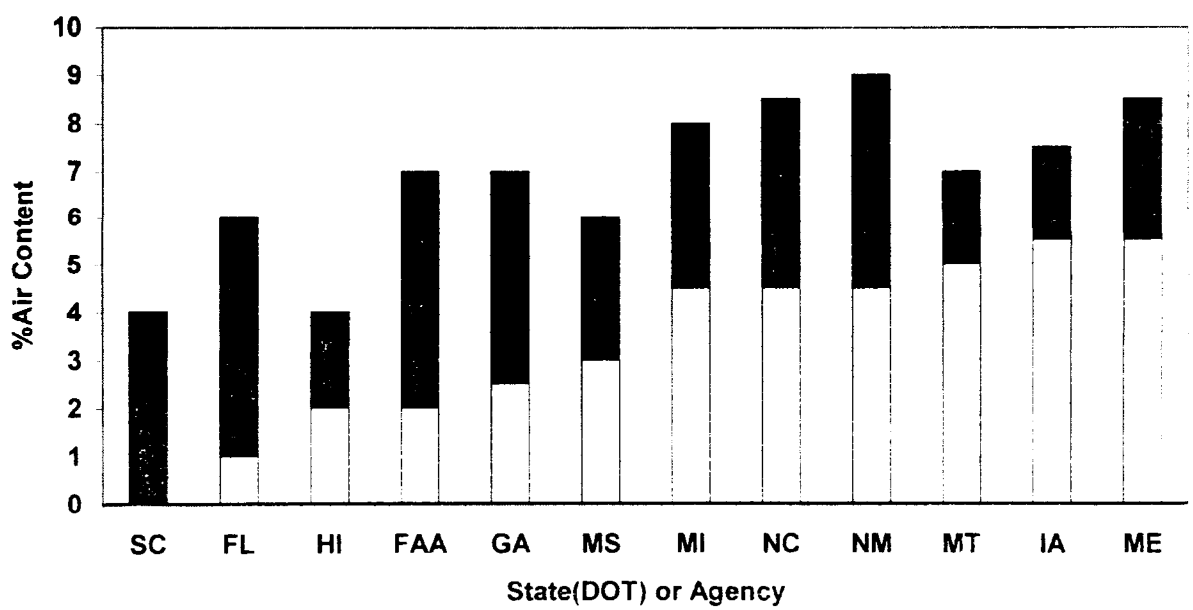

Figure 3b. Allowable Air Content Range for Normal Weight PCC

The four current AASHTO plastic PCC air determination techniques will be described in the following paragraphs.

Pressure Method

The pressure method is based on Boyle's Law ($P_1V_1 = P_2V_2$). A small chamber is pumped up to a predetermined pressure. When the valve to the small chamber is opened, air expands into the bowl containing the consolidated PCC. The pressure drop is proportional to the air content of the PCC sample. An aggregate correction factor is required since the method compresses air within the interconnected porosity within the aggregate particles, thus overestimating the air content of the PCC (2).

A primary advantage of the pressure method is that no knowledge of batch weights or specific gravities are required to conduct an air test. However, the pressure method has two important limitations. First, the complexity of valves and seals makes the apparatus prone to leakage, Second, the pressure method is not appropriate for lightweight PCC or PCC containing high porosity aggregates (6).

A recent controversy has surfaced in the literature over the ability of the pressure method to measure air content accurately when the air void size is very small. Air void size is primarily a function of air-entraining agent chemistry. Apparently, newer synthetic air-entraining agents produce smaller, more stable bubbles than older venisol resin air-entraining agents. Research by Ozyldirim of Virginia DOT showed good agreement between pressure method and gravimetric method air contents. However, gravimetric air content is not a function of air void size. Therefore, underestimation of actual air content of the PCC by the pressure meter (due to small air void size) is not likely to exceed one percent (6).

Volumetric Method

The volumetric method uses water and agitation to displace air in the PCC. 70% isopropyl alcohol is used to dispel any foam generated during agitation. The air content is read directly from the sight glass and corrected for alcohol addition. No aggregate correction factor is required for the volumetric method (3).

The volumetric method is the appropriate test method for determining the air content of PCC containing lightweight aggregates, air-cooled slag, or highly porous or vesicular aggregates since air trapped in the aggregates has no impact on test results. However, the volumetric method also has two significant disadvantages. First, the method may underestimate the air content of PCC containing more than 600 pounds-per-cubic-yard of cementitious material. Such mixtures may require up to 60 minutes of agitation to obtain a stable reading. Second, the method is physically demanding. For accurate results, agitation must continue until no significant change in reading occurs. The method experiences difficulties with very sticky mixtures or sticky mixtures with high air contents (3, 6).

A 979-test study by the West Virginia DOT found that results of tests by two different operators on specimens taken from a single sample of PCC should not differ by more than 32% of their average (6).

Gravimetric Method

The following equations are used to calculate the gravimetric air content (4):

$$\text{Air content in percent, } A = [(T - W) / T] * 100$$

where:

W = unit weight in pounds-per-cubic-foot

Theoretical unit weight air free, $T = W_1 / V$

W_1 = sum of the batch weights in pounds

V = total absolute volume of components in cubic feet

Absolute volume = (batch weight) / [(specific gravity)(62.4)]

As seen in the preceding equations, the gravimetric method requires detailed knowledge of batch weights and material properties not readily available in the field. A change as small as two percent in fine aggregate moisture content or 0.04 in aggregate specific gravities results in a one percent difference in calculated air content. The gravimetric method is not appropriate for lightweight aggregate PCC since lightweight aggregate specific gravities and moisture contents can vary widely (6).

Chace Air Indicator

The Chace Air Indicator is similar in operation and concept to the volumetric method. However, the Chace uses a small sample of mortar passing the number 10 sieve instead of the larger PCC sample of the volumetric method. Further, the Chace uses 70 percent isopropyl alcohol exclusively to displace air. Air content readings from the Chace sight tube require both mortar factor and curve corrections as described in AASHTO T 199-00 (5).

The Chace Air Indicator is satisfactory for determining approximate air content but is not a suitable replacement for the pressure, gravimetric, or volumetric methods. Further, the Chace is not acceptable for determining specification compliance. Current literature indicates that the Chace is not as accurate as the other three current AASHTO methods. The average of five Chace tests has the same statistical level of confidence as one pressure method test (5).

The Chace Air Indicator is useful for determining relative air content, for example high, medium, or low. The Chace is also useful for determining if the air content of PCC is relatively constant batch to batch (5).

PROJECT PROTOCOL

Seven different ready mix producers provided a total of thirty-two three cubic yard batches of TDOT Class A PCC as shown in Table 1. Information on producer names, test locations, and test dates were withheld at the request of the TDOT Materials and Tests Division. Mixture proportions were considered proprietary by the ready mix producers and were also withheld.

Plastic PCC tests were performed and compressive strength specimens were cast from the middle cubic yard of each batch. Plastic tests performed and specimens cast are shown in Table 2. American Concrete Institute Certified Technicians performed all tests. Project technicians are shown in Table 3. All testing was performed in accordance with AASHTO procedures (2, 3, 4, 5, 7, 8, 9, 10) with the exceptions that the research team was forced to violate the AASHTO T 141-97 (11) requirement for all tests to begin within 15 minutes of sample acquisition and the concrete thermometer had not been recently calibrated.

Table 1. Batch and Mixture Information

Producer	Number of Batches	Fly Ash Class	Admixture Brand
1	6	F	MBT
2	5	F	MBT
3	5	C	MBT
4	4	C	MBT
5	4	C	MBT
6	4	C	Euclid
7	4	C	MBT

MBT – Master Builders Technologies

Table 2. Testing Protocol for each 3 Cubic Yard Batch

Test Method or Specimen Cast	Test Method	Number of Replicates
Slump	AASHTO T 119-97	1
Temperature	AASHTO T 309-99	1
Air by Pressure Method	AASHTO T 152-97	2
Volumetric Air	AASHTO T 196-96	2
Gravimetric Air	AASHTO T 121-97	2
Chace air Indicator	AASHTO T 199-00	2
6 x 12 Compressive Strength Cylinder	AASHTO T 23-97 AASHTO T 22-97	4
4 x 8 Compressive Strength Cylinder	AASHTO T 23-97 AASHTO T 22-97	4

Table 3. Technicians

Test Method or Specimen Cast	ACI Certified Technician
Volumetric Air	Keith Honeycutt
Gravimetric Air & Unit Weight	Jamey Dotson
Chace Air Indicator	Heather J. Sauter
Compressive Strength Specimens	Mark Cates
Slump	Provided by TRMCA (varied by location)
Air by Pressure Method	Provided by TRMCA (varied by location)

RESULTS

PCC plastic air results are shown in Table 4. Slump and temperature results are shown in Table 5. Compressive strength results are shown in Table 6. The compressive strength results shown are the mean value of two test specimens. Since compressive results were to be used in subsequent correlations, they were not rounded to the nearest 10-psi.

Table 4. Air Test Results

Producer - Batch	Pressure Method		Volumetric Method		Chace Air Indicator		Gravimetric Method	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
1-1	7.40	7.60	6.50	5.00	9.60	6.10	7.50	7.80
1-2	9.30	8.90	8.00	7.50	9.60	11.10	10.00	10.20
1-3	5.30	5.10	5.50	5.00	5.40	4.00	6.10	6.10
1-4	2.30	2.20	2.00	1.75	2.40	2.40	2.10	2.40
1-5	8.80	8.80	8.50	8.25	9.60	8.20	8.80	9.70
1-6	5.50	5.10	5.00	5.00	5.40	5.40	6.40	5.60
2-1	4.30	4.30	3.50	3.50	4.10	4.10	3.70	3.20
2-2	5.30	5.10	4.25	4.00	7.10	7.70	4.70	4.70
2-3	4.30	4.50	3.25	3.25	6.40	5.50	4.10	3.70
2-4	4.40	4.20	3.25	3.25	7.10	6.40	4.10	3.80
2-5	3.90	4.00	3.25	3.00	4.10	3.40	4.30	2.70
3-1	6.20	6.20	3.50	3.50	5.60	5.60	7.00	6.10
3-2	6.00	6.00	5.50	5.50	6.50	7.20	7.60	6.80
3-3	5.30	5.30	4.75	4.50	4.90	5.60	5.60	6.10
3-4	7.00	7.10	6.00	6.00	7.80	7.80	8.80	8.40
3-5	4.50	4.10	3.50	3.50	4.10	5.60	5.80	4.90
4-1	3.10	3.20	2.00	2.50	1.80	1.80	3.20	2.40
4-2	2.30	2.20	2.25	2.50	1.80	3.20	3.00	1.00
4-3	4.10	4.10	2.75	2.75	3.20	3.90	3.60	3.40
4-4	4.30	4.00	3.00	3.00	2.50	3.20	3.70	2.90
5-1	4.20	3.80	2.50	2.25	2.60	2.60	5.10	4.70
5-2	2.20	3.80	3.00	2.75	3.20	4.00	5.40	5.30
5-3	4.30	4.40	3.25	3.25	2.60	5.40	5.30	4.50
5-4	4.60	4.40	3.50	3.50	2.60	3.20	5.20	5.10
6-1	7.10	7.20	6.00	5.75	7.20	7.80	7.80	5.90
6-2	7.50	7.30	7.00	7.00	7.20	7.80	6.50	5.40
6-3	7.00	6.80	6.00	6.00	6.30	7.80	6.20	5.60
6-4	6.50	5.80	5.75	5.75	7.20	7.80	6.00	5.30
7-1	3.50	3.40	2.75	3.00	2.60	3.30	2.60	2.20
7-2	4.40	4.20	2.25	2.50	1.10	1.80	5.00	3.80
7-3	3.40	3.30	2.50	2.50	1.80	1.80	3.20	4.00
7-4	3.60	3.40	2.25	2.25	2.60	3.30	3.50	2.90

Table 5. Slump and Temperature Results

Producer - Batch	Slump (inches)	PCC Temperature (°F)	Ambient Temperature (°F)
1-1	2.25	80	68
1-2	7.00	80	71
1-3	5.50	80	68
1-4	2.25	81	71
1-5	4.50	84	74
1-6	5.25	85	78
2-1	3.50	70	66
2-2	3.75	78	61
2-3	3.25	80	61
2-4	3.25	79	62
2-5	4.00	92	81
3-1	3.50	84	71
3-2	4.50	88	73
3-3	3.50	87	74
3-4	6.00	87	74
3-5	3.50	92	78
4-1	3.50	98	54
4-2	4.00	94	55
4-3	5.75	94	55
4-4	6.88	91	55
5-1	2.75	81	62
5-2	4.25	82	64
5-3	2.25	79	63
5-4	3.75	79	64
6-1	3.50	85	79
6-2	6.50	86	75
6-3	3.00	87	84
6-4	3.25	79	86
7-1	1.00	83	85
7-2	4.50	87	85
7-3	3.50	83	79
7-4	2.00	84	79

Table 6. Compressive Strength Results

Producer - Batch	Compressive strength in lbs/in^2 (6-by-12-inch cylinders)		Compressive strength in lbs/in^2 (4-by-8-inch cylinders)	
	7-days	28-days	7-days	28-days
1-1	2689	3672	3244	3912
1-2	2344	3026	2434	3469
1-3	3109	4286	3639	4757
1-4	4073	4931	4769	5743
1-5	2684	3486	3043	4058
1-6	3682	4865	4016	5015
2-1	4119	5288	4748	5574
2-2	3710	4804	4224	5286
2-3	3836	5000	4497	5672
2-4	3945	5022	4660	5975
2-5	3770	4525	4367	5086
3-1	3691	5129	3823	5290
3-2	3478	4846	3792	5125
3-3	3941	5336	4209	5656
3-4	3224	4522	3312	4795
3-5	4060	4926	4202	5585
4-1	4396	5525	5109	6569
4-2	4531	6161	4865	6636
4-3	4912	6420	5463	7014
4-4	3743	5150	4143	5522
5-1	4567	5762	4827	5987
5-2	4776	5993	5337	6680
5-3	5439	6707	5680	7416
5-4	5255	6628	5704	7203
6-1	2938	3911	3342	4299
6-2	2838	3831	3106	4144
6-3	3609	4713	4119	4908
6-4	3492	4561	3875	4841
7-1	6746	8801	7486	9364
7-2	4625	6418	4830	6680
7-3	5679	7456	5834	7979
7-4	6294	7863	6900	9018

ANALYSIS OF RESULTS

Specification Compliance

Figures 4 through 10 show mean air contents for the four AASHTO methods for each batch provided. Each figure represents a producer. Dashed lines indicate TDOT Class A PCC air content specification limits.

Figures 11 through 14 show mean compressive strength values by batch for each producer. Figures 11 and 12 show 7 and 28-day compressive strength data respectively for standard 6-by-12-inch cylinders. The dashed line on figures 11 and 12 indicates the TDOT minimum compressive specification for TDOT Class A PCC at 28-days. Figures 13 and 14 show 7 and 28-day compressive strength data respectively for 4-by-8-inch cylinders

Data Quality

Table 7 shows the percent of PCC batches in compliance with TDOT Class A PCC specifications. Unfortunately, 56.25 percent of the batches delivered failed to comply with TDOT specifications. Some producers were obviously working on their mixtures in an attempt to achieve specification compliance. The alteration of mixture proportions from batch to batch made it difficult to isolate test method as the variable being studied. Even a small alteration of mixture proportions can have a large effect on gravimetric and Chace observed air contents. However. the data was real field data and allowed the research team to see how various air determination methods performed on mixtures with air contents outside the TDOT Class A Specification Limits.

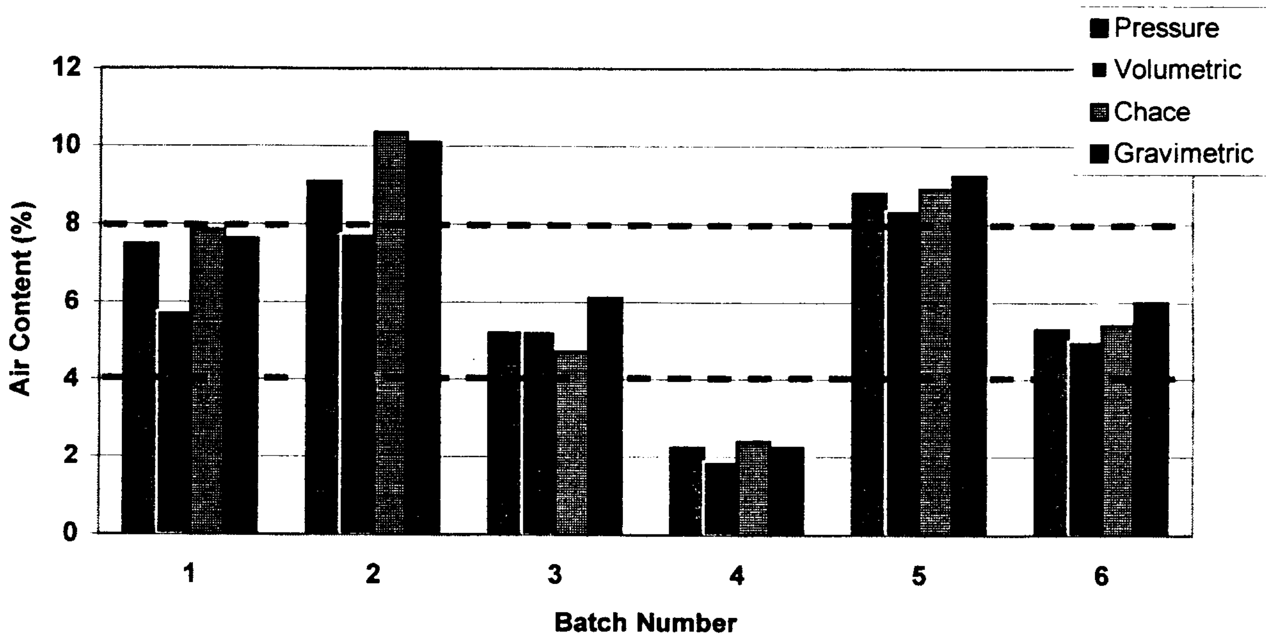

Figure 4. Air Content of Producer 1 Batches

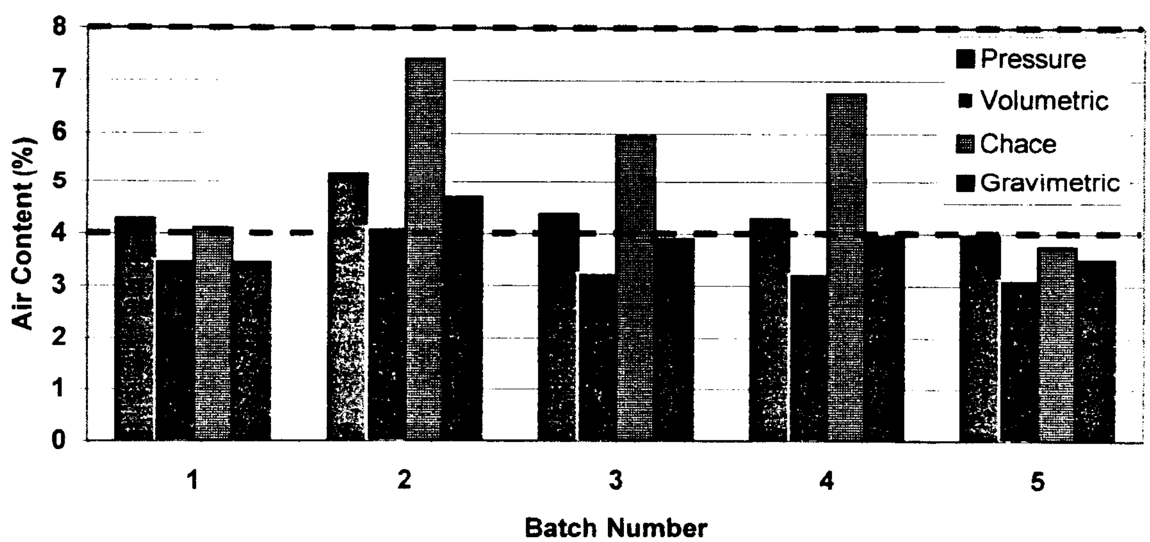

Figure 5. Air Content of Producer 2 Batches

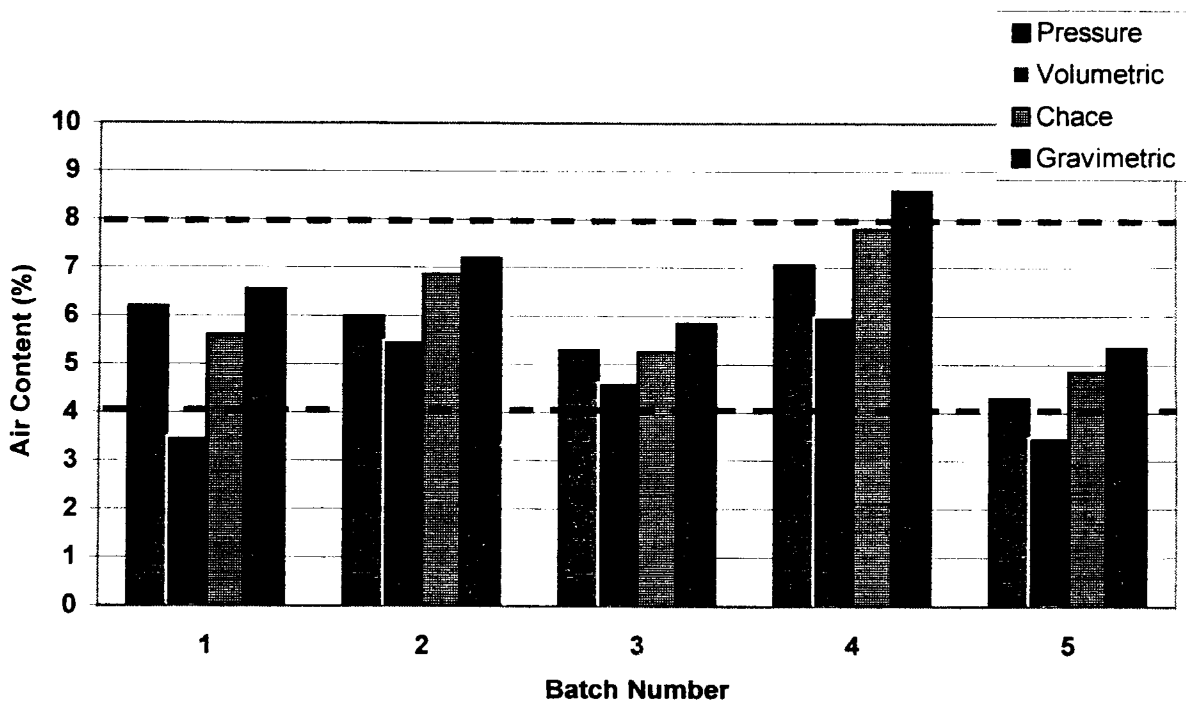

Figure 6. Air Content of Producer 3 Batches

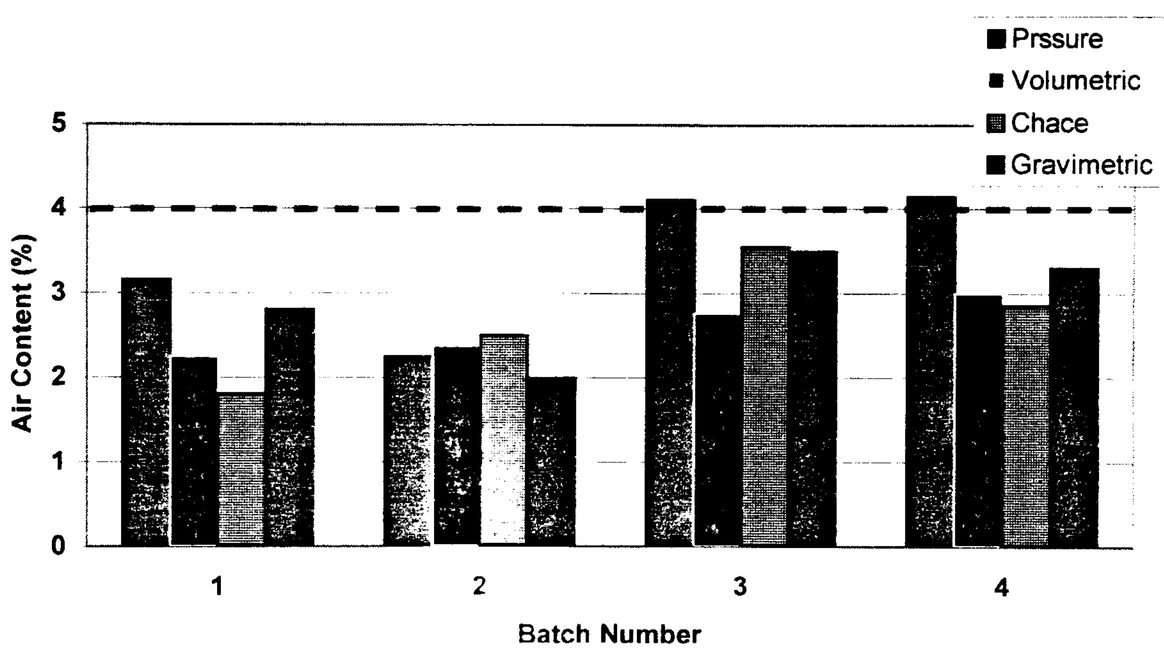

Figure 7. Air Content of Producer 4 Batches

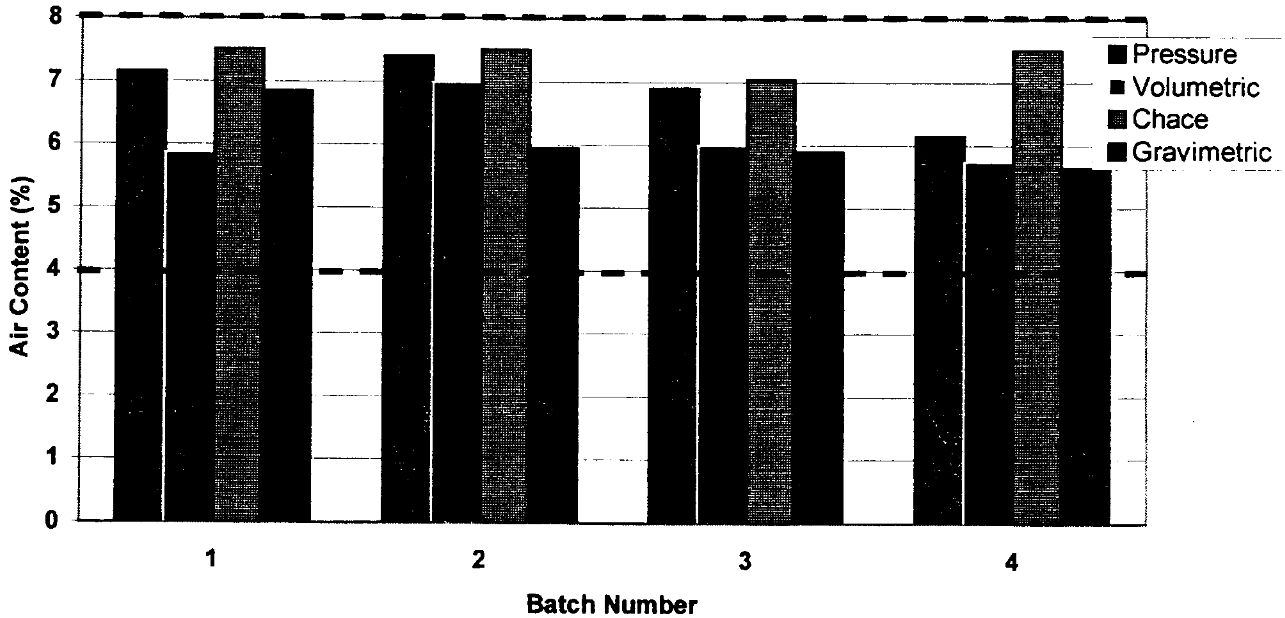

Figure 8. Air Content of Producer 5 Batches

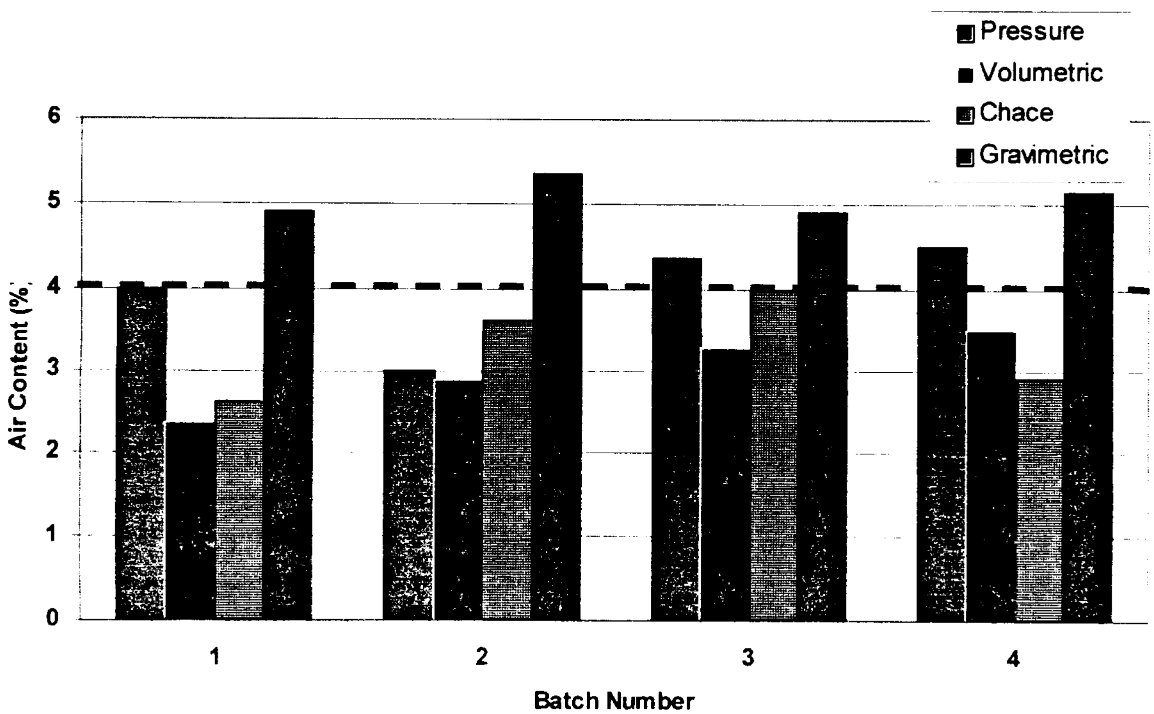

Figure 9. Air Content of Producer 6 Batches

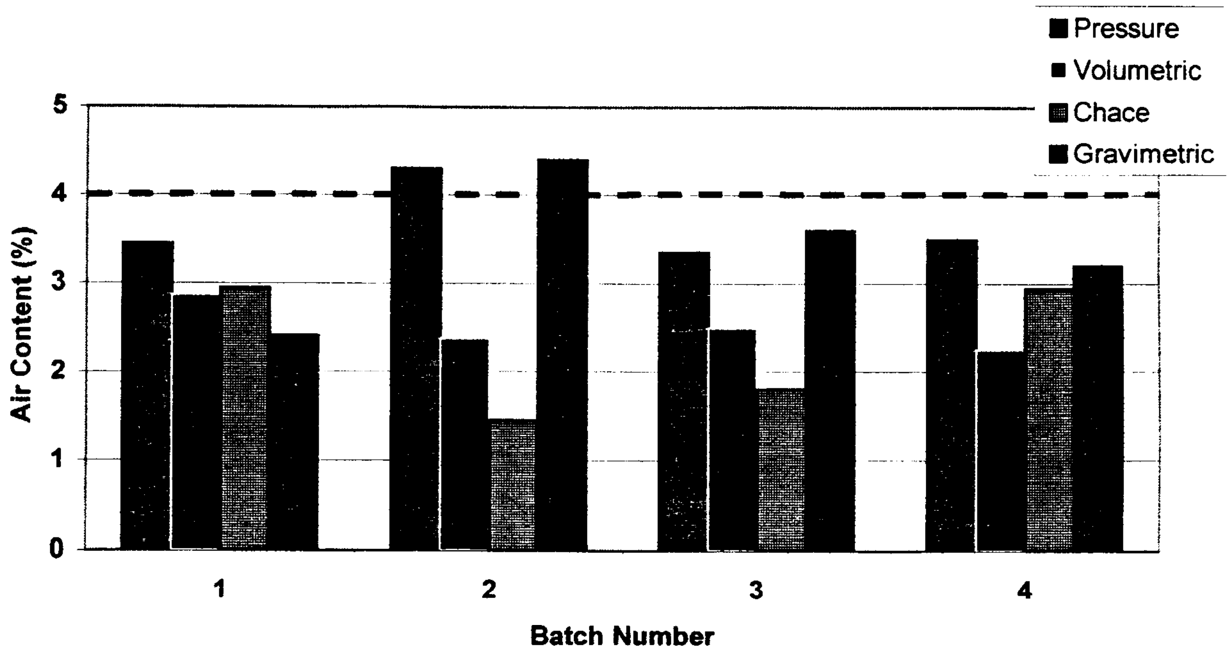

Figure 10. Air Content of Producer 7 Batches

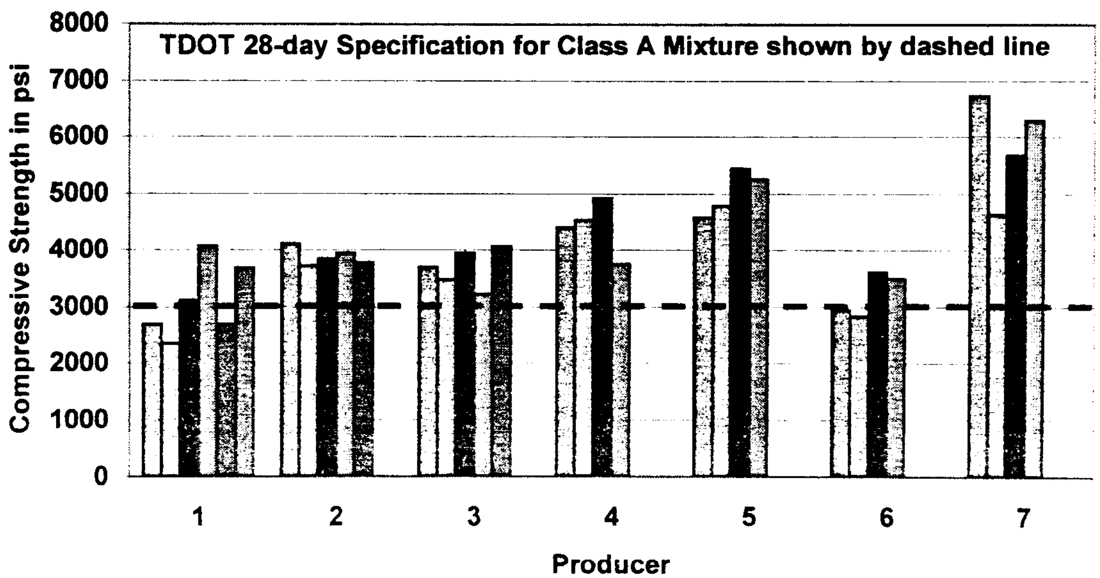

Figure 11. 7-day Compressive Strength in lbs/in^2 (6-by-12-inch cylinders)

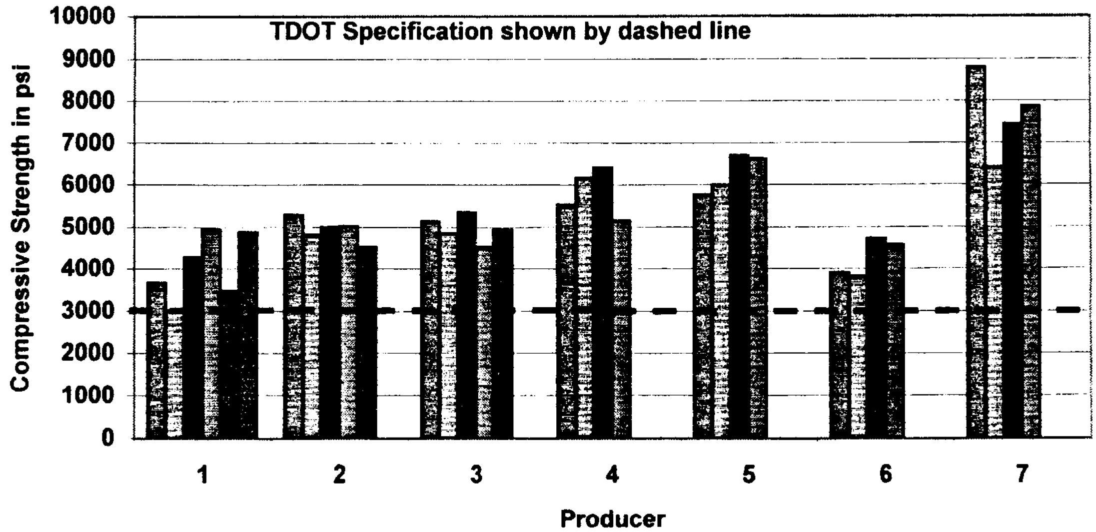

Figure 12. 28-day Compressive Strength in lbs/in^2 (6-by-12-inch cylinders)

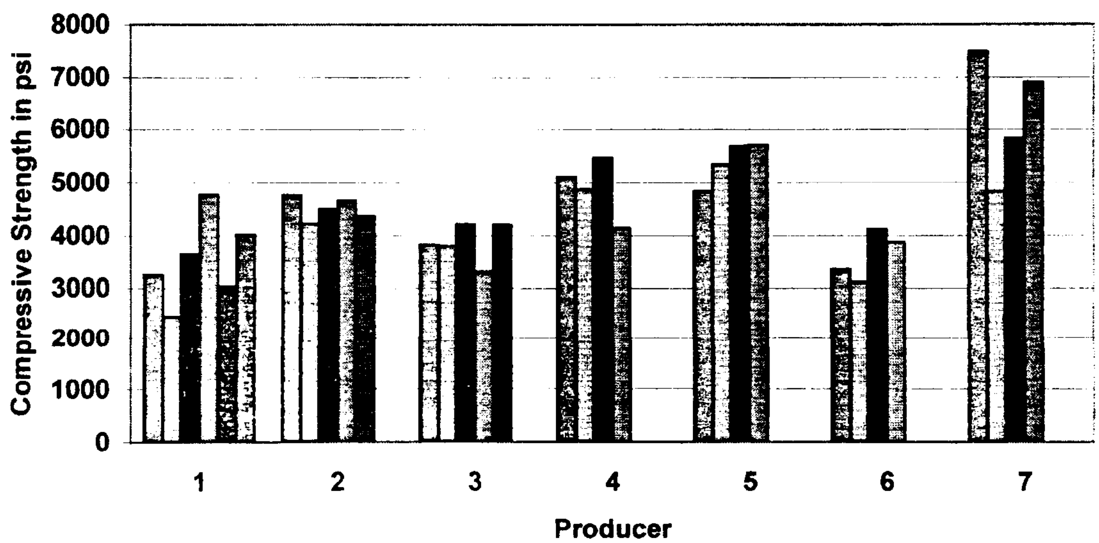

Figure 13. 7-day Compressive Strength in lbs/in^2 (4-by-8-inch cylinders)

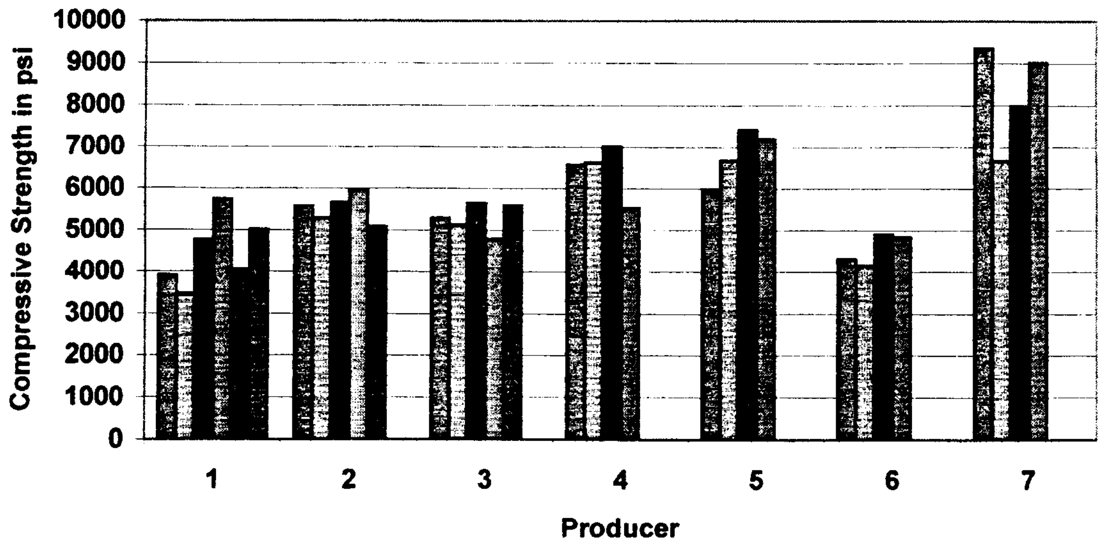

Figure 14. 28-day Compressive Strength in lbs/in^2 (4-by-8-inch cylinders)

Table 7. Percent Compliance with TDOT Specifications

Producer	Slump	Air (Pressure Method)	Compressive Strength	All Specifications
1	33	50	100	17
2	100	80	100	80
3	60	100	100	60
4	50	50	100	0
5	75	75	100	75
6	75	100	100	75
7	50	25	100	0
All Producers	62.5	68.75	100	43.75

Table 8 shows the range of air content by pressure meter, slump range, and compressive strength range for the batches provided by each producer.

Table 8. Producer Batch-to-Batch Variability

Producer	Slump Range (inches)	Air Range (%) (Pressure method)	28-day Compressive Strength (psi) (6-by-12-inch cyl's)
1	4.75	6.85	1905
2	0.75	1.25	763
3	2.5	2.75	814
4	3.38	1.9	1270
5	2	1.5	955
6	3.5	1.3	882
7	3.5	0.95	2383

Logistical Factors

Figure 15 shows the average time to conduct a test for the four air determination methods. The gravimetric and pressure methods each required less than three minutes. The Chace method required approximately twice as long. The volumetric method required over five times as long as to perform a test as the gravimetric or pressure. Further, the physical effort required to conduct a test was much greater for the volumetric method than any other method. From a productivity point of view, the volumetric method was clearly inferior to all other methods.

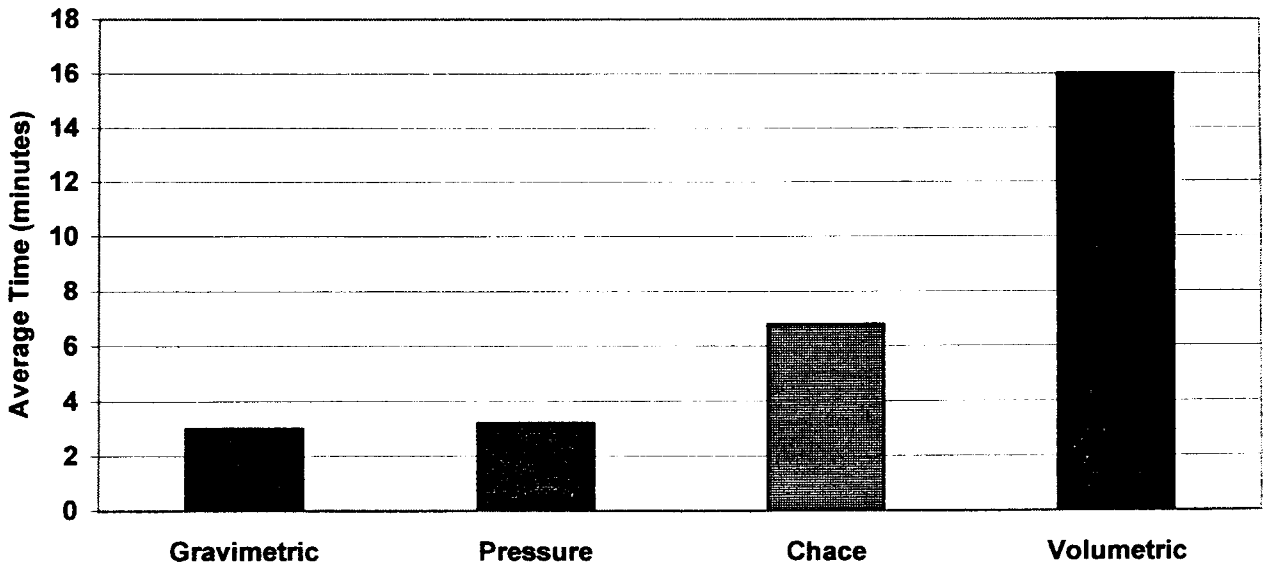

Figure 15. Average Time to Conduct an Air Test

Figure 16 shows the initial cost of the four methods. The Chace Indicator had the lowest initial cost and the gravimetric method had the highest initial cost. The high cost of the gravimetric method was due to the necessity of purchasing a balance. However, initial cost of all the methods was less than $ 1200. Initial cost does not appear to be a critical factor in the selection of the most appropriate AASHTO PCC plastic air determination technique. Figure 17 shows the estimated cost of 10,000 tests for each method. Productivity considerations dominate the trends due to low initial cost of the methods. As previously stated, the volumetric method is clearly inferior in productivity.

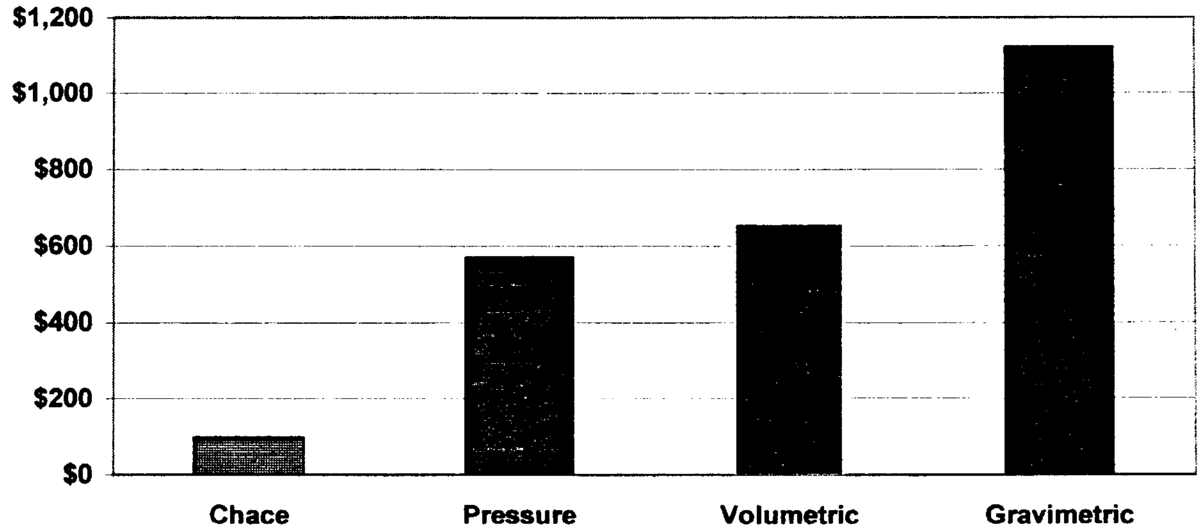

Figure 16. Initial Cost of Method Apparatus

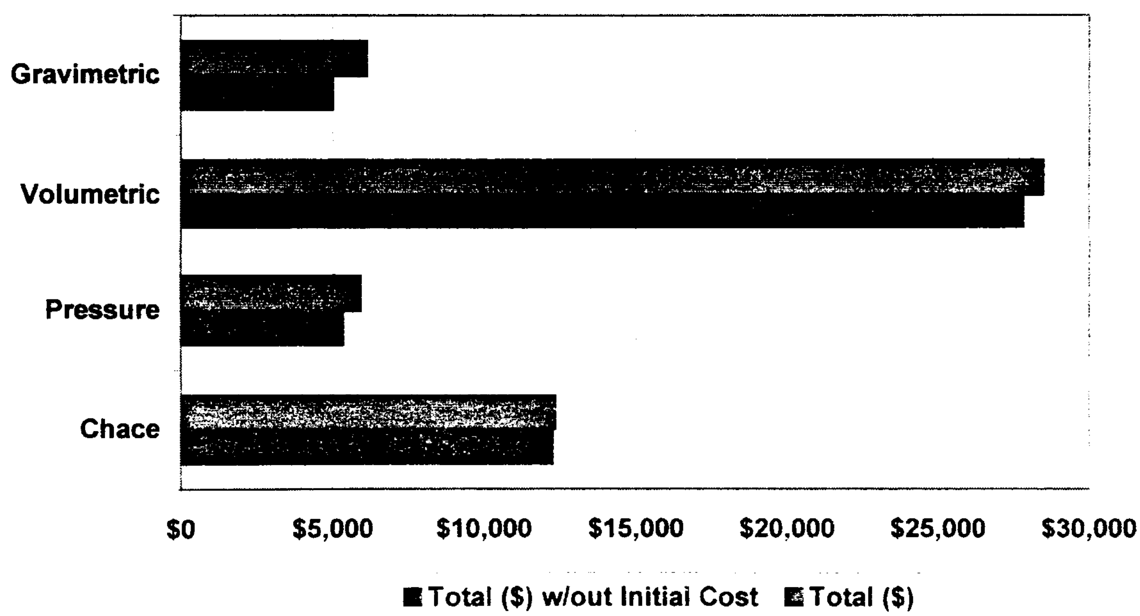

Figure 17. Cost of Methods (assumed life of 10,000 tests)

Precision

Figure 18 shows the average range between the results of test 1 and test 2 for the four air determination techniques. The pressure and volumetric method were the most repeatable methods with average ranges of approximately 0.2. The average range of the gravimetric method was about 3 times that of the pressure and volumetric methods. The Chace Indicator had the worst repeatability of the four methods with an average range almost four times that of the pressure and volumetric methods.

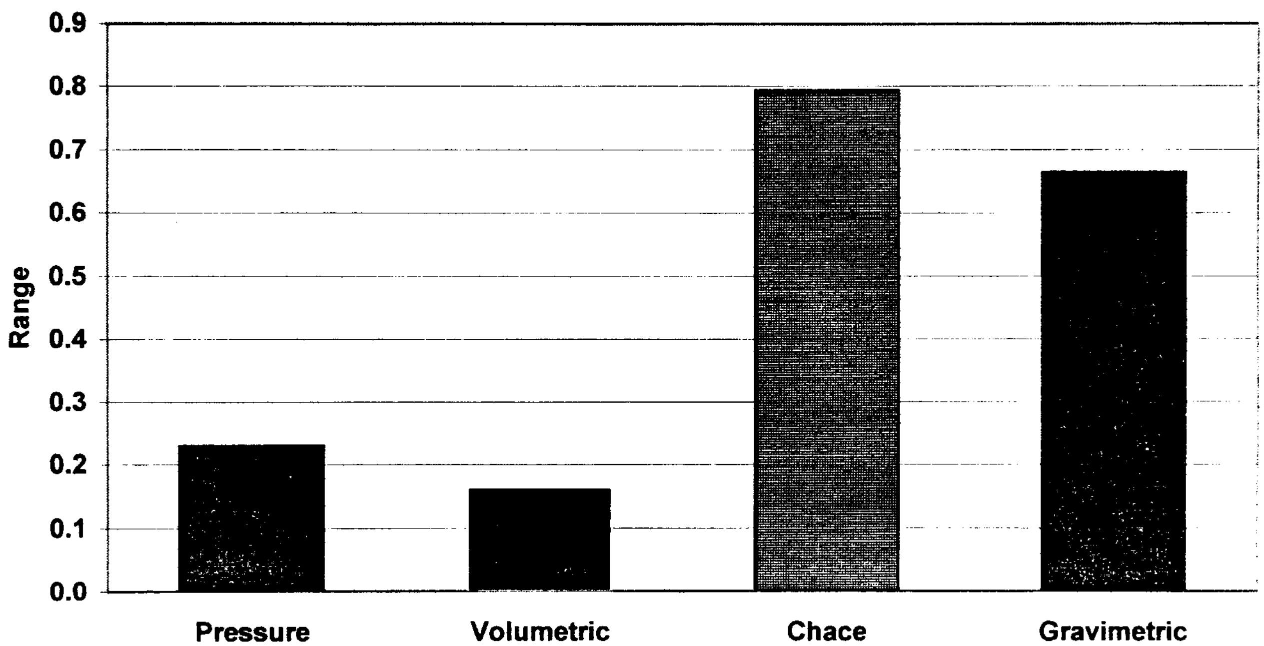

Figure 18. Average Method Range for 32 Batches

A paired t-test at the ninety-five percent confidence interval was conducted on test results 1 and 2 for each method to obtain an additional measure of repeatability. The data from each producer was considered a set for purposes of the t-test. The research team reasoned that a good test method should as minimum show no significant difference in results on the same PCC sample. The results of the t-test are shown in Table 9. The pressure and volumetric method results of test 1 and 2 showed no significant differences for any producer. However, Chace and gravimetric results of tests 1 and 2 each exhibited significant differences for one of the seven producers.

Table 9. Significant Difference (95 % Confidence) in Air Test 1 and Test 2

	Pressure Method	Volumetric Method	Chace Air Indicator	Gravimetric Method
Significant Difference	No	No	Yes 1 of 7 Producers	Yes 1 of 7 Producers

Differences, Correlations, and Rankings

A paired t-test with a two-tailed distribution at the ninety-five percent confidence interval was conducted on the mean air content test results to determine if there was a significant difference between method results. The t-test was conducted in two ways. First, the data from each producer was considered to be a set. Second, all thirty-two batches were considered to be one data set. The results of the t-test are shown in Table 10.

Table 10. Significant Difference (95 % Confidence) Comparing Average Air Results

	Pressure vs. Volumetric	Pressure vs. Chace Indicator	Pressure vs. Gravimetric	Volumetric vs. Chace Indicator	Volumetric vs. Gravimetric	Chace Indicator vs. Gravimetric
Individual Producer	Yes 2 of 7 Producers	Yes 1 of 7 Producers	Yes 1 of 7 Producers	Yes 2 of 7 Producers	Yes 2 of 7 Producers	Yes 2 of 7 Producers
All Producers	Yes	No	No	Yes	Yes	No

Figures 19 through 24 show correlations between the four air determination methods. The dashed line in each figure show the equity line for reference. A solid line and equation in each figure show the linear regression of the data.

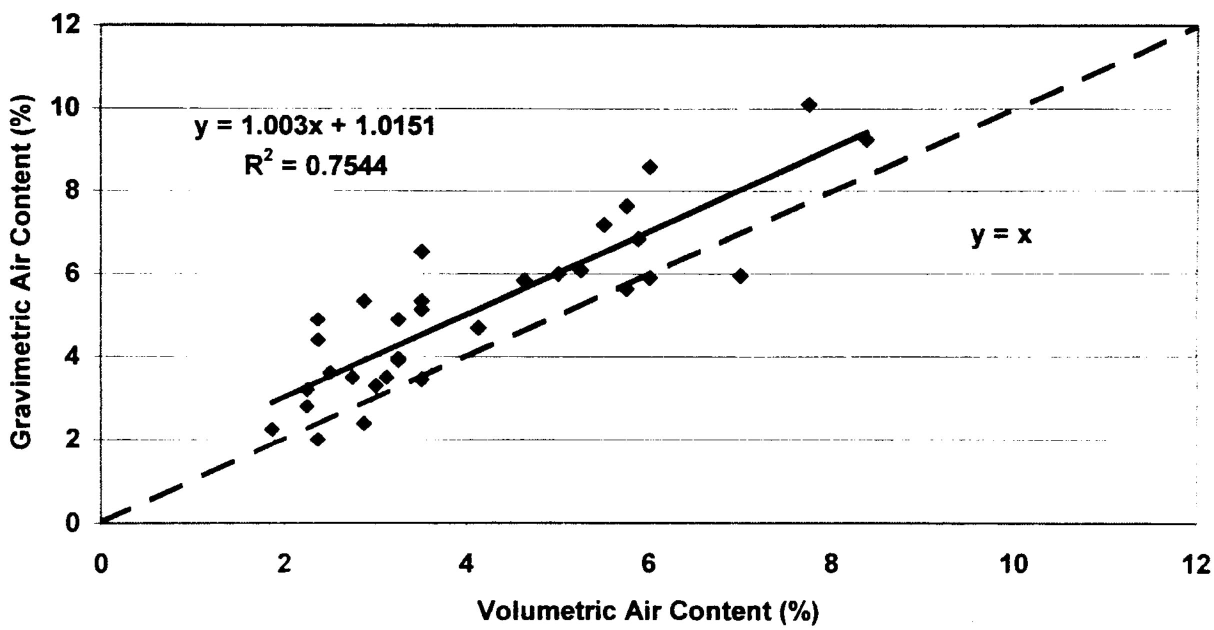

Figure 19. Comparison of Gravimetric and Volumetric Air Contents

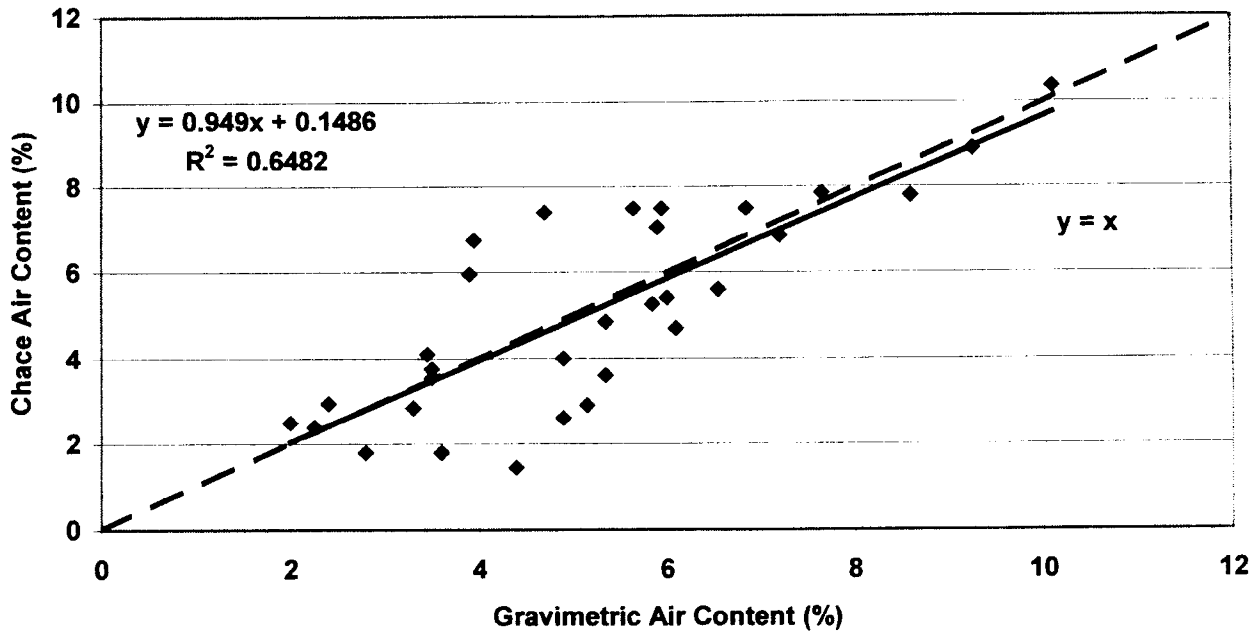

Figure 20. Comparison of Chace and Gravimetric Air Contents

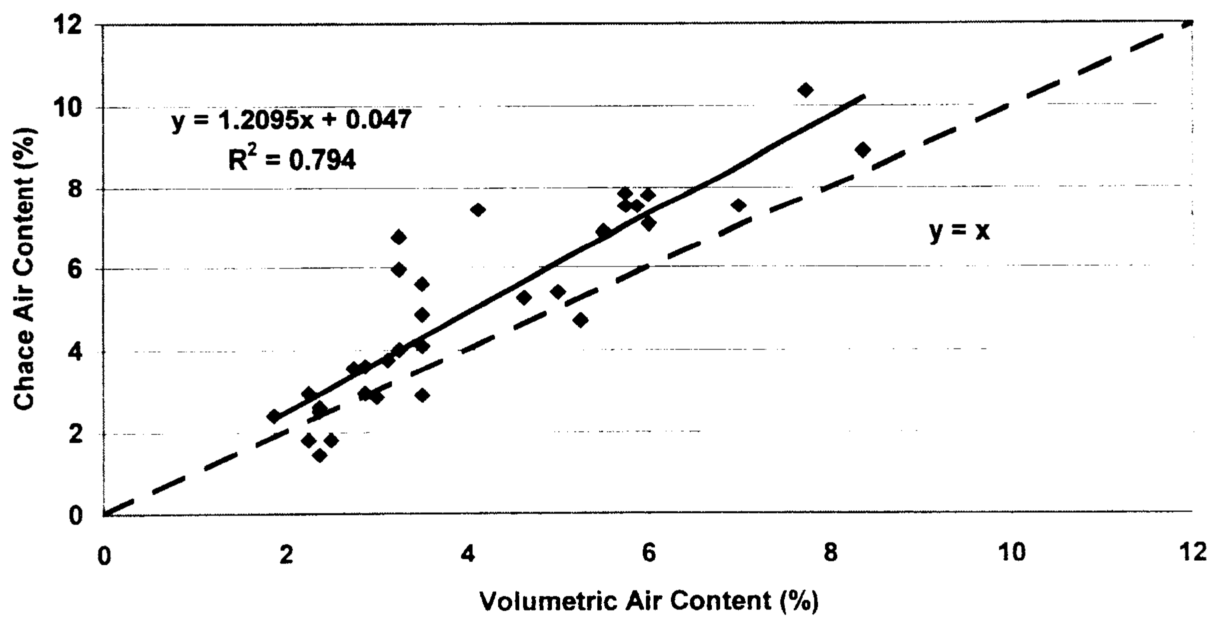

Figure 21. Comparison of Chace and Volumetric Air Contents

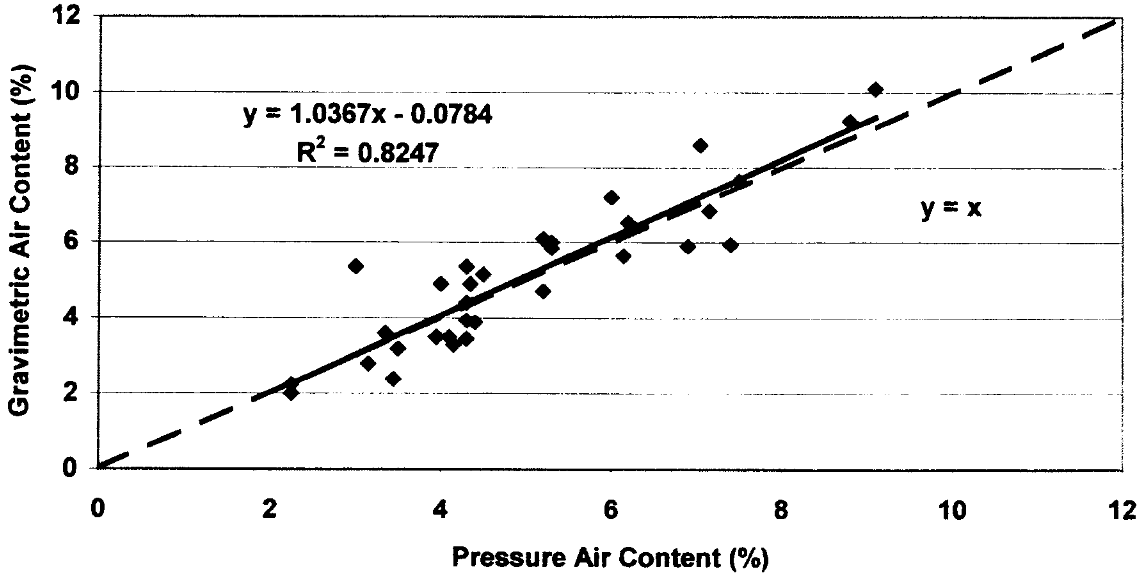

Figure 22. Comparison of Gravimetric and Pressure Air Contents

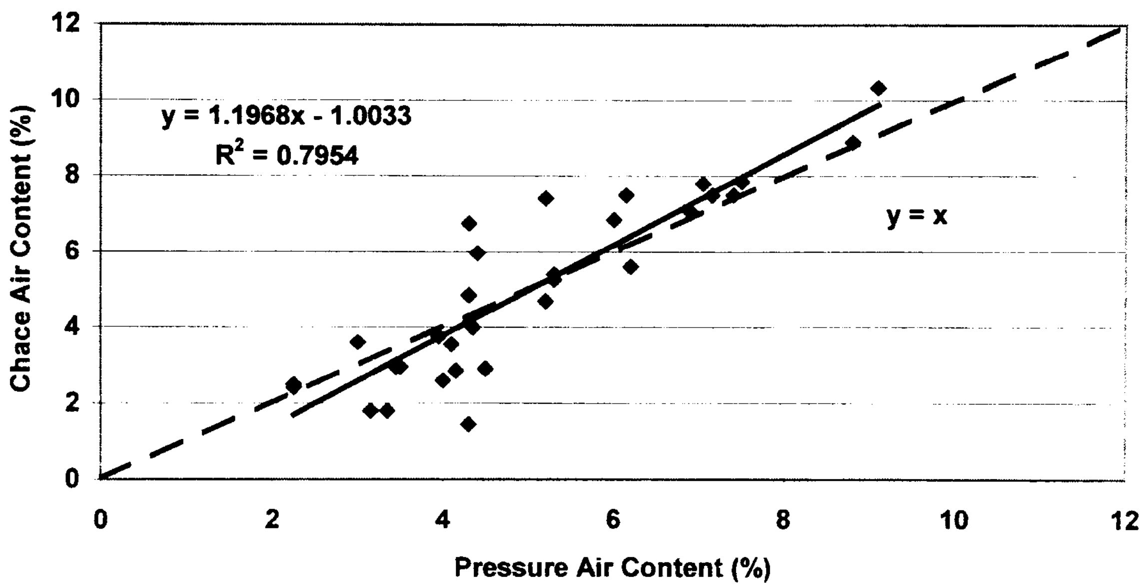

Figure 23. Comparison of Chace and Pressure Air Contents

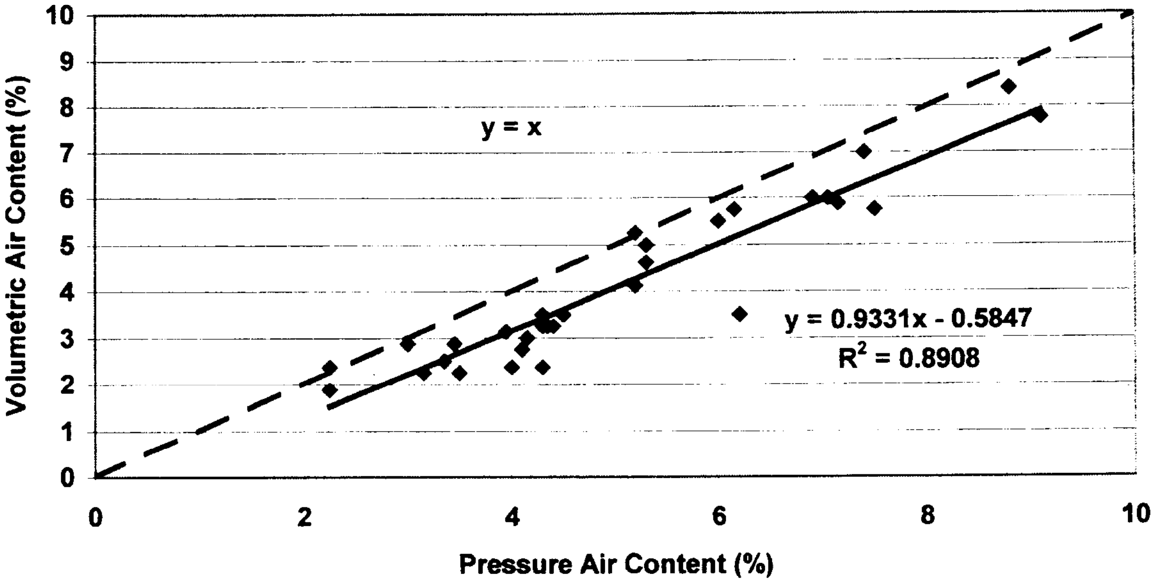

Figure 24. Comparison of Volumetric and Pressure Air Contents

Table 11 shows a summary of the linear regression analysis for the air content plots. The coefficients of determination ranged from 0.6482 to 0.8908. Not surprisingly, the two methods exhibiting the lowest repeatability, Chace and gravimetric, produced the lowest weakest relationship. Similarly, the two most repeatable methods, pressure and volumetric, produced the strongest relationship. It is interesting to note that according to the regression equations, the volumetric method will always produce the lowest air content of all methods.

Table 11. Air Content Regression Summary

	Gravimetric vs. Volumetric	Chace vs. Gravimetric	Chace vs. Volumetric	Gravimetric vs. Pressure	Chace vs. Pressure	Volumetric vs. Pressure
x coeff.	1.003	0.949	1.2095	1.0367	1.1968	0.9331
Constant	1.0151	0.1486	0.047	-0.0784	-1.0033	-0.5847
y = x	Never G > V	x = 2.91 < x, C> > x, G >	Never C > V	x = 2.14 < x, P> > x, G >	x = 5.10 < x, P> > x, C >	Never P > V
R^2	0.7544	0.6482	0.794	0.8247	0.7954	0.8908

Table 12 shows rankings of average method results for each batch. Batches were divided into categories of air content below specification, in specification, and above specification to determine if magnitude of air content effected method rank. For air contents below the specification limit, the pressure method indicated the highest observed content and the volumetric method indicated lowest observed air content for fifty percent of the eight cases. The ranking of the Chace and gravimetric observed air contents was erratic due to the higher variability of results from these methods. No clear trend was evident for Chace or gravimetric method rankings. For air contents within the specification limits, the gravimetric produced the highest observed air contents fifty-five percent of the time and the volumetric method produced the lowest observed air content sixty-four percent of the time. Only two cases of air above specification limits occurred and the research considered this too little data from which to draw any meaningful conclusions. Considering all thirty-two cases as a set, the volumetric method produced

Table 12. Ranking of Air Contents

	Low Air Pressure < 4% (8 of 32)	Air in Spec. 4 < PA < 8 (22 of 32)	High Air Pressure > 8% (2 of 32)	All Air Contents (32 of 32)
Pressure Method	50% highest 0% lowest	14% highest 0% lowest		22% highest 0% lowest
Volumetric Method	0% highest 50% lowest	0% highest 64% lowest	100% lowest	0% highest 63% lowest
Gravimetric Method	25% highest 25% lowest	55% highest 18% lowest	50% highest	47% highest 19% lowest
Chace Air Indicator	25% highest 25% lowest	32% highest 18% lowest	50% highest	31% highest 19% lowest

the lowest observed air content sixty-three percent of the time; the pressure method produced the highest observed air content twenty-two percent of the time, the gravimetric and Chace methods together produced the highest observed air content sevety-eight percent of the time.

Perhaps of the greatest interest is that the pressure method never produced the lowest observed air content and the volumetric method never produced the highest observed air content. Both of these methods showed far greater consistency in ranking than the Chace or gravimetric methods. Consistency of results is an attractive feature for a materials test method.

Non-productive Analysis

Several avenues of analysis were pursued and subsequently abandoned. Specifically, correlations between average method air contents and both hardened PCC cylinder weights and PCC compressive strengths were attempted. Both sets of correlations were extremely poor probably due to several producers altering mixture proportions in an attempt to achieve specification compliance.

The research team also wished to investigate the difference in observed air contents for the four methods resulting from whether the PCC producer used a synthetic air generator or venisol resin. Unfortunately, all PCC producers in the study used a synthetic air generator and no such comparison was possible. A PCC admixture account executive subsequently informed the research team that venisol resin air generators are rarely used due to economic considerations. An accuracy evaluation was planned for the study. However, the research team was unable to produce a material similar to TDOT Class A PCC with a known air content that was compatible with the four AASHTO methods for plastic PCC air determination.

Narrowing the Field

The Chace Air Indicator had numerous disadvantages compared to current TDOT air determination methods. First the Chace average range was approximately four times the ranges of current TDOT methods, indicating inferior precision. In figure 23, the correlation line crosses the line of equity at 5.1 percent, indicating that the Chace produces lower air contents than the pressure method below this value and higher observed air content above this value. A closer look at figure 23 reveals that for seven pressure method results between 4.0 and 4.5 percent, Chace results ranged from 1.5 to 6.75 percent. For the thirty-two batches, the Chace produced the highest observed air content 31 percent of the time and the lowest observed air content 19 percent of the time. The preceding observations coupled with the small sample size of the Chace compared to other methods suggest that results may be highly variable. Logistically, the Chace required twice the time to perform as either current TDOT method, required detailed knowledge of mixture proportions to determine the mortar correction factor required, and was difficult to perform on harsh or dry PCC.

The research team concluded the Chace Air Indicator was not the most suitable currently available AASHTO plastic PCC air determination technique for TDOT. The Chace Air Indicator can be used to determine if the PCC in question is air-entrained. However, the Chace should not be used to quantitatively determine PCC air content for acceptance or quality control due to the high variability of results.

The gravimetric method also had numerous disadvantages compared to current TDOT air determination methods. The gravimetric method average range was approximately three times the average ranges of current TDOT methods, indicating inferior precision. The primary disadvantage of the gravimetric method is that the accuracy of results depend on a detailed knowledge of mixture proportions and component material specific gravities and moisture contents. The method assumes these quantities are constant batch to batch. However, field experience indicates that is rarely true. For the thirty-two batches, the gravimetric method produced the highest observed air content 47 percent of the time and the lowest observed air content 19 percent of the time. The often highest, sometimes lowest behavior indicates considerable variability. From a logistical point of view the gravimetric method was the only method that requires a balance in the field. The balance requirement raises questions of ruggedness and calibration in a field environment therefore introducing another possible source of error. Further, the gravimetric method was difficult to perform on harsh or dry PCC.

The research team concurs with ASTM STP 169C (6); the gravimetric method is much better suited to laboratory use than field use. Therefore the gravimetric method was not the most suitable currently available AASHTO plastic PCC air determination technique for TDOT.

Pressure vs. Volumetric

Elimination of the Chace Air Indicator and the gravimetric method from consideration as the most suitable currently available AASHTO plastic PCC air determination technique, leaves only the pressure method and volumetric method to be considered. Both methods are widely used as indicated in the DOT survey, both methods are currently used by TDOT, and both methods exhibited similar precision. Method rankings, mechanics, and limitations will now be analyzed further.

Referring to Table 4 and figure 24, it can be seen that in thirty of thirty-two cases. 94 percent of the cases, the pressure method produced higher observed average air contents than the volumetric method. The average difference in results was 0.92. The difference was statistically significant at the 0.95 confidence level. In the two cases in which volumetric methods results were greater than pressure method results. the differences were only 0.05 and 0.125. These differences are hardly perceptible, within typical data scatter, and of no practical importance.

The literature review indicated that the pressure method produced observed air content results higher than actual air contents by forcing water into aggregate air voids and compressing the air in the aggregate voids. The literature review also indicated that the volumetric method often produced a lower than actual observed air content due to incomplete agitation resulting in some air not separating from the PCC sample. The rankings of air contents in this study agree with the literature observations of method mechanics for 94 percent of the batches. Therefore, it is very likely that the actual air content lies between the observed values produced by the pressure and volumetric methods. The advantages and limitations of each method are summarized in Table 13.

Table 13. Summary of Pressure and Volumetric Method Comparisons

Parameter	Advantage
Precision	No Advantage
Accuracy	No Advantage
Initial Cost	No Advantage
Physical Effort Required	Pressure Method
Time to Perform a Test	Pressure Method
Applicability to Lightweight Aggregate PCC Mixtures	Volumetric Method
Applicability to High PC Content Mixtures	Pressure Method
Applicability to Sticky PCC Mixtures (i.e. mixtures containing Micro Silica)	Pressure Method

Observed Compressive Strength Correlations

TDOT Materials & Tests Division requested that four-by-eight-inch cylinders be included in the study to provide additional data for an ongoing TDOT investigation on the effect of specimen size on observed compressive strength. Figures 25 and 26 show the difference in observed compressive strength results for four-by-eight-inch and standard six-by-twelve-inch cylinders cast from the same batch for 7 and 28-day results respectively. Each point on the plots represents a pair of four-by-eight-inch and a pair of standard six-by-twelve-inch cylinders. The dashed line on each plot is the line of equity provided for reference. The solid line on each plot is the linear regression line.

Table 14 shows a summary of compressive strength comparisons. Coefficients of determination were very high, 0.9689 for 7-day results and 0.9708 for 28-day results, indicating a very strong correlation. Four-by-eight-inch observed compressive strength results were always higher than the standard six-by-twelve-inch compressive strength results. Average compressive strength differences were 11.1 percent and 9.6 percent respectively at 7 and 28 days.

TDOT Materials & Tests Division was also interested in the relationship between fly ash type and compressive strength. Table 15 shows the results relevant to this correlation. However, the research team believes that the large number of factors influencing compressive strength in this study precluded any meaningful analysis.

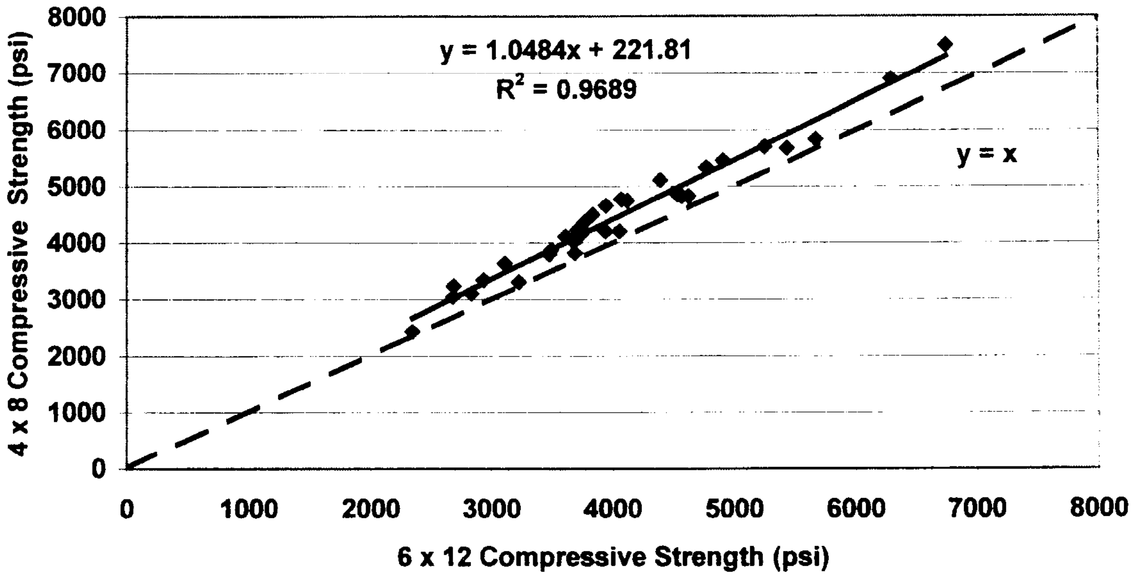

Figure 25. Comparison of 7-day Compressive Strengths

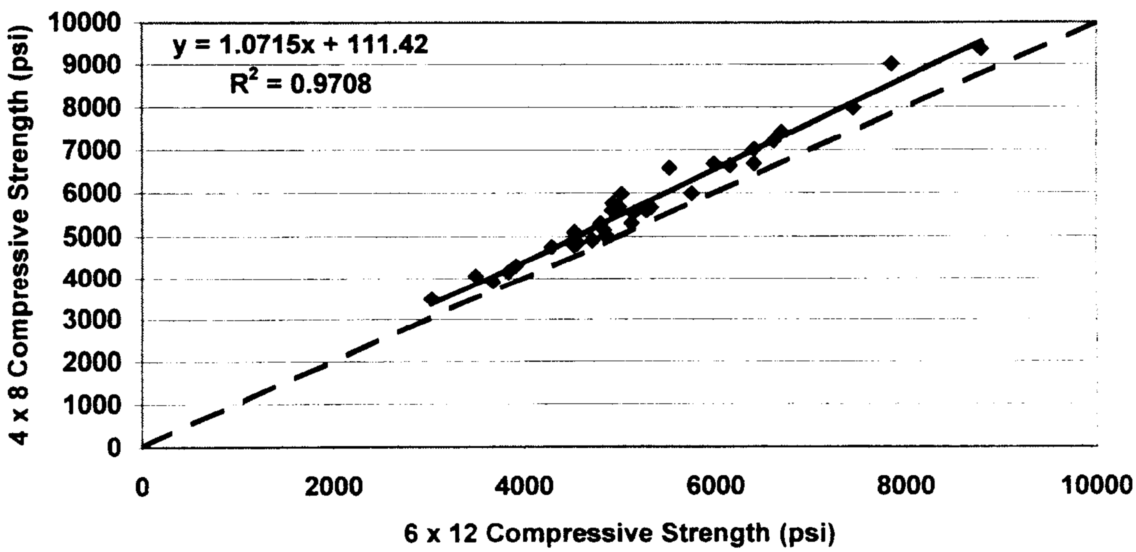

Figure 26. Comparison of 28-day Compressive Strengths

Table 14. Summary of Compressive Strength Comparisons

Parameter	7-day Compressive Strength	28-day Compressive Strength
Minimum % Difference	2.7	3.1
Maximum % Difference	20.6	19.0
Average % Difference	11.1	9.6
X coefficient	1.0484	1.0715
Constant	221.81	111.42
R^2	0.9689	0.9708

Table 15. Effect of Fly Ash Class on 28-day Compressive Strength?

Category / (x) Number of Batches	Class of Fly Ash	Average Compressive Strength in lbs/in^2
Producer 1 (6)	F	4044
Producer 2 (5)	F	4928
Producer 3 (5)	C	4952
Producer 4 (4)	C	5814
Producer 5 (4)	C	6273
Producer 6 (4)	C	4254
Producer 7 (4)	C	7635
All Class F Batches (11)		4446
All Class C Batches (21)		5746
All Batches (32)		5299

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn.

1. The pressure method is the most suitable currently available AASHTO method for determining plastic air content of normal weight aggregate PCC mixtures.

2. The volumetric method is the most suitable currently available AASHTO method for determining plastic air content of lightweight aggregate PCC mixtures.

3. In the vast majority of cases, the true value for plastic PCC air content lies below the observed value determined by the pressure method and above the observed value determined using the volumetric method.

4. Tennessee PCC producer quality control needs improvement.

5. The use of four-by-eight-inch cylinders results in higher observed compressive strengths than standard six-by-twelve-inch cylinders. In this study of TDOT Class A PCC, observed compressive strengths for four-by-eight-inch cylinders averaged 11.1 percent higher at 7 days and 9.6 percent higher at 28 days.

RECOMMENDATIONS

The research team offers the following recommendations to the TDOT Materials and Tests Division.

1. Continue using currently specified AASHTO plastic PCC air determination techniques:
   - Pressure method for normal weight aggregate PCC;
   - Volumetric method for lightweight aggregate PCC;

2. If a more accurate air content is desired, consider:
   - Using aggregate correction factor for pressure method;
   - After conducting a volumetric air test, place the roll-a-meter on a vibrating table and plot of volumetric air content vs. time on the vibrating table (about every 2 minutes for 15 to 30 minutes.

3. To determine the pressure method's ability to accurately measure the air content of PCC with small air voids:
   - Prepare two PCC mixtures (one with venisol resin and one with a synthetic air generator but otherwise identical) in the laboratory under controlled conditions, both mixtures should have a pressure method air content of six percent;
   - Compare gravimetric air contents of the mixtures (gravimetric air content is not influenced by air void size);

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APPENDIX

Cover letter and questionnaire

Date

Dear ----:

The Tennessee Department of Transportation Division of Materials & Tests and the Tennessee Ready Mixed Concrete Association have awarded a contract to Tennessee Technological University for the purpose of comparing AASHTO plastic PCC air determination techniques. The intent of the research is to determine which method consistently provides the most reliable results in field applications. TDOT currently uses the Pressure Method (AASHTO T–152) for most applications and the Volumetric Method (AASHTO T-196) for PCC mixtures containing lightweight aggregates. TDOT & TRMCA would like to benefit from other states experiences with plastic PCC air determination techniques.

Therefore, it would help us to have the attached questionnaire completed so that we may learn what others are doing. It is our intention to keep respondents to our request informed about our progress via e-mail. Thank you for your consideration of this request and should you have a need to discuss, please call or e-mail me.

Sincerely,

L.K. Crouch, Ph.D., P.E.
Principal Investigator

Enclosure

Questionnaire for State Materials Engineers on

Comparison of AASHTO Plastic PCC Air Determination Techniques

To: (name and address) Contact Person: ______________________
(if not same) ______________________
Phone: ______________________
Fax: ______________________
E-mail: ______________________

1. Please indicate your primary field air determination method for **normal-weight aggregate** PCC and which (if any) other methods are allowed.

	Primary	Allowed
Pressure Method AASHTO T 152	________	________
Volumetric Method AASHTO T 196	________	________
Gravimetric Method AASHTO T 121	________	________
Chace Air Indicator AASHTO T 199	________	________
Other ____________________	________	________

2. Please indicate your primary field air determination method for **lightweight aggregate** PCC and which (if any) other methods are allowed.

	Primary	Allowed
Pressure Method AASHTO T 152	________	________
Volumetric Method AASHTO T 196	________	________
Gravimetric Method AASHTO T 121	________	________
Chace Air Indicator AASHTO T 199	________	________
Other ____________________	________	________

3. Please indicate your air content specification for the types of PCC listed (for example the TDOT specification is 4 to 8 percent for all classes of PCC).

	Minimum	Maximum
Normal-weight structural PCC	________	________
Lightweight structural PCC	________	________
Non-structural PCC	________	________
Other ____________________	________	________

4. Are you presently working on a new method and/or a revision in a previous method?
_____ Yes _____ No If yes, please provide details.

5. Please send comments, references, reports, non-standard test methods, etc., that you deem relevant to the study.

If possible, please provide the requested information by 5/14/01. Thank you again.

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