COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

PENNDOT RESEARCH

HARDENED AIR IN CONCRETE ROADWAY PAVEMENTS AND STRUCTURES

Final Report

PennDOT/MAUTC Partnership, Work Order No. 6
Research Agreement No. 510401

January 29, 2007

By D. H. Desai, P. J. Tikalsky and B. E. Scheetz

PENNSTATE

Pennsylvania Transportation Institute

The Pennsylvania State University
Transportation Research Building
University Park, PA 16802-4710
(814) 865-1891 www.pti.psu.edu

Technical Report Documentation Page

1. Report No. FHWA-PA-2007-002-510401-06	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Hardened Air in Concrete Roadway Pavements in Structure		**5. Report Date** January 29, 2007 **6. Performing Organization Code**
7. Author(s) Dhruv H. Desai, Paul J. Tikalsky and Barry E. Scheetz		**8. Performing Organization Report No.** PTI 2007-31
9. Performing Organization Name and Address Pennsylvania Transportation Institute The Pennsylvania State University 201 Transportation Research Building University Park, PA 16802		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** 510401 (WO006)
12. Sponsoring Agency Name and Address The Pennsylvania Department of Transportation Bureau of Planning and Research Commonwealth Keystone Building 400 North Street, 6th Floor Harrisburg, PA 17120-0064		**13. Type of Report and Period Covered** Final Report January 30, 2006 to January 29, 2007 **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

The objectives of this study were to: (1) evaluate the validity of current Pennsylvania Department of Transportation (PennDOT) specifications for plastic and hardened air content for pavements and structures; (2) provide engineering data to correlate the relationship between plastic air measurement instruments (pressure meter), techniques that characterize the air void size and distribution including the Air Void Analyzer (AVA), and the durability of concrete to resist freeze/thaw cycles; (3) resolve PennDOT specifications differences for pavement and structural concrete; and (4) provide a new or revised specification for PennDOT 408 on air content in concrete. To provide supporting experimental evidence for the adoption of the AVA method by PennDOT, the apparatus was evaluated for its internal consistency, the consistency between it and other AVA devices of the same version, consistency between different versions of AVA, comparison between the AVA and the RapidAir 457, comparison with the ASTM C 231 pressure meter, and comparison with the ASTM C 666 performance-based test. The accumulated data were evaluated statistically using standard deviation and coefficient of variation. After performing the analysis of the data collected in this study from intercomparison of different instruments of the same generation, instruments of different generations, and the authors' experience with the robustness of the instrument, it was concluded that this instrument cannot serve as the basis of a specification to evaluate the air content, spacing factors or surface areas in fresh concrete at the job site.

17. Key Words Hardened air, air void, air content, Air Void Analyzer, pressure meter, durability, freeze/thaw cycle, pavement, structural concrete, specifications		**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 66	**22. Price**

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

The objectives of this study were to: (1) evaluate the validity of current Pennsylvania Department of Transportation (PennDOT) specifications for plastic and hardened air content for pavements and structures; (2) provide engineering data to correlate the relationship between plastic air measurement instruments (pressure meter), techniques that characterize the air void size and distribution including the Air Void Analyzer (AVA), and the durability of concrete to resist freeze/thaw cycles; (3) resolve PennDOT specifications differences for pavement and structural concrete; and (4) provide a new or revised specification for PennDOT 408 on air content in concrete.

To provide supporting experimental evidence for the adoption of the AVA method by PennDOT, the apparatus was evaluated for its internal consistency, the consistency between it and other AVA devices of the same version, consistency between different versions of AVA, comparison between the AVA and the RapidAir 457, comparison with the ASTM C 231 pressure meter, and comparison with the ASTM C 666 performance-based test. The accumulated data were evaluated statistically using standard deviation and coefficient of variation.

After performing the analysis of the data collected in this study from intercomparison of different instruments of the same generation, instruments of different generations, and the authors' experience with the robustness of the instrument, it was concluded that this instrument cannot serve as the basis of a specification to evaluate the air content, spacing factors or surface areas in fresh concrete at the job site.

In the intercomparison of AVA instruments of the same generation, the model operated by Penn State showed consistently better results with higher air content value (average difference of 1.23%), lower spacing factor value (average difference of 0.0081 inch), and higher specific surface value (average difference of 163.83 $inch^2/inch^3$). In the intercomparison of AVA instruments of different generations, the model operated by Penn State gave consistently higher air content values, with an average difference of 0.78% . However, the AVA 3000 model operated by PennDOT yielded a lower spacing factor with an average difference of 0.0025 inch, and higher specific surface with an average difference of 313.83 $inch^2/inch^3$. It can be inferred that the results for air void parameters were significantly different, which shows a requirement for careful and precise calibration of the AVA 2000 and AVA 3000 model before use in the field, with checks for calibration at regular intervals.

In the intercomparison study of AVA and RapidAir 457 conducted by Penn State, AVA produced consistently higher spacing factor values and lower specific surface values. The manufacturer claims that the air void parameters calculated by AVA have an average variation of 10% from the air void parameters determined by ASTM C 457, "Standard Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." Assuming that the value of the air void parameters calculated by the RapidAir 457 would be comparable to the manual ASTM C 457 method, the calculated average percentage variation for the air void parameters in the study conducted by Penn State is significantly more than the variation claimed by the manufacturer. In a separate study by the precast industry, given in Appendix C, the spacing factor values determined by AVA were consistently higher and independent of the spacing factor values determined by the manual ASTM C 457 method. In the study carried out for comparing the results for AVA and RapidAir 457 with ASTM C 666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," the durability factor values for ASTM C 666 correlate well with the spacing factor values and specific surface values determined by RapidAir 457, but not with the AVA results.

The existing specifications and recommendations for spacing factor and specific surface are based on empirical correlation between durability of concrete and air void parameters determined by ASTM C 457. Use of AVA will require calibration to known durable concrete. A large-scale study that correlates the air void parameters as determined by AVA with freeze/thaw durability of concrete is required.

1.0 Introduction

Concrete used in the pavements and bridges of Pennsylvania is exposed to moderate to severe winter conditions that can, under the proper circumstances, initiate and accelerate its deterioration. Applications of large quantities of deicing salts and occurrence of freezing and thawing cycles when concrete is in a saturated condition are the two main conditions that contribute to the deterioration of pavements and bridge decks.

In hardened concrete, voids attributable to air that has been "entrapped" during mixing, as well as intentionally added "entrained" voids, can be recognized. Chemical admixtures, known as air-entraining admixtures, produce a stable system of discrete air voids, called "entrained air" in concrete that provides an open space for freezing pore waters to expand into and hence provide freeze/thaw durability to the concrete [11]. The "entrained air" bubbles are between 0.01 mm and 1.3 mm in size and essentially spherical in shape, whereas entrapped voids may range larger in size, from 1 mm to 4 mm, and take on a variety of shapes.

Traditionally as a quality-control measure, the "total" air content, both entrapped and entrained, of fresh concrete is measured on site using test methods like ASTM C 231 pressure method, ASTM C 173 volumetric method or ASTM C 138 gravimetric method [1,4,5].

While evaluating an air void system, in addition to measurement of air content, other metrics are more reliable in describing the potential performance of the concrete. The spacing factor and specific surface measurement have also been found to be good descriptors as the basis for determining the effectiveness of the air void system in providing freeze/thaw durability to the concrete. The "spacing factor," L, is an approximation of the maximum distance the freezing water must travel before it enters an air void. The "specific surface" is the surface area of the air voids divided by their volume. Many specifications use the conservative value of 0.008 inch for the spacing factor as an upper-bound solution, and the specific surface area of a freeze/thaw-resistant air void system in concrete is typically between 600-1,100 in^2/in^3 [2].

The air void system in hardened concrete can be analyzed with a microscope by following the procedure in ASTM C 457, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." This procedure can also be performed using recently developed automated methods such as RapidAir 457. RapidAir 457 calculates the air void parameters based on the principle used by ASTM C 457.

Recently a new method to assess the air void system in fresh mortar derived from concrete in "real time" has been developed and is commercially available. The device used for this assessment is called Air Void Analyzer [AVA]. The instrument is reported to be able to characterize the distribution of air voids in fresh mortars in less than 30 minutes. The problem with C 457 is that when one is determining the air content, it is being done on placed concrete, after the fact. The value of the AVA approach is that it is performed on freshly placed concretes with the potential to identify problems with the air content and make modifications to subsequent concrete batches. The promise of this method is to take this information and use it for quality assurance on site by making adjustments during the concrete batching process to ensure that air voids are spaced properly. Other states and agencies are evaluating its performance; these are summarized in Appendix A.

2.0 Purpose

The objectives of this study were to: (1) evaluate the validity of current PennDOT specifications for plastic and hardened air content for pavements and structures; (2) provide engineering data to correlate the relationship between plastic air measurement instruments (pressure meter), techniques that characterize the air void size and distribution including the Air Void Analyzer (AVA), and the durability of concrete to resist freeze/thaw cycles; (3) resolve PennDOT specifications differences for pavement and structural concrete; and (4) provide a new or revised specification for PennDOT 408 on air content in concrete.

2.1 Approach

To provide supporting experimental evidence for the adoption of the AVA method by PennDOT, the apparatus was evaluated for it internal consistency, the consistency between different AVA devices of the same version, consistency between different versions of AVA, comparison between the AVA and the RapidAir 457, comparison with the ASTM C 231 pressure meter, and comparison with the ASTM C 666 performance-based test.

2.1.1 Tests Conducted

AVA testing was performed both onsite and in the laboratory. For onsite testing, all the locations were near Pittsburgh, PA. Laboratory testing was done at Penn State's Civil Infrastructure Testing and Evaluation Laboratory (CITEL) facilities in State College, Pa. All field samplings are identified in Table 1. These include paving jobs at Findlay and Export and a trial mixture pad at Export.

2.2 Equipment Description

2.2.1 Air Void Analysis Apparatus

The Air Void Analyzer, better known as AVA, was developed by Dansk Beton Teknik (DBT) which is based in Hellerup, Denmark. A photograph of the apparatus is presented in Figure 1 (page 6). The AVA is used to determine parameters of air voids in concrete based on analysis of samples of mortar obtained from fresh concrete.

The AVA measures the volume of the entrained air in the mortar and calculates the size distribution of entrained air voids in fresh concrete by measuring the amount of air as a function of time as it rises through a column of water. The sizes of the air voids are determined by the application of Stokes' Law [18] to the movement of air bubbles rising in a column of water. Subsequent estimates of the spacing factor, the specific surface, and the total amount of entrained air are calculated from the primary data.

Table 1. Sample Identification and Location for All AVA Test Samples.

Mixture No.	Name	Tests Performed	Location
1	Clinton Road	AVA, RapidAir 457, ASTM C 666 , ASTM C 231	Findlay JMF No.: 06- 223
2	Murrysville 1	AVA, ASTM C 231	Export JMF No. : 06- 2A001
3	Murrysville2	AVA, ASTM C 231	Export JMF No. : 06- 2A001
4	Murrysville 3	AVA, ASTM C 231	Export (Batch Plant) JMF No. : 06- 2A001
5	Murrysville Trial Mixture Pad 1	AVA, RapidAir 457, ASTM C 666, ASTM C 231	Export (Batch Plant) JMF No. : 06- 2A001
6	Murrysville Trial Mixture Pad 2	AVA, RapidAir 457, ASTM C 231	Export (Batch Plant) JMF No. : 06- 2A001
7	Murrysville Trial Mixture Pad 3	AVA, RapidAir 457, ASTM C 231	Export (Batch Plant) JMF No. : 06- 2A002
8	Murrysville Trial Mixture Pad 4	AVA, RapidAir 457, ASTM C 231	Export (Batch Plant) JMF No. : 06- 2A002
9	MBVR 1	AVA, RapidAir 457, ASTM C 231	CITEL Penn State
10	MBVR 2	AVA, RapidAir 457, ASTM C 231	CITEL Penn State
11	MicroAir 1	AVA, RapidAir 457, ASTM C 231	CITEL Penn State
12	MicroAir 2	AVA, RapidAir 457, ASTM C 231	CITEL Penn State
13	MBAE 90 1	AVA, RapidAir 457, ASTM C 231	CITEL Penn State
14	MBAE 90 2	AVA, RapidAir 457, ASTM C 231	CITEL Penn State
15	Treated Fly Ash	AVA, RapidAir 457, ASTM C 666, ASTM C 231	CITEL Penn State
16	Untreated Fly Ash	AVA, RapidAir 457, ASTM C 666 , ASTM C 231	CITEL Penn State

Figure 1. Air Void Analyzer[16].

2.2.1.1 Principle

The mortar sample containing entrained air is transferred to glycerol, which is at the bottom of the cylinder and stirred using a stirring rod. The entrained air bubbles released in the glycerol as a result of stirring do not coalesce or disintegrate into smaller bubbles, provided that the glycerol has proper viscosity and hydrophilic character.

A column of de-aerated water is in contact above the glycerol, in which the released air bubbles rise as shown in Figure 2.

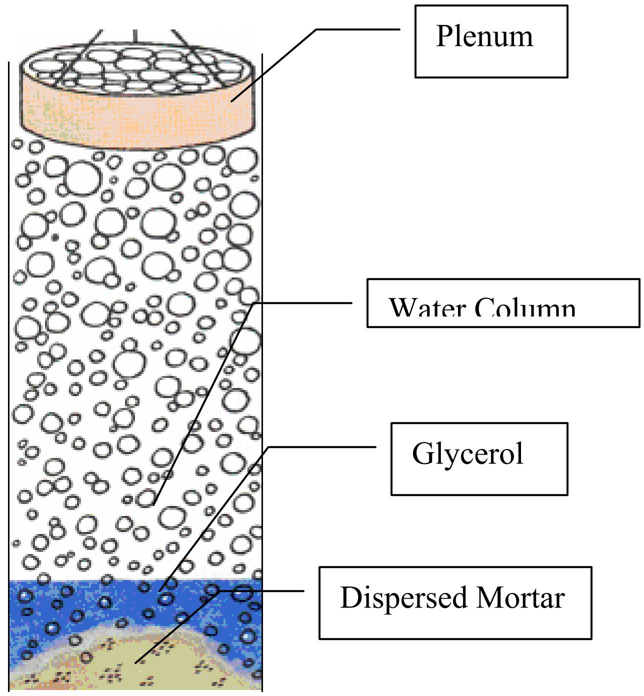

Figure 2. Rise of Bubbles through Glycerol and Water Column in AVA [16].

According to Stokes' Law, larger bubbles will rise faster and smaller bubbles slower. The frictional force exerted on spherical objects in a viscous fluid is given by [18]

$$F = 6\pi\eta r v$$

where:

F = frictional force
r = Stokes' radius of the particle
η = fluid viscosity, and
υ = particle speed

If the particles are falling in the viscous fluid by their own weight, then a terminal velocity, also known as the settling velocity, is reached when this frictional force combined with the bouyant force exactly balance the gravitational force. The resulting settling velocity is given by [18]

$$V_S = \frac{2r^2 g(\rho_p - \rho_f)}{9\eta}$$

where:

V_s = the particles' settling velocity (vertically downwards if $\rho_p > \rho_f$, vertically upwards if $\rho_p < \rho_f$)
g = the acceleration due to gravity,
ρ_p = the density of the particles, and
ρ_f = the density of the fluid

In the case of the AVA, the air voids are the spherical particles that rise in the upward direction.

The air bubbles rising through the water column are collected in a submerged plenum, which in turn is attached to a balance. The analytical balance measures the change in weight in the plenum, and a computer reads the mass change every 1 minute once the data collection has been initiated. The change in weight per minute should decrease with time. This is because the larger bubbles rise faster, and with the passage of time the size of the bubbles accumulating under the plenum decreases. The calculations made by the algorithm are based on the assumption that specific diameter sizes of bubbles rise during a certain time period, and it divides the total weight change by the diameter of bubble for that time period to get the number of bubbles and thus obtain the air void size distribution. The data are presented as a graph of cumulative fraction of voids versus void diameter and a bar chart of the actual void volume in different ranges of void diameter.

The air content (%), spacing factor, and specific surface are calculated to correspond to those that would be obtained from linear traverse measurements on a planar surface of the hardened concrete using the assumptions outlined in ASTM C 457, namely that (1) the average measured chord length is equal to 2/3 of the true air void parameter [6] and (2) for the calculation of specific surface and spacing factor, the voids are all of the same size and are located in lattice points of a regular cubic array [6].

2.2.1.2 Procedure

The AVA is a sensitive instrument and needs to be operated in a proper manner to produce reliable results. The recommended operating procedure for AVA is given below along with the list of components.

List of All Components

The components of AVA, with a brief explanation of each, are listed below [7].

Riser Cylinder: A clear plastic cylinder with a base and a collar. The base should have an integral heating element capable of maintaining the temperature in glycerol between 21–25 ^{o}C and entry holes for the plastic rod and the sample syringe with gaskets to make a water-tight seal.
Magnetic Stirrer: A magnetic stirrer capable of maintaining 300 rpm during mixing.
Balance: The electronic balance should meet the requirements of AASHTO M 231 class G1. The balance shall also have a integral arm from which the dish can be suspended.
Cabinet: The cabinet shall house or correctly mount the riser cylinder, magnetic stirrer and balance.
Stirrer Rod: A ferromagnetic steel rod approximately 5 mm in diameter and 62 mm in length.
Temperature Sensor: The temperature sensor shall detect the temperature of the glycerol at the bottom of the cylinder. The temperature sensor is capable of measuring the temperature to within 1.0 ^{o}F in the range of 59–86 ^{o}F and of transmitting such measurements to the computer through an appropriate interface.

Syringes: 20 ml plastic syringes, with the tapered end removed, and marked for collecting the specified sample.
Plastic Rod: The cylindrical plastic rod is at least 35 mm longer than the width of the base. The outside diameter of the body of the rod is the same as the syringes used in the test. A 1-mm length at the end of the rod shall have a reduced diameter that fits tightly within the inside diameter of the syringe.
Dish (Plenum): The clear, shallow dish is large enough to cover the entire area of the cylinder, retain the rising bubbles and fit within the collar. The dish shall have an opening on the side to allow entrapped air to be removed.
Suspension Device: A device to suspend the dish (plenum) from a balance arm by a single wire.
Control System: A computer, software and interface system capable of controlling the test, recording data, and displaying data at least once per minute during the test. It shall also calculate, display and record the air content(s), air void spacing factor, and specific surface of the air void system.
Sampling Assembly: The sampling assembly shall hold the syringe and a wire cage and should vibrate at approximately 50 Hz with an amplitude that allows the mortar to flow into the wire cage. *Note*: A percussion drill operating at 3,000 rpm with an eccentrically forked assembly can fulfill these requirements.
Wire Cage: The cage is of sufficient size to obtain a sample of fresh concrete mortar. The cage wires shall have a clear spacing of 6 mm.
Plastic Plate: A rigid, clear plastic plate approximately 250 x 250 x 3 mm with a center hole of a diameter approximately 3 mm greater than the wire cage.
Funnel: A funnel marked for measuring a specified amount of glycerol and capable of introducing the glycerol into the bottom of the water-filled riser cylinder with a minimum of mixing.
Spatula: A spatula to trim the mortar sample flush with the end of the syringe.
Water Container: A container with a 4-liter minimum capacity.
Heating Element: An immersible heating element capable of maintaining the water in the container at approximately 70–77 ^{o}F.
Thermometer: A thermometer accurate to 1.0 ^{o}F over a range of 50–86 ^{o}F.
Brush: A brush with a handle longer than the riser cylinder with a tall and angled head.
Insulated Box: An insulated “cooler type” lunchbox is useful.
Sealable Plastic Bags: Commercially available in pint and quart sizes.

2.2.1.2.1 Sampling Procedure

The sampling procedure for taking the samples is explained below [6,7].

1. After the concrete is cast in the form (can be cylinder or a deep beam), samples should be taken as soon as possible. Depending on the purpose of the test, the samples can be extracted from concrete in place, or from beam molds or cylinder molds fabricated according to ASTM C 192, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.”

2. Insert the syringe into the sampling assembly consisting of an aluminum forked holder and mount the wire cage onto the sampling assembly. After assembling, close the syringe completely.

3. Place the plexiglass plate in good contact with the surface of the concrete to be sampled. Hold the drill so that the aluminum holder is gripped in one hand and while pressing it against the drill, start the percussion drill (also known as a rotary hammer drill) to begin the roto-vibration of the sampling assembly and lower the wire cage through the hole in the plexiglass plate into the concrete. The vibration will cause the mortar fraction (i.e., concrete excluding the aggregate > 6 mm) of the concrete to flow into the wire cage. The wire cage should be advanced into the concrete at a rate such that the concrete surface under the plate and the surface of the mortar within the cage remain at approximately the same level at all times. Care should be taken to prevent the surface mortar from entering the wire cage. This can be ensured by pushing the plate against the fresh concrete, applying adequate pressure and by ensuring that air bubbles under the plate do not move toward the hole while sampling.

4. Advance the wire cage into the concrete until the end of the syringe plunger is in full contact with the surface of the mortar. While maintaining the vibration, push the syringe smoothly and fully into the mortar, filling the syringe. Stop the vibration and withdraw the wire cage and syringe from the concrete.

5. Remove the wire cage from the holder by removing it while pressing the prongs of the fork together. After removal of the wire cage, remove the syringe by rotating the piston in the syringe 90^{o} out of the keyways in the fork.

6. Remove the excess mortar from the outside of the syringe and rinse the outside of the syringe with water. Advance the plunger to the 20 cm^3 mark and trim the mortar flush with the end of the syringe cylinder using the spatula. Retract the plunger approximately 1 mm to allow room for the recessed end of the plastic rod.

7. Samples that will not be analyzed promptly should be placed in a plastic bag on ice or freezer packs in the insulated box to retard the onset of the initial set.

2.2.1.2.2 Preparation of Apparatus

Preparation of the apparatus for AVA is explained below [6,7].

1. The water applied in the riser column should be de-aerated. For de-aeration, the water should be heated in a microwave oven until it starts boiling and bubbles start forming. Liberation of air due to temperature changes takes a relatively long time, and after heating, the water shall always be stored at approximately 20 ^{o}C for a minimum of 12 hours before use.

2. Heat up or cool the de-aerated water and the glycerol so that they are in the required temperature range of 21–25 ^{o}C, with a target temperature of 23 ^{o}C. If the ambient

temperature is much lower than 23 ^{o}C, the starting temperature of the liquids should be close to 25 ^{o}C, whereas if the ambient temperature is much higher than 23 ^{o}C, the starting temperature of the liquids should be close to 21 ^{o}C. Additionally, the riser column may be heated or cooled depending on the ambient temperature immediately before the liquids are poured in, to help in maintaining the temperature of the de-aerated water and the glycerol with the required range.

3. Select a test location protected from any wind, vibration or movement that may affect the balance readings and place the cabinet on a stable and level surface. Allow the balance to stabilize so that it does not drift more than 0.01 g in 4 minutes. For this, the apparatus should be set up and switched on at least 30 minutes in advance. During this time the electronic components will transmit heat to the inner parts of the balance. After the temperature of the balance has reached a constant level, the balance will stop drifting.

4. Connect the control system as follows. The AVA and the PC are connected to the AVA connector box. There are three wires extending from one end of the AVA connector box: two wires with round DIN plugs, which are to be connected to the back of the AVA, and one wire with a banana plug, which is to be connected to a temperature sensor. The AVA connector box is connected to the PC with the interface wire. The interface wire must be connected to:

   - The 37-pin plug outlet of the ISA board, for desktop PCs, or
   - The outlet of the PCMCIA card, for laptop PCs.

   A wire running from the backside of the AVA to a vacant 9-pin plug in the PC connects the balance to the PC.

2.2.1.2.3 Operational Procedure

The actual procedure for operating the AVA is given below [6,7].

1. Input all the data required in the control system. The information required for identification of the sample is as follows:
   - Sampler (name of the person or institution taking the sample)
   - Ordered by
   - Sample Location
   - Case Number
   - Sample Number

   The input data used in the calculation of results are:
   - Mortar < 6mm (0.25 in) , in volume %
   - Paste Content, in volume %
   - Expected Air Content, in volume %
   - Sample Volume, in cm^3 (normally the sample volume is 20 cm^3)

   The mortar content < 6 mm (0.25 in), the paste content, and the expected air content are calculated from the mix proportions.

2. Place the stirrer rod flat on the riser cylinder. Insert the temperature sensor through the holes in the base of the riser cylinder so that the full diameter of the temperature sensor protrudes on the opposite side of the base. A light coat of waterproof grease can be used on the rubber O-rings to improve the seal between the plastic rod and the base of the cylinder.

3. Pour the de-aerated water into the column to a level of 0.5 inch above the upper wide section. Use the brush to remove all the air bubbles from the stirrer rod, the plastic rod and the riser column. While removing the air bubbles rotate the temperature sensor to ensure that all bubbles are removed.

4. Mount the riser cylinder in position on the cabinet and fix it in the two bushings that also act as connectors between the power supply and the heating element at the bottom of the column. Ensure that the heating element is covered with analytical liquid before it is switched on.

5. Fill the flask up to the specified mark with glycerol and lower the flask to the bottom of the riser column. Raise the flask approximately 1 cm while the bottom valve is still resting on the bottom of the column. With the flask in this position, allow the liquid to run slowly into the bottom of the column.

6. Connect the integral heating element of the riser cylinder and the temperature sensor to the control system.

7. Mount the glass plenum as follows.
    - Lower the plenum into the water at an oblique angle with the hole facing upward so that the trapped air can escape.
    - Rotate and pull out the balance arm gently to its full extension.
    - Hang the plenum in the groove on the balance pin so that it is approximately centered and does not touch the column walls.
    - Make sure that the welding of the wire holding the plenum is submerged in water.

8. Seat the syringe containing the sample on the reduced end of the temperature sensor so that it fits approximately 1 mm in the syringe. Twist and move the temperature sensor and the syringe through the two O-rings until the end of the syringe is flush with the inside of the bottom chamber. Leaving the syringe in position, continue withdrawing the temperature sensor until the reduced end is flush with the opposite inside edge of the riser cylinder. To make positioning the temperature sensor and the syringe with respect to the riser cylinder easier, mark the correct position on the temperature sensor and note the position of the syringe before starting the test. A small amount of waterproof grease can be applied on the sides of the syringe and temperature sensor to ease the moving of the same.

9. Remove enough of the air that may have risen during the separation of the syringe and the temperature sensor from under the plenum so that the plenum is neither touching nor close to the wall of the riser cylinder columns.

10. When the temperature of the glycerol as measured by the temperature sensor is between 21–25 ^{o}C, inject the mortar from the syringe into the riser cylinder and immediately start the mixing and data collection.

11. If any of the recorded temperature readings are outside the range of 21–25 ^{o}C, discard the test.

12. If unusual variations that may be due to vibration or disturbance are noted in the data, discard the test.

13. Analyze samples as soon as possible (generally within 2-3 hours of mixing).

14. At the end of the test, check for any lump of mortar at the bottom of the riser cylinder. The test is valid only if the sample is completely dispersed in the glycerol by the stirring action.

2.2.1.2.4 Reporting

The recommended reporting procedure is given below [7].

The report shall include the following information:

1. Project Identification
2. Test Identification Number
3. Date of Test
4. Sampling Location
5. Slump by AASHTO T 119 (if known)
6. Air Content by AASHTO T 152 or T 196 (if known)
7. Unit Weight by AASHTO T 121 (if known)
8. Mortar (material less than 6 mm) Volume, %, as calculated from the mix design
9. Paste Volume, %, as calculated from the mix design
10. Sample Volume, ml
11. Test Temperature Range, ^{o}C (^{o}F)
12. Air Content(s), %
13. Spacing factor, mm (in)
14. Specific Surface, mm^2/mm^3

2.2.1.2.5 Measuring Ranges

The operational limit for AVA in relation to the required temperature and air content range is explained below [6].

Temperature

It is essential that the temperature during the measurement procedure remain within the range for which the system is calibrated (21 to 25^{o}C). If the temperature is out of range, it will affect the viscosity of the liquids in the riser column and the results will be erroneous. If the temperature is outside the allowable range, it will be noted on screen and on the printout.

Air Content

Only concrete with an entrained air content between 3.5% and 10% should be used.

- If the air content is too low, the weight (buoyancy) changes after the first minutes [entrapped air] will be very small compared to the accuracy of the balance of 0.01 g. [6] This may result in lack of precision and possible ignorance of parts of the fine air voids system, as the measurement may be stopped early.
- If the air content is too high, turbulence may arise in the liquid.

If the air content is <3.5% or > 10% (by volume of concrete) it will be noted on the screen as well as on the printout.

2.2.1.2.6 Precision and Bias

Precision

The study data from this method are not sufficient to develop a precision statement. The necessary data could be generated by performing a "round robin" test.

Bias

No bias statement has been developed. There is no accepted reference material suitable for determining bias from the true air void characteristics of concrete.

2.2.1.3 Limitations of the AVA Apparatus

Results for both the AVA 2000 and the new generation AVA 3000 lose accuracy if the air content measured is out of the range of 3.5% to 10%. Apparently, below 3.5% the balance is not sensitive enough to record the changes accurately and above 10% there is too much air to maintain stability in the water and the water becomes too turbulent [6].

AVA is sensitive to minor mishandling that might occur during transportation.

The weigh balance is sensitive to temperature changes and vibrations that might be caused due to wind or other movements.

AVA requires a setup with a stable foundation and isolation from any wind movements.

The sample size is very small (20 cc) and is assumed to be representative of the whole concrete batch.

2.2.2 RapidAir 457

The RapidAir 457 shown in Figure 3 is an automated image analysis system and performs analysis of the air void distribution of hardened concrete according to the ASTM C 457, “Standard Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete” [10]. It has been developed by Concrete Experts International which is based in Denmark.

Figure 3. RapidAir 457 System [14].

For this method, the concrete samples to be analyzed are to be cut using a saw with a blade with a continuing rim and a fine cutting diamond edge and then polished by lapping with abrasives. After this, contrast enhancement using black ink or black marker is done on the polished surface of the sample to obtain a black surface with white air voids. A brief explanation of the procedure used at Penn State’s CITEL facilities to prepare cut samples is given below.

Lapping:

- Clean the sample with a soft brush under running tap water in a gentle manner.
- Dry the surface to be lapped by using a blow dryer or compressed air.
- Prepare a solution of lacquer and acetone with a ratio of approximately 1:10.
- Apply lacquer solution with a soft brush**.**
- Soak the lacquer out by using the paper towel.
- Again, blow dry the surface to be lapped, apply the lacquer solution with soft brush and soak the lacquer out by using the paper towel in the same order.
- Again, blow dry the surface to be lapped.
- Then apply yellow crayon on the surface to form a grid of yellow lines. It is important to note that application of yellow crayon should be done only up to 320 grit size.
- Then fill the vibro lap with a solution of water and a super plasticizer (1:1 ratio)
- After this, put an approximate quantity of grit as required in the solution.
- Put the sample (with a weight of approximately 3.2 lb on it) on the vibro lap and put a rubber barrier around it.
- Start the vibro lap.
- The approximate time of running the vibro lap is 20 minutes with grit added in every 5 minutes. This time varies depending on the saw used for cutting the sample. The above-mentioned time is for the automated saw with a continuous diamond rim at the CITEL lab. Also, while the lapping occurs, it should be checked that there are cement slurry and

yellow colored particles in suspension on the boundary of the sample. This indicates that the sample is actually undergoing lapping.

- After the lapping observe the sample under the microscope and if satisfied with the extent of grinding on the surface, proceed to the next grit size and repeat the above-mentioned procedure. It should be noted that the edges of voids should get sharper with every step. The recommended size of grits to be used is 80, 220, 320, 600, and 800, and it is to be used in the order as mentioned.
- After a satisfactory surface is obtained, remove the lacquer by putting the sample in a closed glass container containing lacquer thinner.
- After this, soak and dry the surface using a paper towel.
- Then use a black marker with broad nib to cover the whole surface of the prepared sample. While using the marker it is recommended to first draw lines in one direction and, once the whole surface is covered, draw lines in a direction perpendicular to the previous direction. It should be ensured that the darkness of black color is uniform throughout the surface.
- After this, sprinkle the $BaSO_4$ powder over the surface. Then use the rubber stopper and tamp the powder into the voids. After sufficient tamping is done, spread the powder on the surface. Push the rubber stopper with an angle to the surface and ensure that this is done on the whole surface. After this pull the rubber stopper at an angle and in the opposite direction and remove the powder in this manner. After this use, take the palm of the hand and rub it on an oily portion of the body and then clean the surface by rubbing the palm in revolutions on the surface of the specimen.

2.2.2.1 Principle

After the concrete sample has been properly polished and contrast enhancement has been applied, the sample is placed in sample holder in a manner so that it is aligned with the holder, as shown in Figure 4.

Figure 4. Polished Contrast Enhanced Concrete Plane Section under the Objective [14].

After the Analysis Wizard of the RapidAir 457 is started, all inputs are provided and the threshold intensity level is set. The inputs given for the automatic linear traverse follow [10].

1. Miscellaneous information.
   - Test Lab Name
   - Sample ID
   - Project Number
   - Operator ID
   - Remarks
2. Report type and paper format.
3. Select the image to appear in the report (optional).
4. Enter the filename under which the report will be saved.
5. Enter the paste content of the sample in volume, %.
6. Enter the desire traverse length, in mm.
7. Enter the length and the width of the sample and the area to be traversed, all in mm.
8. Enter the number of traverse lines per video frame (1 to 10).
9. After ensuring that the sample is correctly placed, bring the sample into focus and set the threshold level that best isolates the air voids as white objects on the "Analysis Image." Position the camera over the upper left-hand corner of the area to be traversed. Press NEXT to start the analysis.

After the analysis is started, the X-table will move the camera over the sample in a manner such that the traverse lines are evenly spaced. After the specified length of traverse is reached, the X-table will return to the position from which the analysis was initiated and a report file will be generated.

During the analysis the X-table moves in carefully calculated step lengths so that the edges of two consecutive grabbed video frames match each other. However, the video signals often contain noise at the very edges—20 pixels of the total 768-pixel frame width, or 10 pixels at each side of image. These 10 pixels at the edges are not used in the analysis [10]. A 1-pixel-wide line running across the frames records the chord lengths [10]. The active pixel range of 748 is indicated by the red pixel line on the analysis image (binary image). When the line intersects a void, it turns blue. As the active pixel range is only 748 pixels wide, a 20-pixel-wide overlap exists between consecutive frames; that is, the X-table should, in traveling one frame ahead, move the pixel just right of the end of the probe line to a position as the first pixel at the left end of the probe line on the following image [10]. Air voids extending from one frame into another do not pose a problem, as the software remembers the previous frame and continues white pixel arrays into the next frame. [10] The white and black pixel arrays of 1, 2, and 3 pixels are both regarded as noise by the software [10]. The number of white 3-pixel arrows is recorded under the raw data tap in the report file; however, the 3-pixel-long arrays are not included in the calculations and plots. As the pixel size is about 2.1 microns, the lower cutoff corresponds to a chord of less than 8.4 microns. The pixel resolution of the RapidAir system is 2.1 microns and the magnification is 100x.

2.2.3 ASTM C 666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing"

The ASTM C 666 test method is used to determine the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing [3]. For the current study, the test was used to correlate the results for resistance to freezing and thawing with the air void parameters determined by AVA and RapidAir 457.

2.2.4 ASTM C 231, "Air Content of Freshly Mixed Concrete by the Pressure Method"

The ASTM C 231 test method is used to determine the air content of freshly mixed concrete from the observation of the change in volume of concrete with a change in pressure [1]. For the current study, the test was used to correlate the results for air content with the air content determined by AVA [Figure 1, page 6] and RapidAir 457 [Figure 3, page 15]. The pressure meter used for this method is shown in Figure 5.

Figure 5. Pressure Meter [15].

2.3 Field Sampling

2.3.1 Clinton Road

Location: Findlay
JMF No.: 06- 223

For the paving job at Clinton Road in Pittsburgh, Pa., the AVA was set up in a nearby hotel. All efforts were made to ensure that the AVA was isolated from vibrations due to movement and wind. The temperature inside the hotel room was within the required range of 21–25 ^{o}C. Samples for AVA were taken directly from the point of placement (i.e., from concrete that had already been put in place, vibrated and finished). The slab for RapidAir 457 analysis and beams for ASTM C 666 were fabricated on location from concrete taken directly from the ready-mix truck.

2.3.2 Murrysville Paving Job

Location: Export
JMF No.: 06- 2A001

On-site testing was done at a paving job in Murrysville, Pa. There were two models of the AVA instrument on site, the new-generation AVA 3000 and the older AVA 2000. The new version was used by PennDOT and the old version was used by Penn State. Samples were taken directly from the point of placement (i.e., from concrete that had already been put in place, vibrated and finished) and were taken immediately after the paver had passed. Samples for both instruments were taken from adjacent locations to compare the data. A total of six samples were taken for each instrument from three different locations. From each location, two samples were taken for each instrument. Concrete placed at each location was of the same mixture design but from different truck loads.

2.3.3 Murrysville Trial Mixture Pads

Location: Export (Batch Plant)
JMF No.: 06- 2A001, 06- 2A002

At Murrysville it was planned to cast trial slabs at the batching plant. For the trial mixture pads, two AVA models of the same make, one from Penn State and one from FHWA were used. Two different mixture designs were tested; for each mixture design there was a batch with high air content and a batch with low air content. Samples were taken for all the batches both before and after the paver had passed. For the samples to be taken before the AVA had passed, beams were fabricated on site from concrete load and samples were taken from the same. The other set of samples to be taken after the paver had passed, were taken directly from the point of placement after the paver had passed (i.e., from concrete that had already been put in place, vibrated and finished). The slab for RapidAir 457 analysis and beams for ASTM C 666 were fabricated at the trial mixture pads at Murrysville.

2.4 Laboratory Testing

For the laboratory testing, the AVA was set up on a stable base and confirmed to be isolated from vibrations due to movement and wind. The temperature inside the laboratory was within the required range of 21–25 ^{o}C. A total of eight batches were prepared in the laboratory. Three types of air-entraining admixtures, namely MB-VR, MB-AE 90 and MicroAir, were evaluated. Each type of admixture was used in two batches for a total of six batches of the same mixture design. Two batches containing fly ash, treated and untreated, were prepared. MB-VR was used in these batches. Of the above-mentioned admixtures, MB-AE 90 and MicroAir are synthetic in nature and MB-VR is based on neutralized Vinsol Resin. For each batch, one beam and one slab were fabricated. Samples for AVA were taken from the beam immediately after fabrication and samples for RapidAir 457 analysis were taken from the slab after the concrete had hardened. Samples for ASTM C 666 were fabricated for the batches containing treated and untreated fly ash. The laboratory concrete mix design is summarized in Table 2. Table 3 summarizes all of the air-entraining agents from all of the field and laboratory samples.

Table 2. **Field and Laboratory Concrete Mixture Design.**

Mixture No.	Mixture Name	Cementitious Materials (lb/yd^3)		Water (lb/yd^3)	Aggregate (lb/yd^3)		Chemical Admixtures (oz/100 lb)	
		Cement	**Fly Ash**		**Coarse**	**Fine**	**AEA**	**WR**
1	Clinton Road	611		254	1771	1142	0.75	2
2	Murrysville 1	500	88	225	1840	1252	1.25	4.81
3	Murrysville2	500	88	242	1840	1206	1.25	4.81
4	Murrysville 3	500	88	225	1840	1252	1.25	4.81
5	Murrysville Trial Mixture Pad 1	500	88	260	1840	1160	2.1	5.88
6	Murrysville Trial Mixture Pad 2	500	88	260	1840	1160	5.3	5.88
7	Murrysville Trial Mixture Pad 3	500	88	251	1840	1183	2.2	4.7
8	Murrysville Trial Mixture Pad 4	500	88	251	1840	1183	5.3	4.7
9	MBVR 1	611		274.94	1965.84	1088.22	2	
10	MBVR 2	611		274.94	1965.84	1088.22	1.8	
11	MicroAir 1	611		293.72	1959.96	1075.32	0.96	
12	MicroAir 2	611		293.72	1959.96	1075.32	0.9	
13	MBAE 90 1	611		274.94	1965.84	1067.2	2.4	
14	MBAE 90 2	611		274.94	1965.84	1067.2	2.4	
15	Treated Fly Ash	519.6	91.7	274.94	1965.84	1067.2	3.8	
16	Untreated Fly Ash	519.6	91.7	274.94	1965.84	1067.2	5	

Table 3. Summary of the Field and Laboratory Admixtures Used in This Study.

Mixture No.	Mixture Name	Air Entraining Admixture	Water Reducer
1	Clinton Road	CATEXOL AE 360 (Axim Concrete Tech. Inc.)	CATEXOL 1000N (Axim Concrete Tech. Inc.)
2	Murrysville 1	AEA 92 (Euclid Chemical Co.)	EUCON WR 91 (Euclid Chemical Co.)
3	Murrysville2	AEA 92 (Euclid Chemical Co.)	EUCON WR 91 (Euclid Chemical Co.)
4	Murrysville 3	AEA 92 (Euclid Chemical Co.)	EUCON WR 91 (Euclid Chemical Co.)
5	Murrysville Trial Mixture Pad 1	AEA 92 (Euclid Chemical Co.)	EUCON WR 91 (Euclid Chemical Co.)
6	Murrysville Trial Mixture Pad 2	AEA 92 (Euclid Chemical Co.)	EUCON WR 91 (Euclid Chemical Co.)
7	Murrysville Trial Mixture Pad 3	AEA 92 (Euclid Chemical Co.)	EUCON WR 91 (Euclid Chemical Co.)
8	Murrysville Trial Mixture Pad 4	AEA 92 (Euclid Chemical Co.)	EUCON WR 91 (Euclid Chemical Co.)
9	MBVR 1	MB-VR Neutralized Vinsol Resin (BASF)	
10	MBVR 2	MB-VR Neutralized Vinsol Resin (BASF)	
11	MicroAir 1	MicroAir (BASF)	
12	MicroAir 2	MicroAir (BASF)	
13	MBAE 90 1	MB-AE 90 (BASF)	
14	MBAE 90 2	MB-AE 90 (BASF)	
15	Treated Fly Ash	MB-VR Neutralized Vinsol Resin (BASF)	
16	Untreated Fly Ash	MB-VR Neutralized Vinsol Resin (BASF)	

3.0 Results

The approach taken for the evaluation of the AVA instrumentation involved an evaluation for its internal consistency, consistency between different AVA devices of the same model, consistency between different models of AVA, comparison between the AVA and the RapidAir 457, comparison with the ASTM C 231 pressure meter, and comparison with the ASTM C 666 performance-based test.

3.1 Evaluation of the Internal Consistency of the AVA Apparatus

Six batches of concrete with three different mixture designs were prepared at Penn State's CITEL facility and on-site testing was done at a concrete job for shoulder work near Clinton Road, Findlay. For each of these batches, three samples were taken for testing with the AVA. The resultant data from AVA were statistically analyzed using standard deviation and coefficient of variation.

3.1.1 Standard Deviation

For a given data set, the standard deviation is the root mean square deviation of the values from their arithmetic mean [12]. Standard deviation is used to measure the statistical dispersion of a given data set (i.e., to measure how spread out the values in a data set are). In a given data set, the more close data points are to the mean, the better is the value of standard deviation for that data set. When all the data values are of equal value, the standard deviation is zero.

If the random variable X takes on the values $x_1,\ldots,x_N$ (which are real numbers) with equal probability, then its standard deviation can be computed as follows. First, the mean of X, x_m, is defined as

$$x_m = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{x_1 + x_2 + \ldots\ldots x_n}{N}$$

Standard deviation (σ) of random variable X is given by

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - x_m\right)^2}$$

where N = number of data points in a given population

For the present study standard deviation was calculated for the air void parameters for all the batches prepared in the lab and for a batch of concrete placed at a concrete paving job on Clinton Road, Pittsburgh.

The standard deviation values for the air void parameters of different batches are given in Table 4.

The average values for standard deviation for air content, specific surface, and spacing factor were 0.46%, 64.89 in^2/in^3 and 0.0010 in, respectively. Thus it can be inferred that AVA has a good internal consistency when measuring air content, specific surface, and spacing factor in samples from the same batch.

Table 4. Standard Deviation for the Air Void Parameters Measured by AVA 2000.

Batch	Air Content (%)	Specific Surface (in^2/in^3)	Spacing Factor (in)
MicroAir 1	0.97	128.25	0.0022
MicroAir 2	0.21	56.67	0.00069
MBAE 90 1	0.45	6.02	0.00038
MBAE 90 2	0.50	16.31	0.00024
Clinton Road	0.38	165.33	0.002
MBVR 1	0.49	32.15	0.0003
MBVR 2	0.19	49.47	0.0010
Average	0.46	64.89	0.0010

3.1.2 Coefficient of Variation

The actual variation or dispersion as determined from standard deviation is called the absolute dispersion. However, a variation or dispersion of 0.5% in measuring air content in a concrete batch with 2% air content is quite different in effect from the same variation of 0.5% in measuring air content in a concrete batch with 6% air content. A measure of this effect is given by relative dispersion as follows [8]:

Relative Dispersion = Absolute Dispersion / Average

If the absolute dispersion is the standard deviation, s, and the average is the mean, x_m, the relative dispersion is called the coefficient of variation given by

$$\text{Coefficient of Variation} = V = \sigma / x_m$$

where

σ = standard deviation

x_m = mean

This parameter is more useful than standard deviation when comparing the variability of data sets that have different arithmetic means because it takes into account the magnitude of value of an arithmetic mean of a given data set and can be expressed as a percentage by multiplying the above calculation by 100.

These data are used to establish an accuracy for the method, which in Table 5 is estimated to be 12.5% for the air content. The average value of coefficient of variability for air content, specific surface, and spacing factor summarized in Table 5 is similar. The relative dispersions or variation for measurement of air content, specific surface, and spacing factor values are similar.

Table 5. Coefficient of Variability for the Air Void Parameters Measured by AVA 2000.

Batch	Air Content (%)	Specific Surface (%)	Spacing Factor (%)
MicroAir 1	28.29	23.99	32.66
MicroAir 2	5.38	9.52	7.53
MBAE 90 1	12.38	0.94	4.00
MBAE 90 2	11.83	2.66	2.89
Clinton Road	7.59	25.00	23.00
MBVR 1	14.85	6.00	3.00
MBVR 2	7.00	10.00	8.00
Average	12.47	11.16	11.58

Note: The data showing air void parameters for different batches as measured by AVA 2000 operated by Penn State are given in Appendix B.

3.1.3 Effect of Time on Measurement of Air Void Parameters

A study to observe the effect of time from actual mixing of concrete to actual running of the sample in the AVA, on the results for air void parameters was conducted in the laboratory to address the manufacturer's claim that "samples can be run anytime after they are collected." The time study was conducted over a period of approximately 4-5 hours from the time of actual mixing of concrete. The average time between running the samples was 30 minutes and the same has been used for plotting the air void results against the time. A total of three batches of concrete, two with MicroAir air-entraining admixture and one with MBVR air-entraining admixture, were prepared. For each batch, eight samples for the AVA were taken, one slab for RapidAir was fabricated and a reading for air content using the pressure meter was taken.

All of the samples for the AVA measurements were stored in a refrigerator at a temperature of 37 ^{0}F to retard the rate of initial set.

3.1.3.1 MicroAir 1 Batch

The results showing effect of time on measurement of air void parameters for the first batch using MicroAir air-entraining admixture are given in Table 6 and presented graphically in Figures 6, 7, and 8. The air content in some samples was outside the measurable range of 3.5% to 10%. However, the main purpose of this study was to observe the relative trend of the air void parameters as a function of time and the data presented can be used for studying the same.

Table 6. MicroAir 1 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content(%)	Spacing factor(in)	Specific Surface (in^2/in^3)
1	5.6	0.0057	817
2	3.9	0.0094	581
3	3.3	0.0096	612
4	3.4	0.0113	514
5	2.7	0.0099	644
6	2.3	0.0111	615
7	2.4	0.0135	499
8	2.5	0.0135	491

Figure 6 as a function of time shows a significant decrease in measured air content keeping in mind that these data are considered outside the operational accuracy of the instrument.

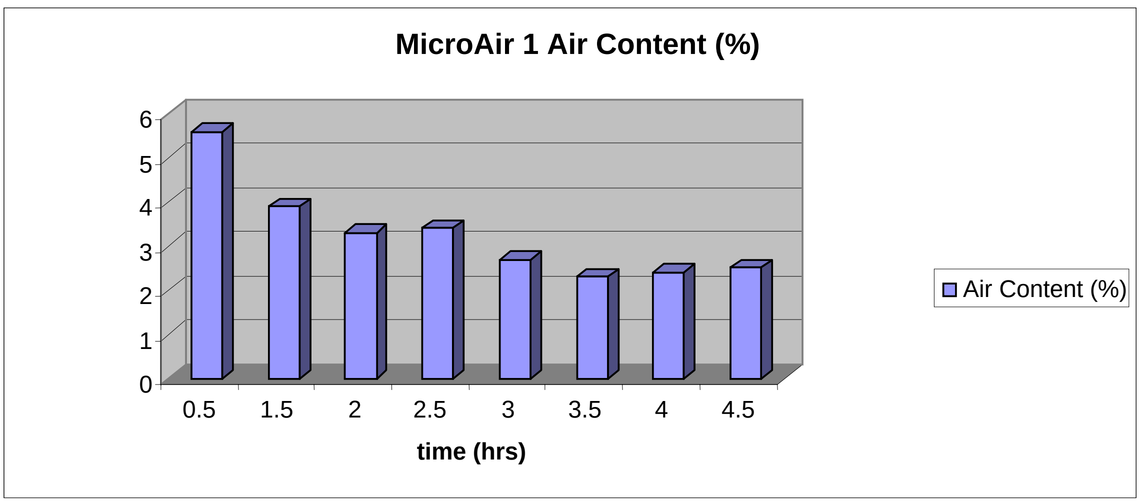

Figure 6. Air Content Measured by AVA 2000 Over a Period of Time (MicroAir 1).

Figure 7 as a function of time shows a significant increase in measured spacing factor, keeping in mind that these data are considered outside the operational accuracy of the instrument.

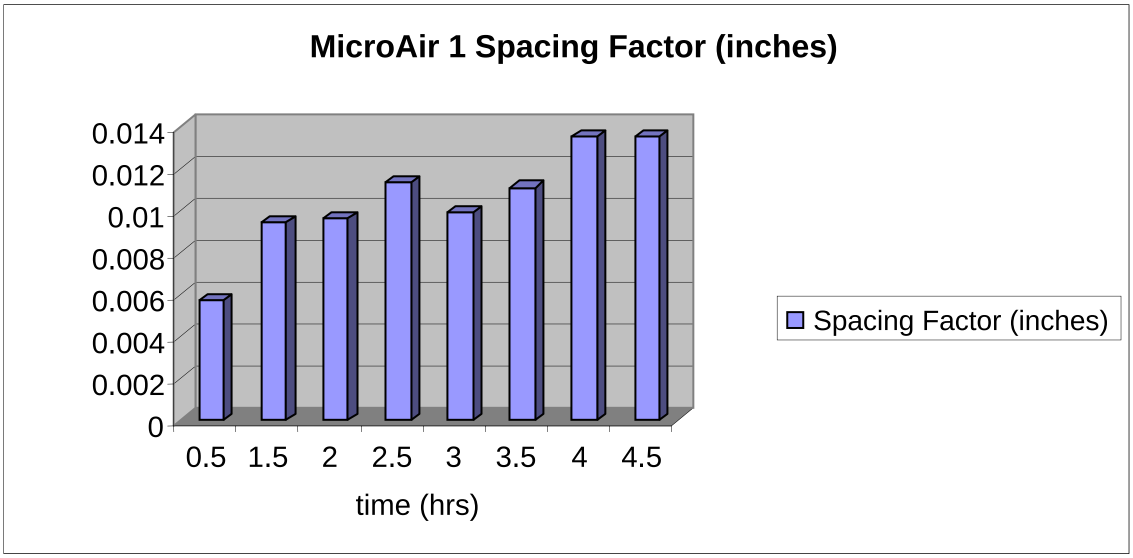

Figure 7. Spacing Factor Measured by AVA 2000 Over a Period of Time (MicroAir 1).

Figure 8 as a function of time shows a decrease in the measured specific surface, keeping in mind that these data are considered outside the operational accuracy of the instrument.

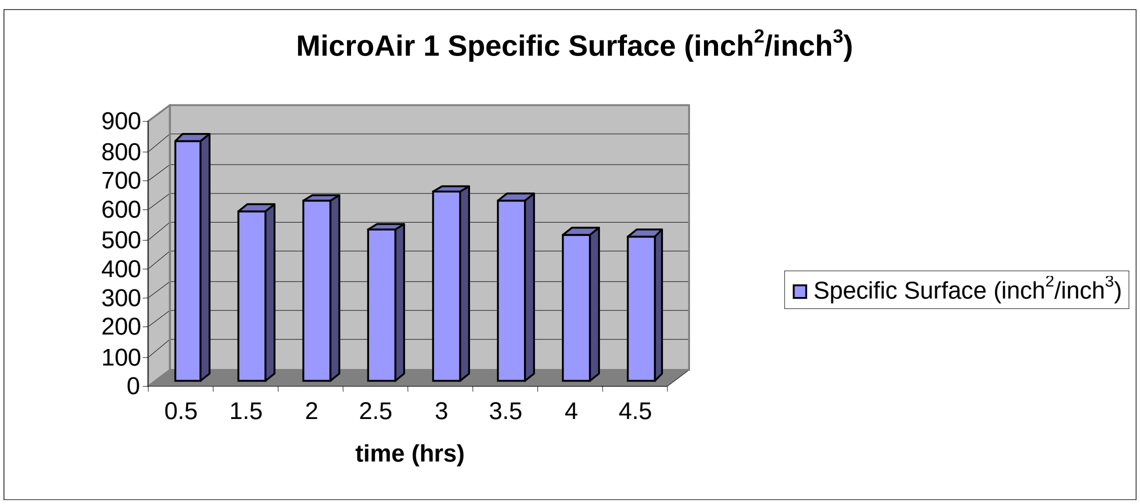

Figure 8. Specific Surface Measured by AVA 2000 Over a Period of Time (MicroAir 1).

From Figures 6, 7, and 8, the air content data demonstrate that as a function of time after sample collection, the air content decreases, the spacing factor increases, and the specific surface decreases. The magnitude of decrease in specific surface value is less compared to the air content and spacing factor.

One of the possible reasons that has been suggested by the manufacturer is that this might be due to the incomplete dispersion of the sample due to onset of initial set with passage of time. As a result, part of the sample does not disperse and the air bubbles in the same do not disperse, resulting in the above-mentioned trend of decreasing air content and an increase in the spacing factor. However, at the end of every test, the bottom of the AVA cylinder was checked for lumps of mortar that might be present due to incomplete dispersion of the sample. It was observed that there was no lump of mortar at the end of all tests for this study. Thus the above-mentioned reason did not affect the results.

3.1.3.2 MicroAir 2 Batch

The results showing the effect of time on measurement of air void parameters using MicroAir air-entraining admixture are given in Table 7 and presented graphically in Figures 9, 10, and 11. The air content in one sample was outside the measurable range of 3.5% to 10% specified by the manufacturer.

Table 7. MicroAir 2 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing Factor (in)	Specific Surface (in^2/in^3)
1	4.1	0.0096	556
2	3.8	0.0084	660
3	3.7	0.0096	569
4	3.7	0.0092	604
5	3.4	0.0083	699
6	4.6	0.0093	545
7	3.7	0.0091	613
8	3.3	0.0079	742

Figure 9 as a function of time shows a small decrease in measured air content, but all the recorded air content values are within the operational accuracy of the instrument. It should be noted that most of the air content values were within the measurable range of 3.5-10%.

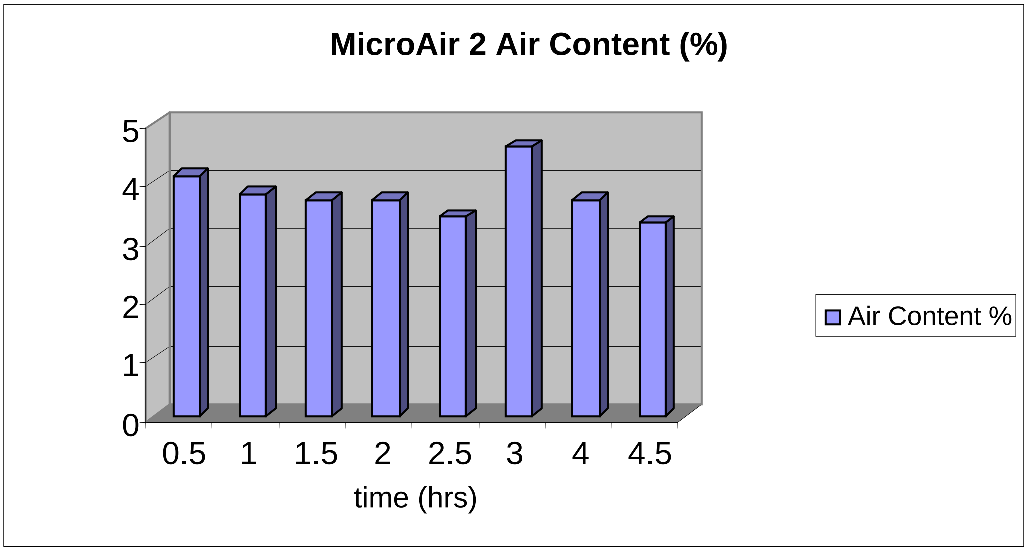

Figure 9. Air Content Measured by AVA 2000 Over a Period of Time (MicroAir 2).

Figure 10 as a function of time shows a very small decrease in measured spacing factor, keeping in mind that these data are considered operational accuracy of the instrument.

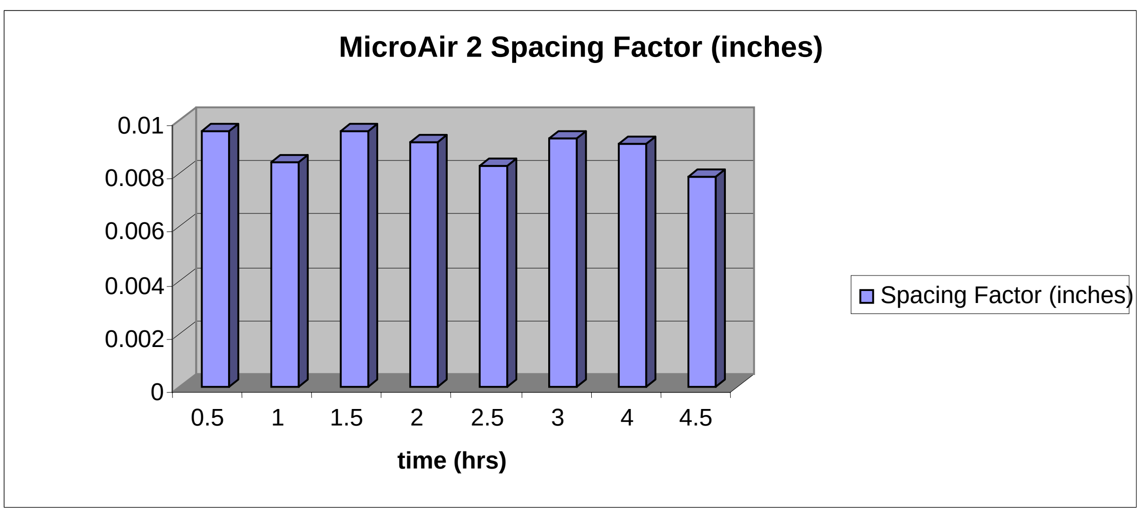

Figure 10. Spacing Factor Measured by AVA 2000 Over a Period of Time (MicroAir 2).

Figure 11 as a function of time shows an increase in measured specific surface, keeping in mind that these data are considered outside the operational accuracy of the instrument.

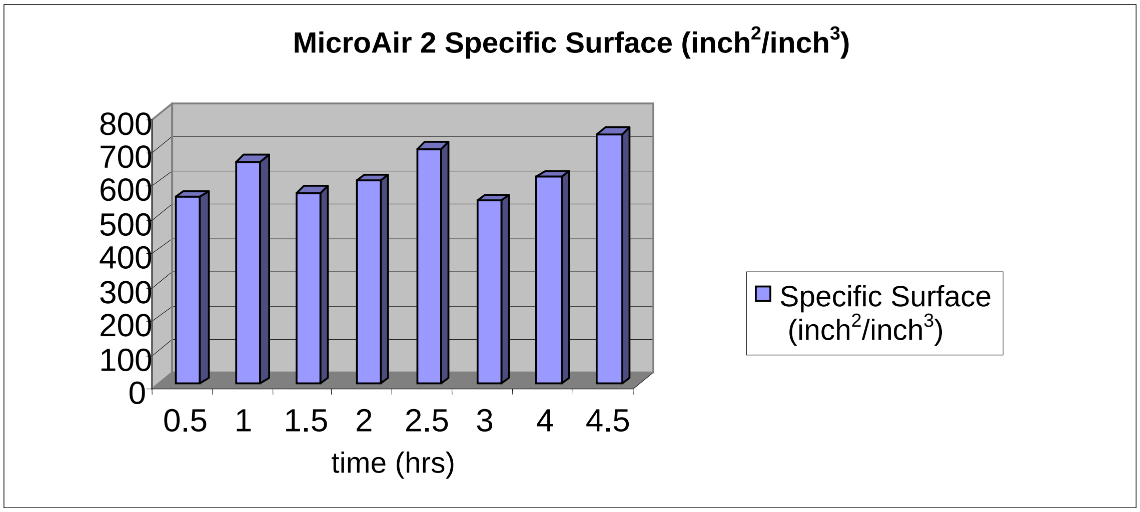

Figure 11. Specific Surface Measured by AVA 2000 Over a Period of Time (MicroAir 2).

From Figures 9, 10, and 11 there is no significant trend of decrease or increase in value of air content, spacing factor, or specific surface over a period of time. This variation over a period of time is small in magnitude and might be due to inherent variability in the air void parameters of different samples.

From this study, there is no observed effect of time on the measurement of air void parameters.

3.1.3.3 MBVR 2 Batch

The results showing the effect of time on measurement of air void parameters for the batch using the MBVR air-entraining admixture are given in Table 8 and presented graphically in Figures 12, 13, and 14. Air content in all the samples was outside the measurable range of 3.5% to 10%. However, all of the samples had air content within a small range, so the loss of accuracy, if any, would not have an effect on the trend of increase or decrease in the air void parameter as a function of time.

From the data in Figures 12, 13, and 14, it can be inferred that as a function of time there is a small decrease in air content and small increase in spacing factor. There is no significant trend of decrease or increase in value of specific surface with time. This variation over a period of time is small in magnitude and might be due to inherent variability in the air void parameters of different samples. Thus there is no observed effect of time on the measurement of air void parameters.

Table 8. MBVR 2 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing Factor (in)	Specific Surface (in^2/in^3)
1	2.7	0.0118	546
2	2.7	0.013	491
3	3.1	0.0143	425
4	2	0.0135	540
5	1.7	0.014	566
6	1.9	0.0138	540
7	1.9	0.0183	411
8	2.1	0.0162	448

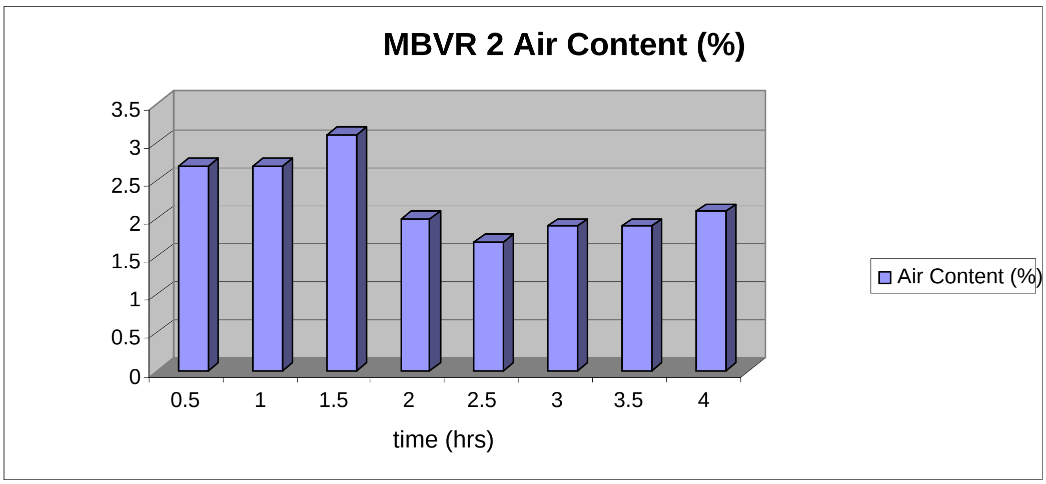

Figure 12. Air Content Measured by AVA 2000 Over a Period of Time (MBVR 2).

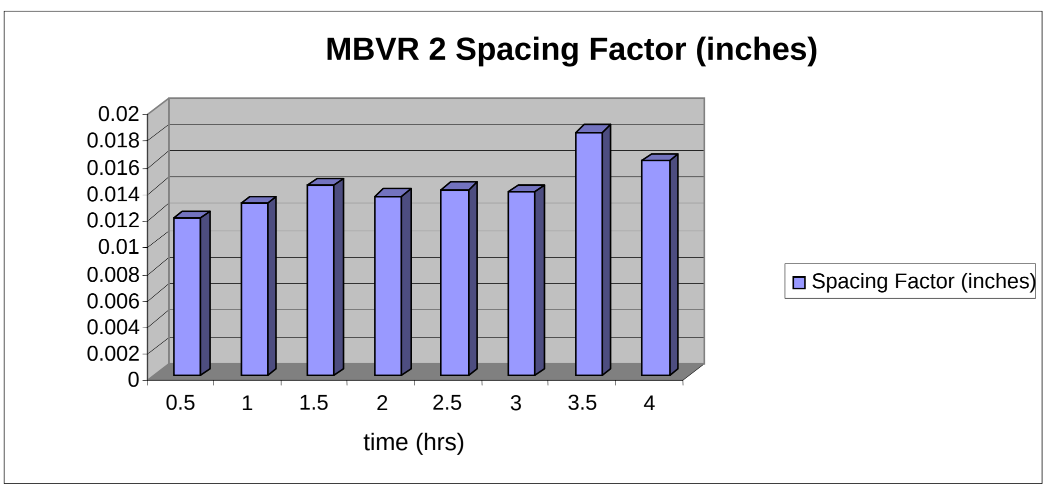

Figure 13. Spacing Factor Measured by AVA 2000 Over a Period of Time (MBVR 2).

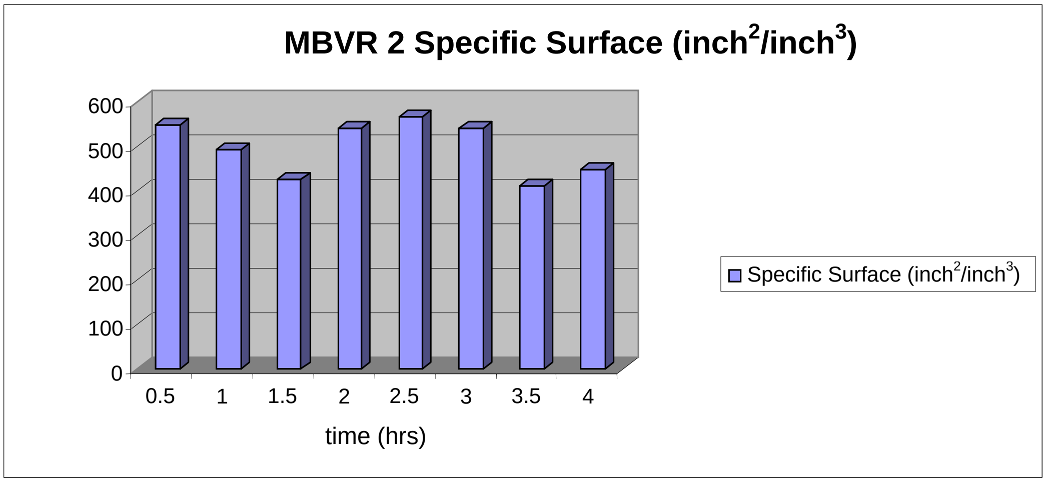

Figure 14. Specific Surface Measured by AVA 2000 Over a Period of Time (MBVR 2).

3.2 Comparison of Different Model 2000 AVA Devices

Location: Export (Batch Plant)

JMF No. : 06- 2A001 (1^{st} mixture design)
JMF No. : 06- 2A002 (2^{nd} mixture design)

For the trial mixture pads, two AVA models of the same make, one from Penn State and one from FHWA, were evaluated. The instruments were set up at the PennDOT office in Murrysville, Pa. During the testing, the temperature of glycerol exceeded the allowable range of 70–77 ^{o}F for both the instruments and was 2–3 ^{o}F more than the maximum allowable temperature. However, the main purpose of this study was to compare the air void parameter results measured by the two instruments for the samples coming from the same batch, and find out whether there is a effect of the instruments used on the final air void parameter results. Both instruments were operated in similar conditions at the same location; thus the comparison results for the measurements from both instruments can be considered valid. Two different mixture designs were used; for each mixture design there was a batch with high air content and a batch with low air content. Samples were taken for all the batches both before and after the paver had passed. What “before and after” means is that samples were taken from beams fabricated on site with concrete taken from concrete load before the paver had passed, versus samples taken directly from the point of placement after the paver had passed (i.e., from concrete that had already been put in place, vibrated, and finished).

The data for measured air void parameters determined by the AVA 2000 operated by Penn State and and the AVA 2000 operated by FHWA are given in Tables 9, 10, 11, and 12.

Table 9. Murrysville Trial Mixture Pad 1 Air Void Parameters.

Sample No.	Air Content (%)	Spacing Factor (in)	Specific Surface (in^{-1})
1st mixture design low air before paver FHWA AVA:			
1	1.1	0.0244	368.3
1st mixture design low air before paver Penn State AVA:			
1	2.2	0.0208	325.12
2	2.5	0.0201	314.96
1st mixture design low air after paver Penn State AVA:			
1	1.6	0.0185	419.1
2	1.4	0.0224	363.22

Table 10. Murrysville Trial Mixture Pad 2 Air Void Parameters.

Sample No.	Air Content (%)	Spacing Factor (in)	Specific Surface (in^{-1})
2nd mixture design low air before paver FHWA AVA:			
1	1	0.0233	388.62
2nd mixture design low air before paver Penn State AVA:			
1	2.4	0.0151	426.72
2	1.4	0.0110	741.68
2nd mixture design low air after paver FHWA AVA:			
1	1	0.0281	332.74
2nd mixture design low air after paver Penn State AVA:			
1	1.6	0.0124	622.3

Table 11. Murrysville Trial Mixture Pad 3 Air Void Parameters.

Sample No.	Air Content (%)	Spacing Factor (in)	Specific Surface (in^{-1})
1st mixture design high air before paver FHWA AVA:			
1	2.1	0.0163	414.02
1st mixture design high air before paver Penn State AVA:			
1	3.3	0.0185	523.24
2	4.2	0.0224	518.16
1st mixture design high air after paver FHWA AVA:			
1	1.7	0.0183	411.48
1st mixture design high air after paver Penn State AVA:			
1	3	0.0111	525.78
2	3.6	0.0115	472.44

Table 12. Murrysville Trial Mixture Pad 4 Air Void Parameters.

Sample No.	Air Content (%)	Spacing Factor (in)	Specific Surface (in^{-1})
2nd mixture design high air before paver FHWA AVA:			
1	1.3	0.0177	419.1
2nd mixture design high air before paver Penn State AVA:			
1	3.5	0.0106	520.7
2nd mixture design high air after paver FHWA AVA:			
1	1.7	0.0162	332.74
2nd mixture design high air after paver Penn State AVA:			
1	2.4	0.0108	599.44

From Tables 9, 10, 11, and 12 the following average differences for air content, spacing factor, and specific surface were determined:

- Average air content difference between FHWA AVA 2000 and Penn State AVA 2000: 1.23 %.
- Average spacing factor difference between FHWA AVA 2000 and Penn State AVA 2000: 0.0081 inch.
- Average specific surface difference between FHWA AVA 2000 and Penn State AVA 2000: 163.83 $inch^{-1}$.

The diagonal line in Figure 15 represents the response that would be anticipated if the two instruments were reading exactly the same air content for the same batch of concrete. This line is used in all successive comparisons as a reference for identical measurements between the instruments. Departures from this idealized line reflect the magnitude of the instrumental differences. In all cases, the reported values fall below this 1:1 line, demonstrating that, within the experimental accuracy of the instruments, the AVA 2000 instrument operated by Penn State provided a larger air content than did the AVA 2000 instrument operated by FHWA.

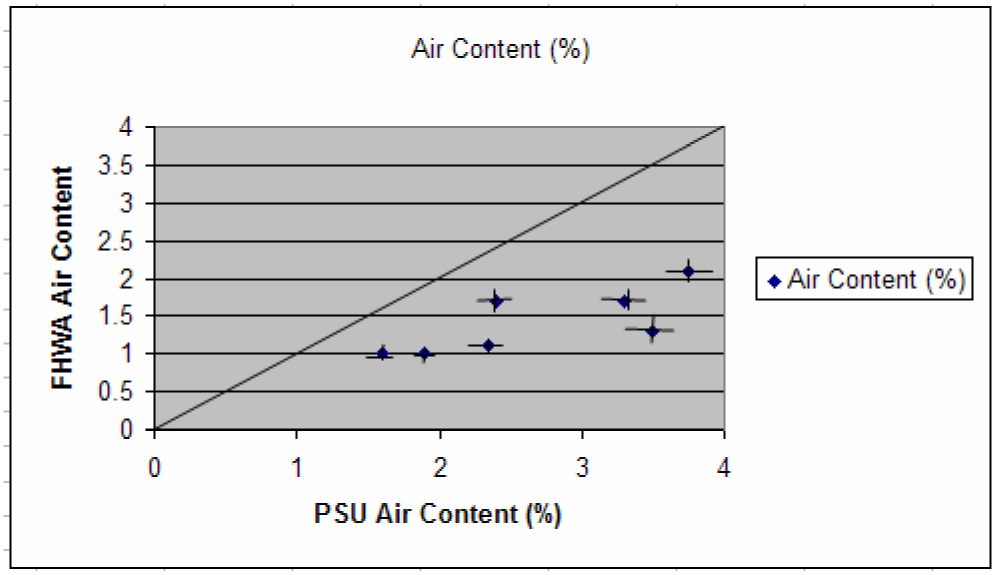

Figure 15. Comparison of Air Content Measured by AVA 2000 Operated by Penn State and AVA 2000 Operated by FHWA. The Error Bars Represent the Average Variation (10%) Specified by the Manufacturer as Compared to ASTM C 457.

In Figure 16, in all cases the reported values fall above this 1:1 line, demonstrating that within experimental accuracy of the instruments, the AVA 2000 instrument operated by Penn State provided a lower spacing factor.

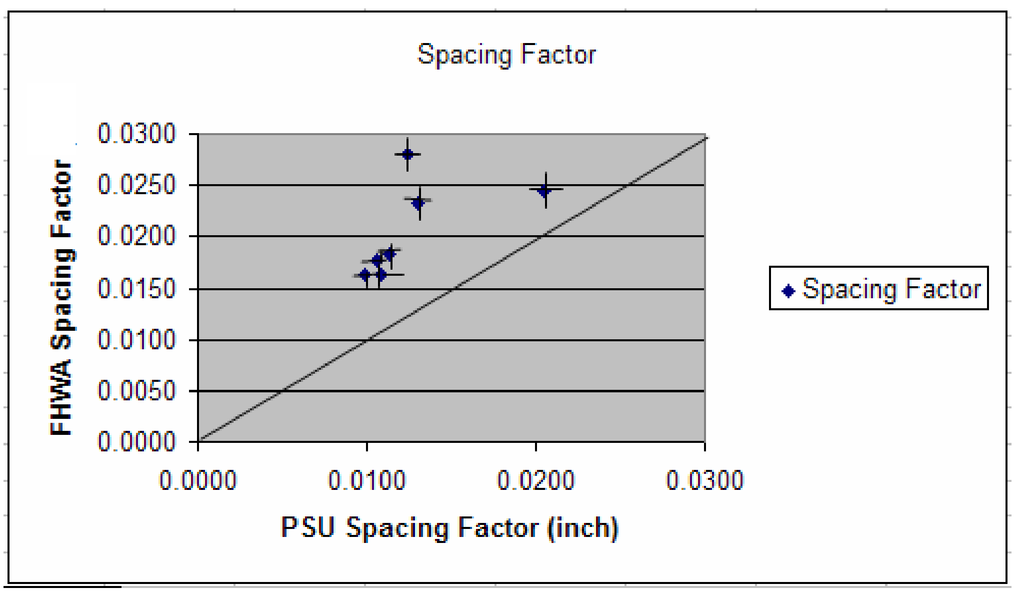

Figure 16. Comparison of Spacing Factor Measured by AVA 2000 Operated by Penn State and AVA 2000 Operated by FHWA.

In figure 17, in all cases, the reported values fall below this 1:1 line, demonstrating that within experimental accuracy of the instruments the AVA 2000 instrument operated by Penn State provided a larger specific surface than did the AVA 2000 instrument operated by FHWA.

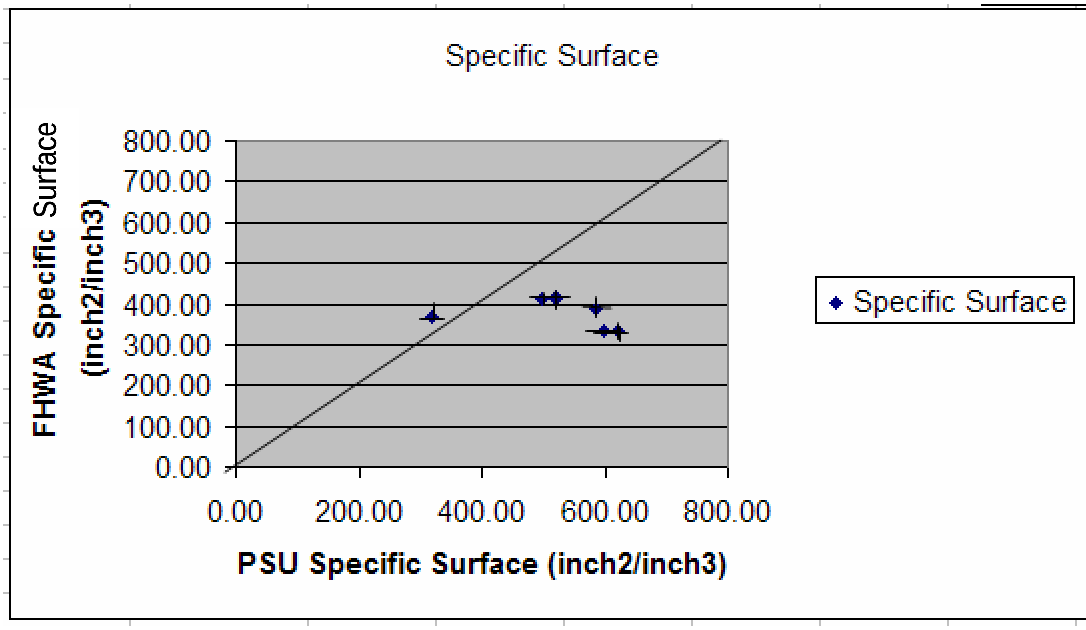

Figure 17. Comparison of Specific Surface Measured by AVA 2000 Operated by Penn State and AVA 2000 Operated by FHWA.

The AVA operated by Penn State gave higher air content, lower spacing factor, and—except for one data point—gave higher specific surface values than the same model instrument operated by FHWA. From Figures 15, 16, and 17 it can be inferred that the air void system as measured by Penn State had a better air void size distribution with smaller air bubbles and a lower average spacing when compared to the air void system measured by FHWA. This supports the need for careful and precise calibration of AVA 2000 model instruments before use in the field and the requirement of checks for calibration at regular intervals.

3.3 Comparison of Different Generation AVA Instruments

The main purpose of this study was to compare the AVA 2000 with the next-generation AVA 3000 by comparing the air void results determined by both instruments.

3.3.1 Field Comparison of AVA 2000 and AVA 3000

Location: Export, PA
JMF No. : 06- 2A001

The results for air content, spacing factor, and specific surface as determined by AVA 2000 and AVA 3000 were compared (presented in Tables 13 through 15 and shown graphically in Figures 18 through 20). On-site testing was done at a paving job in Murrysville, Pa. There were two AVA instruments on site, the new AVA 3000 and the older AVA 2000. The new version was used by PennDOT and the old version was used by Penn State. Samples were taken directly from the point of placement. Samples for both the instruments were taken from adjacent locations to compare the data. A total of six samples were taken for each instrument from three different locations. From each location, two samples were taken for each instrument. Concrete placed at each location was of the same mixture design but from different truck loads.

Table 13. Air Content for AVA 3000 versus AVA 2000.

Sample Number	AVA 3000 (%)	AVA 2000 (%)
1	1.3	1.5
2	1.2	1.4
3	1.7	3.3
4	2.8	3.3
5	2.4	3.6
6	2.5	3.5

Average difference of air content between AVA 3000 and AVA 2000: 0.78%.

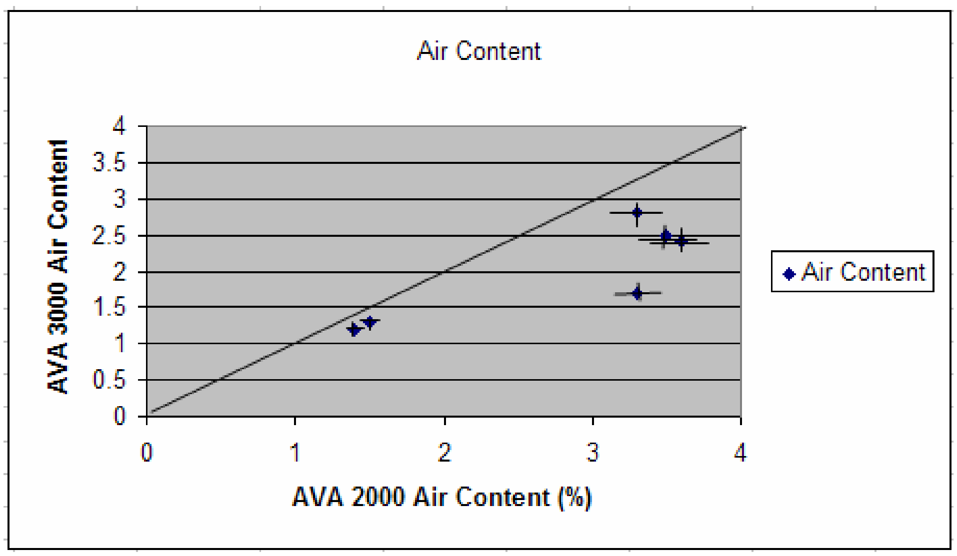

Figure 18. Comparison of Air Content Measured by AVA 2000 Operated by Penn State and AVA 3000 Operated by PennDOT.

In all cases, the reported values fall below this 1:1 line, demonstrating that within experimental accuracy of the instruments the model 2000 instrument operated by Penn State provided a larger air content than did the model 3000 instrument.

Taking the calculated spacing factor from these data shows a trend that approached an agreement with 1:1 relationship but is still skewed toward a large spacing factor for the model 2000 instrument, as presented in Table 14.

Table 14. Spacing Factor for AVA 3000 versus AVA 2000.

Sample Number	AVA 3000 (inch)	AVA 2000 (inch)
1	0.0123	0.0134
2	0.0128	0.017
3	0.0072	0.0098
4	0.0081	0.0068
5	0.0069	0.0101
6	0.0045	0.0072

From the data in Table 14, the average difference of spacing factor between AVA 3000 and AVA 2000 is 0.0025 inch.

The reported values fall below the 1:1 line in Figure 19, demonstrating that within the experimental accuracy of the instruments the model 2000 instrument operated by Penn State provided a larger spacing factor value than did the model 3000 instrument.

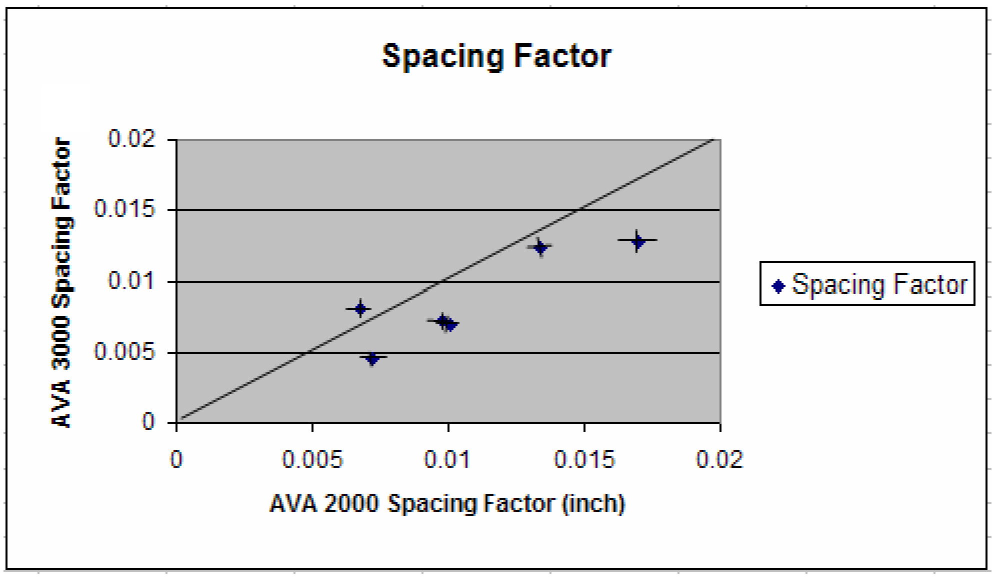

Figure 19. Comparison of Spacing Factor Measured by AVA 2000 Operated by Penn State and AVA 3000 Operated by PennDOT.

Table 15. Specific Surface for AVA 3000 versus AVA 2000.

Sample Number	AVA 3000 (inch^2/inch^3)	AVA 2000 (inch^2/inch^3)
1	681	583
2	683	478
3	1,046	568
4	752	822
5	927	532
6	1,389	752

Average difference of specific surface between AVA 3000 and AVA 2000: 313.83 inch^2/inch^3.

In most of the cases, the reported values fall above the 1:1 line in Figure 20, demonstrating that within experimental accuracy of the instruments the model 2000 instrument operated by Penn State provided a lower specific surface value than did the model 3000 instrument.

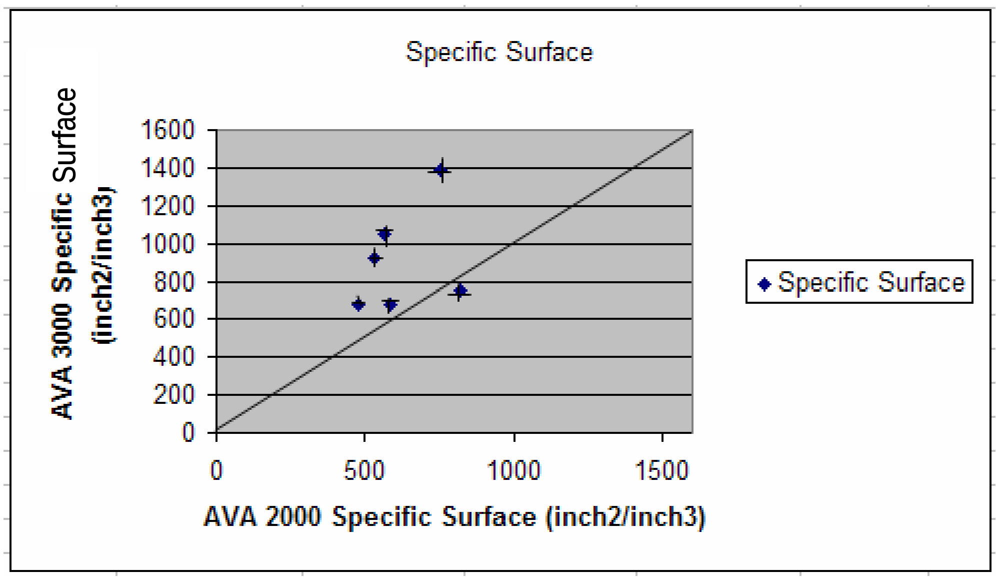

Figure 20. Comparison of Specific Surface Measured by AVA 2000 Operated by Penn State and AVA 3000 Operated by PennDOT.

3.4 Comparison of AVA 2000 and RapidAir 457

A comparison was made between the air void results obtained by AVA 2000 and RapidAir 457. For this purpose, the average values of air content, spacing factor and specific surface, as determined by both the instrument and given in Tables 16, 17, and 18 and shown graphically in Figures 21, 22, and 23 were compared.

Table 16. Air Content for AVA 2000 versus RapidAir 457.

	AVA 2000 (%)	RapidAir 457 (%)
MicroAir 2	3.87	4.33
Murrysville Trial Mixture Pad 2	3.75	4.39
Murrysville Trial Mixture Pad 1	2.35	4.21
Murrysville Trial Mixture Pad 3	1.9	3.87
Clinton Road	4.97	4.37
Treated Fly Ash	3.75	4.94
Untreated Fly Ash	6.21	5.61

Average difference of air content between AVA and RapidAir 457: 1.05%.

The reported values in Figure 21 approach the diagonal line, demonstrating that within experimental accuracy of the instruments the AVA 2000 instrument operated by Penn State provided air content values similar to the RapidAir 457 operated by Penn State.

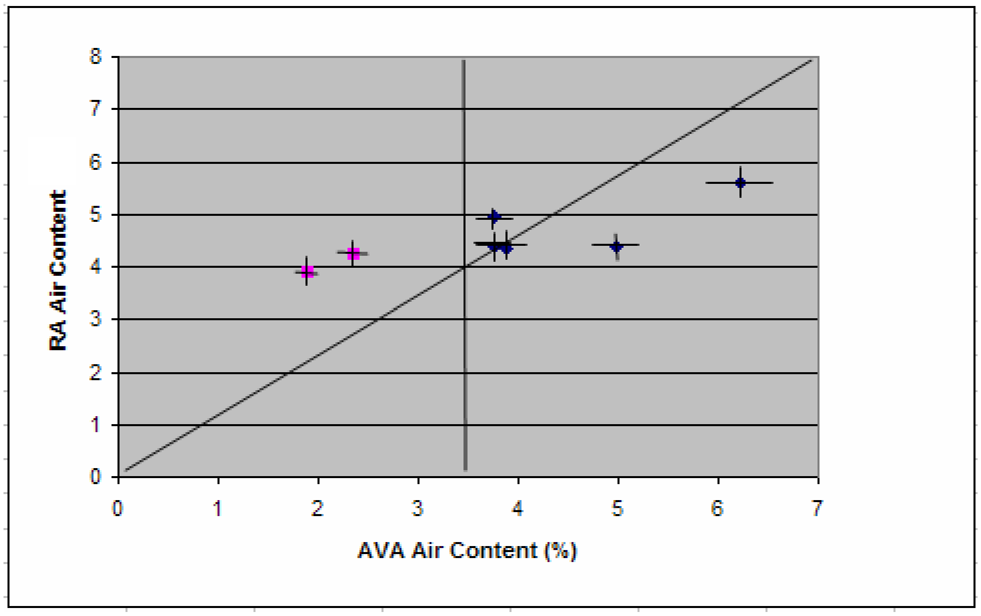

Figure 21. Comparison of Air Content Measured by AVA 2000 Operated by Penn State and RapidAir 457 Operated by Penn State.

Table 17. Spacing Factor for AVA 2000 versus RapidAir 457.

	AVA 2000 (inch)	RapidAir 457 (inch)
MicroAir 2	0.0092	0.00385
Murrysville Trial Mixture Pad 2	0.0099	0.00535
Murrysville Trial Mixture Pad 1	0.0205	0.0059
Murrysville Trial Mixture Pad 3	0.0131	0.0057
Clinton Road	0.0088	0.0074
Treated Fly Ash	0.0106	0.0087
Untreated Fly Ash	0.0103	0.0042

Average difference of spacing factor between AVA and RapidAir 457: 0.0059 inch.

In all cases, the reported values fall below the 1:1 line in Figure 22, demonstrating that within experimental accuracy of the instruments the AVA 2000 instrument operated by Penn State provided a larger spacing factor than did the RapidAir 457 instrument operated by Penn State**.**

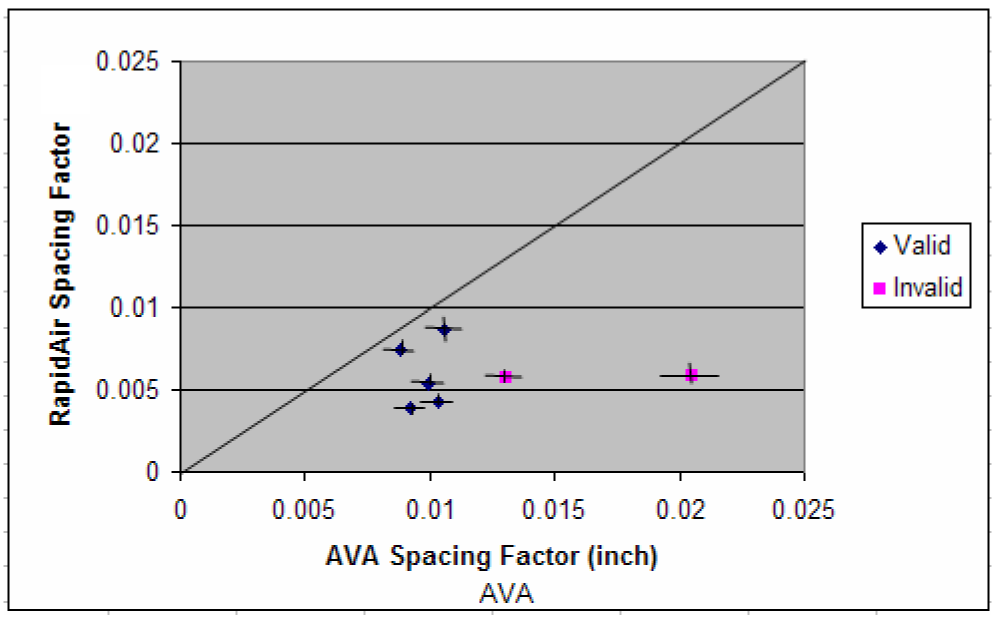

Figure 22. Comparison of Spacing Factor Measured by AVA 2000 Operated by Penn State and RapidAir 457 Operated by Penn State.

Table 18. Specific Surface for AVA 2000 versus RapidAir 457.

	AVA 2000 (inch^{-1})	**RapidAir 457** (inch^{-1})
MicroAir 2	595	1355.05
Murrysville Trial Mixture Pad 2	520.7	971.3
Murrysville Trial Mixture Pad 1	320.04	874.8
Murrysville Trial Mixture Pad 3	584.2	945.25
Clinton Road	672	801.45
Treated Fly Ash	516.5	560.5
Untreated Fly Ash	420	1105.95

Average difference of specific surface between AVA and RapidAir 457: 426.551 inch^{-1}

In all cases, the reported values are above the 1:1 line in Figure 23, demonstrating that within experimental accuracy of the instruments the AVA 2000 instrument operated by Penn State provided a smaller specific surface than did the RapidAir 457 instrument operated by Penn State.

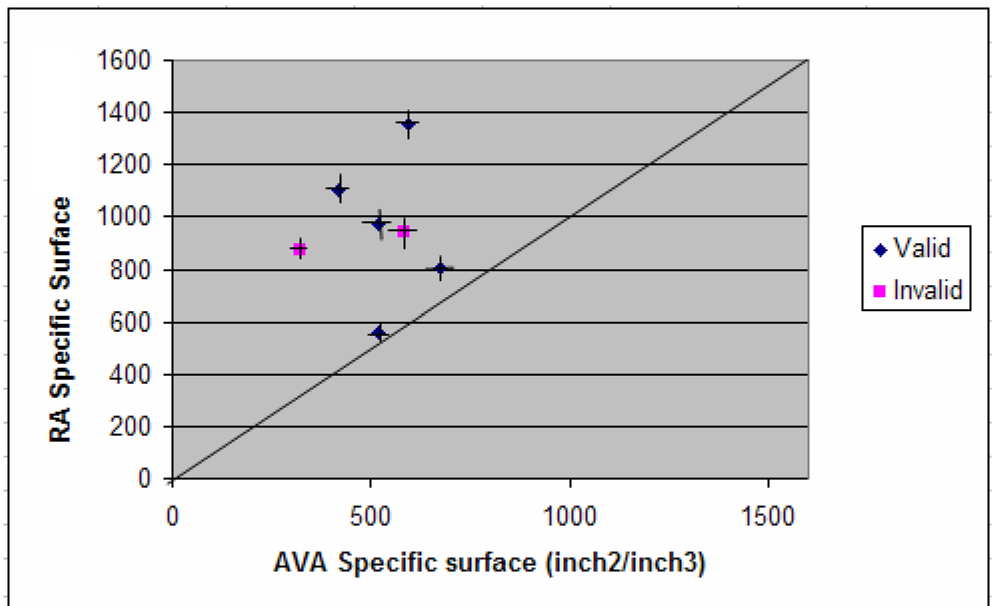

Figure 23. Comparison of Specific Surface Measured by AVA 2000 Operated by Penn State and RapidAir 457 Operated by Penn State.

From Figures 22 and 23, it can be seen that the air void system as measured by RapidAir 457 had lower spacing factor values and higher specific surface values. From this it can be inferred that the air void system as measured by RapidAir 457 had a better air void size distribution with smaller bubbles and lower average spacing between bubbles.

Average percentage variation for air content, spacing factor and specific surface was calculated. The mean value of the air void parameters of different batches for each method was calculated and the average of the means for both methods was calculated. The average percentage variation for each air void parameter is the average difference of the value between the two methods for the air void parameter expressed as a percentage of the average of means of both methods. The average percentage variation for air content, spacing factor and specific surface is 25%, 66.7% and 58.3%, respectively. Assuming that the value of the air void parameters calculated by the RapidAir 457 would be comparable to the manual ASTM C 457 method, the calculated average percentage variation for the air void parameters is significantly more than the 10% average difference between the AVA and the manual ASTM C 457 claimed by the manufacturer [16].

3.5 Comparison of AVA 2000 and ASTM C 231 Pressure Method

The pressure method is used to determine the air content of freshly mixed concrete from the observation of the change in volume of concrete with a change in pressure. For the current study the test was used to correlate the results for air content with the air content determined by AVA. The values for the same are given in Table 19 and shown graphically in Figure 24.

Table 19. Air Content for AVA 2000 versus ASTM C 231 Pressure Method.

Mixture Name	AVA 2000 Air Content (%)	ASTM C 231 Air Content (%)
MicroAir 2	3.87	7.1
Murrysville Trial Mixture Pad 2	3.75	7.7
Murrysville Trial Mixture Pad 1	2.35	4.7
Murrysville Trial Mixture Pad 3	1.9	4.9
Clinton Road	4.97	7.5
Treated Fly Ash	3.75	7.0
Untreated Fly Ash	6.21	6.5

Average difference between AVA and Pressure meter: 2.66 %

The diagonal line in Figure 24 represents the response that would be anticipated if the AVA 2000 instrument and the ASTM C 231 pressure meter were reading exactly the same air content for the same batch of concrete. In all cases, the reported values were above this 1:1 line, demonstrating that within experimental accuracy of the instruments the AVA 2000 instrument operated by Penn State provided smaller air content than the pressure meter operated by Penn State.

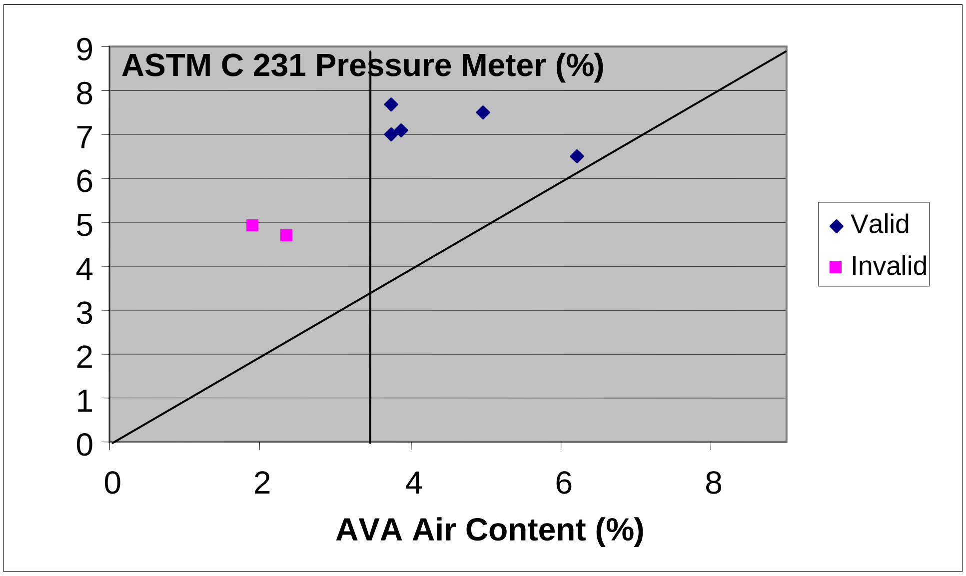

Figure 24. Comparison of Air Content Measured by AVA 2000 Operated by Penn State and Pressure Meter (ASTM C 231) Operated by Penn State.

3.6 Comparison of AVA 2000, RapidAir 457 and ASTM C666

The ASTM C 666 method is used for determining the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing. This procedure would not have significantly damaging effects on frost-resistant concrete, which may be defined as (1) any concrete not critically saturated with water (that is, not sufficiently saturated to be damaged by freezing) and (2) concrete made with frost-resistant aggregates and having an adequate air void system that has achieved appropriate maturity and thus will prevent critical saturation by water under critical conditions. For the existing study this test was used to correlate the results for resistance to freezing and thawing with the air void parameters determined by AVA and RapidAir 457. Many specifications use the value of 0.008 inch for the spacing factor as an upper bound solution for specifying freeze/thaw concrete. The specific surface area of a freeze/thaw-resistant air void system in concrete is typically between [ASTM C 457] 600-1,100 $in.^2/in.^3$ The air content, spacing factor and specific surface value as determined by the AVA and RapidAir 457 and the durability factor value are given in Table 20. The number of cycles in Table 20 indicates the total number of cycles to which a specimen has been subjected.

Table 20. Comparison of Air Void Results for AVA 2000 and RapidAir 457 with Durability Factor Determined by ASTM C 666.

Name	AVA Air (%)	Rapid Air 457 Air (%)	AVA Spacing Factor (inch)	Rapid Air 457 Spacing Factor (inch)	AVA Specific Surface ($inch^2$/ $inch^3$)	Rapid Air 457 Specific Surface ($inch^2$/ $inch^3$)	ASTM C 666 Durability Factor	Number of Cycles
Clinton Road, Findlay	4.97	4.37	0.0088	0.0074	672	801.45	109.7	318
Treated Fly Ash	3.75	4.94	0.0106	0.0087	516.5	560.5	112.2	318
Untreated Fly Ash	6.21	5.61	0.0103	0.0042	420	1105.95	112.2	318
Murrysville Trial Mixture Pad 2	3.75	4.39	0.0099	0.00535	520.7	971.3	112.3	210

The durability factor for all the specimens in Table 20 is good, which shows good resistance of the concrete to freezing and thawing.

The durability factor value for ASTM C 666 correlates well with the spacing factor values and specific surface values determined by RapidAir 457.

Spacing factor value and specific surface value as determined by AVA for the specimens from Clinton Road, Findlay and shown in Table 20 correlate with the durability factor determined by the ASTM C 666 test. However, the spacing factor value and specific surface value for the remaining specimens, as shown in Table 20 do not correlate well with the durability factor determined by the ASTM C 666 test.

4.0 Summary

The main purpose of this study was to provide supporting experimental evidence for the preparation of a specification for the AVA method by PennDOT. The method was evaluated for its internal consistency using statistical analysis. The parameters used for analysis were standard deviation and coefficient of variation and each data set had three data points. The standard deviation of all three parameters—air content, spacing factor, and specific surface—was small, which indicates that all the data points are clustered around the mean. Thus the AVA showed good internal consistency in measuring the air void parameters.

The average value of coefficient of variation for all the air void parameters is similar, which shows that the relative dispersion or variation for air content, specific surface, and spacing factor values is similar. The magnitude of the coefficient of variation indicates that the variability for measurement of air void parameters of samples from the same batch is low and the consistency of results is good.

With regard to the effect of time, from the taking of sample to the actual running of the sample, on the measurement of air void parameters in two batches, one with MicroAir and one with MBVR air-entraining admixture, there was no observed effect of time on the measurement of air void parameters. In one batch with MicroAir as the air-entraining admixture, the measured air content decreased over a period of time with a corresponding increase in the spacing factor value and decrease in the specific surface value.

Comparing the results for air void parameters from two AVA 2000 model instruments, one operated by Penn State and one operated by FHWA, the model operated by Penn State showed consistently better results with higher air content value (average difference of 1.23%), lower spacing factor value (average difference of 0.0081 in), and higher specific surface value (average difference of 163.83 in^2/in^3), which indicates a bias in the machine operated by FHWA toward measuring an air void system with lower results.

Measuring the results for air void parameters from the AVA 3000 model operated by PennDOT and the AVA 2000 model operated by Penn State, the model operated by Penn State yielded consistently higher air content values (an average difference of 0.78%). However, the AVA 3000 model gave a lower spacing factor value (average difference of 0.0025 in) and higher specific surface value (average difference of 313.83 in^2/in^3). From this it can be inferred that the AVA 3000 measured an air void system that had very small bubbles when compared to the air void system measured by the AVA 2000. The calculated spacing factor from the data given in Table 14 shows a trend that approached an agreement with 1:1 relationship but is still skewed toward a large spacing factor for the model 2000 instrument.

Examining the results for air void parameters measured by the AVA 2000 in fresh concrete with those of the RapidAir 457 measured on hardened concrete, within experimental accuracy of the instruments the AVA 2000 instrument operated by Penn State provided air content values similar to the RapidAir 457 operated by Penn State, with an average difference of 1.05%. However, the AVA 2000 gave consistently higher spacing factor values with an average difference of 0.0059 inches and lower specific surface values with an average difference of 426.5

inch^{-1}, indicating a bias toward measuring an air void system with larger air voids. The average percentage variation for air content, spacing factor and specific surface was 25%, 66.7%, and 58.3%, respectively. It is important to note that AVA 2000 measures air voids less than 2 mm in size and RapidAir 457 measures air voids less than 4 mm in size.

Comparing the results for air content measured by the ASTM C 231 pressure method with the AVA 2000, the air content measured by the pressure method was consistently higher, with an average air content difference of 2.66%. However, it is worth noting that AVA only measures air voids less than 2 mm in size, whereas the pressure meter also measures entrapped air bubbles, due to which the pressure meter gives higher air content.

With regard to the results from AVA and RapidAir 457 with ASTM C 666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," the durability factor value for ASTM C 666 correlates well with the spacing factor values and specific surface values determined by RapidAir 457. Spacing factor value and specific surface value as determined by AVA for the specimens from Clinton Road, Findlay correlate with the durability factor determined by the ASTM C 666 test. However, the spacing factor value and specific surface value for the remaining specimens do not correlate well with the durability factor determined by ASTM C 666 test.

5.0 Conclusions

From the data collected in this study based upon intercomparison of different instruments, different generations of instruments, and the authors' experience with the robustness of the instrument, it is the authors' conclusion that this instrument cannot serve as the basis of a specification to evaluate the air content, spacing factors or surface areas in fresh concrete at the job site.

In the intercomparison of AVA instruments of the same generation and AVA instruments of different generations, the results for air void parameters did not compare well. This shows that there is a requirement for careful and precise calibration of the AVA 2000 and the AVA 3000 model before use in the field, and there should be checks for calibration at regular intervals.

There is a bias for the AVA to show higher spacing factor values and lower specific surface values compared to the RapidAir 457, as observed in the study conducted by Penn State. Assuming that the value of the air void parameters calculated by the RapidAir 457 would be comparable to the manual ASTM C 457 method, the calculated average percentage variation for the air void parameters in the study conducted by Penn State is significantly more than the 10% average difference between the AVA and the manual ASTM C 457 claimed by the manufacturer [16]. In a separate study by the precast industry given in Appendix C, the AVA showed consistently higher spacing factor values than the manual ASTM C 457 method. At the same time, the spacing factor values determined by the AVA were independent of the values calculated from the manual ASTM C 457 method. Moreover, in the comparison study carried out for the AVA and the RapidAir 457 with ASTM C 666, the durability factor value for ASTM C 666 correlates well with the spacing factor values and specific surface values determined by RapidAir 457 but not with AVA results.

The existing specifications and recommendations for spacing factor and specific surface are based on empirical correlation between durability of concrete and air void parameters determined by ASTM C 457. Use of AVA will require calibration to known durable concrete. A large-scale study that correlates the air void parameters as determined by AVA with freeze/thaw durability of concrete is required.

5.1 Guideline

From the activities conducted during this research, the authors' observations suggest that potential enhancement of current PennDOT specifications could be made as follows:

Change 408 Section 704 (c) 1 paragraph 3 to read:

"If the hardened concrete exhibits deficiencies or is suspected by the engineer to have deficiencies, and, if directed, to determine the percent of total hardened air and total entrained air according to PTM No. 623, and the computed spacing factor according to ASTM C457. The specification shall be met if the total hardened air is greater than 4.0 percent and the spacing factor does not exceed 0.010 inches (0.25 mm) on a hardened prismatic concrete beam specimen obtained from the structure or pavement in accordance with ASTM C803. The specimens for use in this test method shall be prismatic and shall not be less than 3 in. (76 mm) nor more than 5 in. (127 mm) in width or depth, and not less than 11 in. (279 mm) nor more than 16 in. (406 mm) in length."

ASTM C 666 should be used to evaluate the freeze/thaw durability of suspect concrete that is placed with low air. This is cumbersome, but a strong legal foundation for reducing payment.

6.0 References

1. ASTM C 231, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method," ASTM International Standards Worldwide, West Conshohocken, PA, 2006.

2. ASTM C 457, "Standard Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete," ASTM International Standards Worldwide, West Conshohocken, PA, 2006.

3. ASTM C 666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," ASTM International Standards Worldwide, West Conshohocken, PA, 2006.

4. ASTM C 173 /C 173M, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method," ASTM International Standards Worldwide, West Conshohocken, PA, 2006.

5. ASTM C 138/C 138M, “A Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete,” ASTM International Standards Worldwide, West Conshohocken, PA, 2006.

6. Manual on “The DBT Air Void Analyzer for Assesment of Quality of Air Void Structures in the Fresh, Still Plastic Concrete,” Germann Instruments, Copenhagen NV, Denmark, 2006 (For AVA 2000 and AVA 3000).

7. “Standard Test Method for Air Void Characteristics of Freshly Mixed Concrete by Buoyancy Change,” AASHTO Designation: TP xx-xx, American Association of State Highway and Transportation Officials, Washington D.C. (no date).

8. Spiegel, M., Chapter 4, “The Standard Deviation and other Measures of Dispersion,” *Theory and Problems of Statistics*, Schaum Publishing Co., 1961.

9. Spiegel, M., Chapter 10, “Statistical Decision Theory, Tests of Hypotheses and Significance,” *Theory and Problems of Statistics*, Schaum Publishing Co.,1961.

10. *User’s Manual RapidAir 457 Version 2*, Concrete Experts International, Vedbaek, Denmark, 2006.

11. Whiting, D., and Nagi, M., *Manual on Air Content in Concrete*, Portland Cement Association, 1998.

12.http://en.wikipedia.org/wiki/Standard_Deviation , Wikipedia, The Free Encyclopedia.

13. http://www-micro.msb.le.ac.uk/1010/1011-20.html, Inferential Statistics - Comparing Groups I.

14. http://www.concrete-experts.com/pages/air_void.htm, Concrete Experts International.

15. http://www.controls.it/products.php?code=22&page=Air_content, Controls Group.

16. http://www.germann.org/, Germann Instruments.

17.http://tig.transportation.org/?siteid=57&pageid=715,AASHTO’S Technology Implementation Group.

18. http://en.wikipedia.org/wiki/Stokes_law , Wikipedia The Free Encyclopedia.

Appendix A

Innovative Projects – Comments by State and Industry Users on the Air Void Analyzer

AASHTO'S Technology Implementation Group

The state of implementation of AVA in various states across the United States as given on the AASHTO website is given below [17].

American Concrete Paving Association (ACPA)

The concrete paving industry in Kansas has seen the benefits of the Air Void Analyzer (AVA) first hand. When premature joint distress began to manifest itself on a number of concrete pavements constructed in the 1990's Industry and Kansas Department of Transportation (KDOT) worked together to identify the cause of the problem and come up with a solution. The cause was identified as an inadequate air void system in the surface of the concrete and the solution the AVA. By incorporating the AVA into KDOT paving specs KDOT and Industry are now able to check and monitor the air void characteristics in fresh concrete allowing changes to be made in essentially real time. In an age of QC/QA, incentives/disincentives, performance related specifications, design/build, and warranties contractors need tools which provide immediate and meaningful results. The AVA is such a tool and is capable of not only benefiting our contractors but also extending the life of our product.

— Todd M. LaTorella, P.E., Missouri/Kansas Chapter Director of Engineering

---

California Department of Transportation (Caltrans)

Caltrans has an interest in using the Air Void Analyzer (AVA), which is designed to measure the air content of concrete while in the wet condition. Our initial intention was to use the AVA for field support for our San Francisco Oakland Bay Bridge (SFOBB) construction. The concrete mix designed called for 8% air content which would require monitoring that the AVA could perform. After training our Rigid Pavement laboratory staff for using the AVA equipment, we determined the AVA would not work for our needs at SFOBB. The AVA process requires a very stable base to allow the finite air bubbles to be measured. The SFOBB project requires measuring the air content from a barge, which is positioned at the construction site.

Caltrans will be using the AVA system for our concrete application where freeze-thaw is a consideration. Caltrans has developed a draft California Test Method with the help of Chetana Rao, ERES Consultants, a Division of Applied Research Associates, Inc.

— Charles Dayton, P.E., Caltrans Division of Engineering Services

---

Kansas Department of Transportation (KDOT)

Kansas pavements less than 10 years old showed cracking at longitudinal joints, distress at edge of milled transverse joints, distress at transverse joints on super-elevated curves, and centerline cracking.

Upon examination of the distressed concrete, it was found that the distress was not aggregate-related. Petrography of core samples showed poor spacing factors of the air voids in the paste, even though the total air contents met the specifications (5½ % on average).

KDOT found that the most effective distress prevention strategy was to assure an adequate spacing factor on projects under construction, but petrographic analyses were not rapid enough for this application. An Air Void Analyzer (AVA) was purchased in April 2001, and was used for monitoring concrete paving projects during 2001 and 2002 construction seasons.

With the immediate results contractors made immediate improvements in the air-void system on on-going projects. A KDOT spacing factor specification was developed and used on three projects in 2002.

In order to estimate cost savings, the spacing factors on monitored pavements were compared with previous results, and durability was estimated from the spacing factors. Cost savings were estimated from the reduced repair costs for the more durable pavements. Even though only longitudinal joint repair costs were included, for the 2001-2002 projects future savings from the improving spacing factor was estimated to be $1,136,000.

The AVA test is the only test that needs to be run on fresh concrete to assure durability.

— John Wojakowski, P.E., Concrete Research Engineer

Master Builders Technologies

Master Builders Technologies determined to buy a plastic Air Void Analyzer (AVA) primarily because of the rapid feedback from the instrument. Previously, as part of the admixture product development process, we relied upon results from petrographic examination on hardened specimens (by ASTM C457) to determine the characteristics of the air-void system. This process typically takes a minimum of 3 days from the time of casting to get the results. By use of the AVA, this time was cut down to a matter of 1 hour or less from the time of casting. And though the AVA does not always give perfect agreement with the results obtained by ASTM C457, it does give sufficient immediate information to provide direction in the admixture development process.

— Bruce Christensen, P.E., Master Builders Inc.

Minnesota Department of Transportation

The Concrete Air Void Analyzer provides information on the air content and distribution in plastic concrete so that appropriate adjustments can be made in a timely manner to ensure that quality concrete is being produced.

Historically, air entrained concrete has been accepted on the basis of either the pressure method or the volumetric method. These test procedure provided the total air content in the concrete mix but do not provide information on the bubble size or distribution in the air-entrained concrete mixture. To produce a freeze-thaw resistant concrete structure, it is necessary to know the total air content, size and distribution of air voids. The Linear Traverse Test provides this information but it cannot be used for quality control since it involves testing hardened concrete, too late to make adjustments to the mixture.

The Air Void Analyzer produces all the necessary data on air-void characteristics to produce quality concrete, therefore, the Minnesota Department of Transportation strongly endorses the implementation of this procedure.

— Douglas Schwartz, P.E., Concrete Engineer

Missouri Department of Transportation

The AVA offers Missouri the never-before opportunity to obtain valuable and reliable data concerning the air-void system in freshly mixed concrete. Like many others, Missouri has always relied on mix air content measured during construction to indicate future concrete freeze thaw durability. Information concerning air-void spacing factor and specific surface, which more accurately indicate freeze thaw durability (as opposed to total air content), can only be determined following concrete hardening using conventional methods. Analysis is then tedious and requires a highly skilled operator, limiting it only for special circumstances or for research purposes in Missouri. Thus, frequent questions or concerns initiated during construction regarding adequate in-place air are either answered long after placement or often remain unanswered. The ability to obtain timely answers to these questions, which would then allow immediate mix or production changes, is an ideal opportunity for Missouri to place a more appropriate focus on quality instead of quantity of air during construction. Missouri is highly interested in the AVA and anticipates that its implementation should result in valuable and timely data used to enhance and ensure future in-place concrete performance.

— Patty Brake Lemongelli, P.E., Concrete Researcher

New York Department of Transportation

NY DOT has worked with the Air Void Analyzer (AVA) for approximately 3 months on precast concrete production projects. The intent was to have the precasters/industry become familiar with the equipment. Using the AVA in precast work provides benefits to both the precast industry and the Department. The current process involves taking cores from precast units at a set frequency and testing for air content and compressive strength. When air contents are low, projects are frequently delayed until corrective actions are taken. The process of taking and testing cores takes 2 to 4 weeks and creates considerable work for the Department, as well as a backlog at the precast facility before units can be accepted and shipped.

Implementing use of the AVA provides the precasters with a quality control tool that, when used daily in conjunction with a pressure meter, maintains a quality air-void system in concrete. The Department will accept the AVA results as representative of a day's production and therefore eliminate the need for hardened concrete sampling and testing. With this equipment in use, the precasters will know in 30 to 60 minutes that his materials will be accepted for that day's production, rather than the normal 14 to 28 days. The Department will benefit in that much less testing will be performed at the Department Laboratory on hardened concrete samples. The Department has recently implemented a QC/QA program for precast concrete production. Through this program, the Department will routinely observe the precasters operation and use of the AVA, and possibly run our own tests on companion samples as part of a QA procedure.

NY DOT is also considering the use of the AVA on critical concrete placements where freeze thaw durability is important. The AVA could be used on bridge decks and other critical flat work to assure both the quality of the material (as sampled during delivery) and the quality of the construction practices (as sampled immediately after placement).

— Donald Streeter, P.E., Concrete Section Program Manager

National Ready Mixed Concrete Association (NRMCA)

The Air Void Analyzer (AVA) provides a tool for quality control and concrete mixture evaluation based on sound science to establish the potential durability of concrete exposed to freezing and thawing environments. The advantage of this method is that it provides information on the air void characteristics of concrete in real time so that concrete ingredients and production and placement processes can be modified to rectify a deficient situation. The method provides the flexibility of establishing whether the cause of an inadequate air void system in concrete is a result of materials, production or placement and consolidation procedures. The AVA has shown good success in reducing the propensity of durability failures in Europe where it has been used extensively. Using this technology in the US will promote the use of hydraulic cement concrete for long service life in severe exposures.

While the basic concepts of a desirable air void system in concrete have been established in research literature, the criteria for acceptable concrete using the AVA have to be established with a proper understanding of the data provided in relationship to traditional methods of evaluating and testing concrete mixtures.

— Colin Lobo, P.E., Vice President, Engineering

North Carolina Department of Transportation

NCDOT purchased the “Air Void Analyzer” for two solid reasons: concise data, and innovative technology. North Carolina currently uses the pressure meter and/or the volumetric method to measure “air content” in concrete. These methods measure both entrapped and entrained air, but fail to establish their individual parameters. Based on continuous data collection, these methods continue to supply questionable results. Utilizing the AVA eliminates this confusion and clearly defines the separate air amounts with the addition of potential design related specifications. The field of concrete technology and design continues to change daily. NCDOT is seizing the opportunity to improve efficiency and reliability by adopting its newest product: the AVA. This is an important step in moving towards the future. The Air Void Analyzer has been assigned to selected projects throughout the state to further enhance our production of quality concrete.

— Sam Frederick, P.E., Field Concrete Engineer

Appendix B

Air Void Parameters measured by AVA 2000 in Laboratory and in the Field

Table 21. MicroAir 1 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing Factor (inch)	Specific Surface ($inch^2/inch^3$)
1	5.60	0.0057	817.00
2	3.90	0.0094	581.00
3	3.30	0.0096	612.00
Standard Deviation	0.97	0.002	128.25
Mean	3.44	0.0067	534.56
Coefficient of Variability	0.28	0.3266	0.24

Table 22. MicroAir 2 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing factor (inch)	Specific Surface ($inch^2/inch^3$)
1	4.10	0.0096	556.00
2	3.80	0.0084	660.00
3	3.70	0.0096	569.00
Standard Deviation	0.21	0.0007	56.67
Mean	3.87	0.0092	595.00
Coefficient of Variability	0.05	0.0753	0.10

Table 23. MBVR 1 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing Factor (inch)	Specific Surface ($inch^2/inch^3$)
1	3.90	0.0098	558.00
2	3.30	0.0106	552.00
3	2.70	0.0103	623.00
Standard Deviation	0.49	0.00033	32.15
Mean	3.30	0.0102	577.67
Coefficient of Variability	0.15	0.0322	0.06

Table 24. MBVR 2 Air Void Parameters Measured by AVA 2000.

Sample Number	Air Content (%)	Spacing Factor (inch)	Specific Surface ($inch^2/inch^3$)
1	2.7	0.0118	546
2	2.7	0.013	491
3	3.1	0.0143	425
Standard Deviation	0.19	0.0010	49.47
Mean	2.83	0.0130	487.33
Coefficient of Variability	0.07	0.08	0.10

Table 25. MBAE 90 1 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing Factor (inch)	Specific Surface ($inch^2/inch^3$)
1	4.00	0.0084	636.00
2	3.00	0.0092	650.00
3	3.90	0.0084	639.00
Standard Deviation	0.45	0.00038	6.02
Mean	3.63	0.01	641.67
Coefficient of Variability	0.12	0.0435	0.009

Table 26. MBAE 90 2 Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing Factor (inch)	Specific Surface ($inch^2/inch^3$)
1	3.90	0.0092	581.00
2	4.90	0.0089	542.00
3	3.80	0.0095	569.00
Standard Deviation	0.50	0.00024	16.31
Mean	4.20	0.01	564.00
Coefficient of Variability	0.12	0.0266	0.03

Table 27. Clinton Road Air Void Parameters Measured by AVA 2000.

Sample No.	Air Content (%)	Spacing Factor (inch)	Specific Surface ($inch^2/inch^3$)
1	4.70	0.0113	510.00
2	4.70	0.0064	899.00
3	5.50	0.0088	607.00
Standard Deviation	0.38	0.0020	165.33
Mean	4.97	0.0088	672.00
Coefficient of Variability	0.08	0.2265	0.25

Appendix C

Summary of Testing Data from Precast Manufacturer's AVA Testing

Table 28. Air Content Determined by AVA, ASTM C 457 and ASTM C 231 (Precast Study).

Name	AVA (1mm)	ASTM 457 (1 mm)	ASTM C 231 Pressure Method	ASTM C 457 Total
Faddis New Castle	4.04%	4.3%	6.30%	6.0%
Faddis New Castle	2.95%	5.9%	5.90%	6.8%
A.C. Miller	2.56%	2.5%	6.00%	4.5%
A.C. Miller	2.54%	4.5%	6.80%	6.8%
A.C. Miller	1.61%	2.7%	7.00%	4.8%
New Enterprise	6.40%	4.7%	7.50%	6.5%
New Enterprise	2.85%	5.2%	7.00%	6.8%
New Enterprise	4.95%	3.2%	6.50%	5.3%
New Enterprise	1.95%	5.0%	5.90%	5.4%
K.J. Williams	2.92%	3.3%	5.70%	5.0%
K.J. Williams	3.86%	4.1%	6.40%	5.9%
K.J. Williams	2.21%	2.9%	6.00%	4.9%
Eagle Concrete	4.91%	3.8%	6.80%	6.2%
Eagle Concrete	5.72%	6.1%	7.20%	8.8%
Eagle Concrete	3.82%	6.9%	6.40%	8.3%
Faddis Downington	1.74%	4.3%	6.40%	5.4%
Faddis Downington	1.86%	2.9%	6.20%	4.0%
By-Crete	-	-	5.40%	4.8%
By-Crete	-	-	6.80%	7.9%

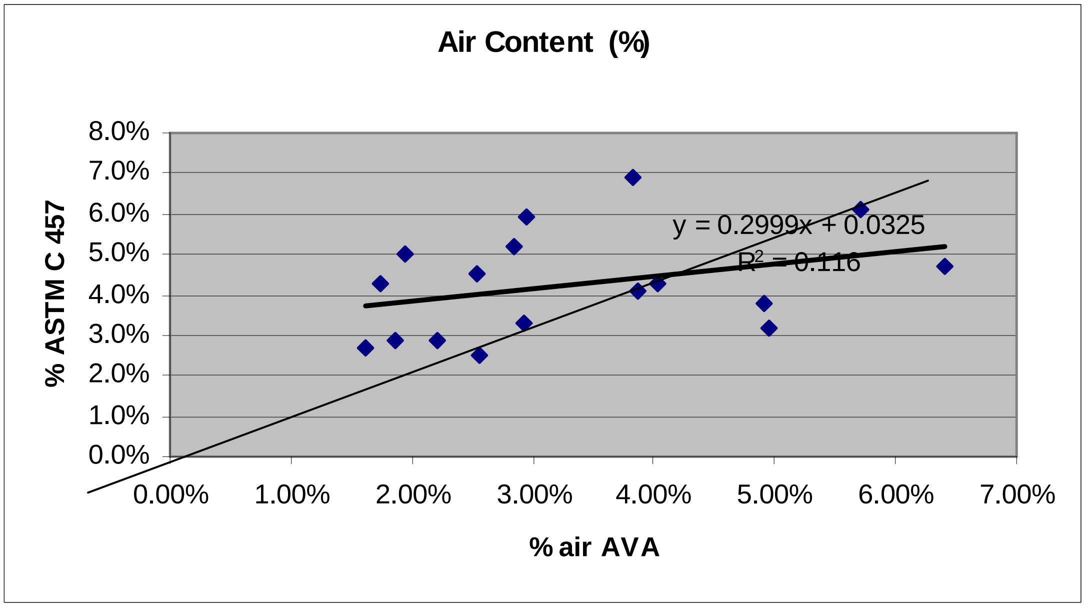

Figure 25. Comparison of Air Content Measured by AVA and Manual ASTM C 457 Method.

The diagonal line in Figure 25 represents the response that would be anticipated if both methods were reading exactly the same air content for the same batch of concrete. The trend line for the data set suggests that the air content as measured by AVA is essentially independent of that measured by ASTM C 457.

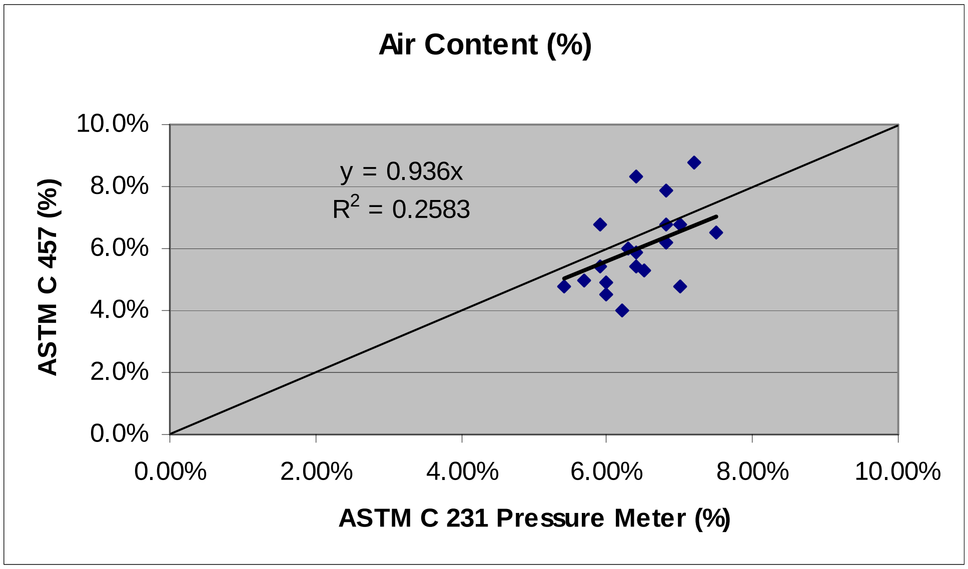

Figure 26. Comparison of Air Content Measured by Pressure Meter (ASTM C 231) and Manual ASTM C 457 Method.

The trend line for the data set in Figure 26 clusters on both sides of 1:1 diagonal line, but also suggests that the measured values by AVA are independent of the values measured by ASTM C 457.

Table 29. Spacing Factor Determined by AVA and ASTM C 457 (Precast Study).

Name	AVA Spacing Factor (inch)	ASTM C 457 Spacing Factor (inch)
Faddis New Castle	0.0072	0.0052
Faddis New Castle	0.0158	0.0044
A.C. Miller	0.0146	0.0137
A.C. Miller	0.0231	0.0081
A.C. Miller	0.018	0.0138
New Enterprise	0.0133	0.0045
New Enterprise	0.0057	0.008
New Enterprise	0.012	0.0129
New Enterprise	0.033	0.0049
K.J. Williams	0.0124	0.0087
K.J. Williams	0.0166	0.0077
K.J. Williams	0.0188	0.0095
Eagle Concrete	0.0105	0.0053
Eagle Concrete	0.0096	0.0038
Eagle Concrete	0.0142	0.0043
Faddis Downington	0.0279	0.0069
Faddis Downington	0.0274	0.0087

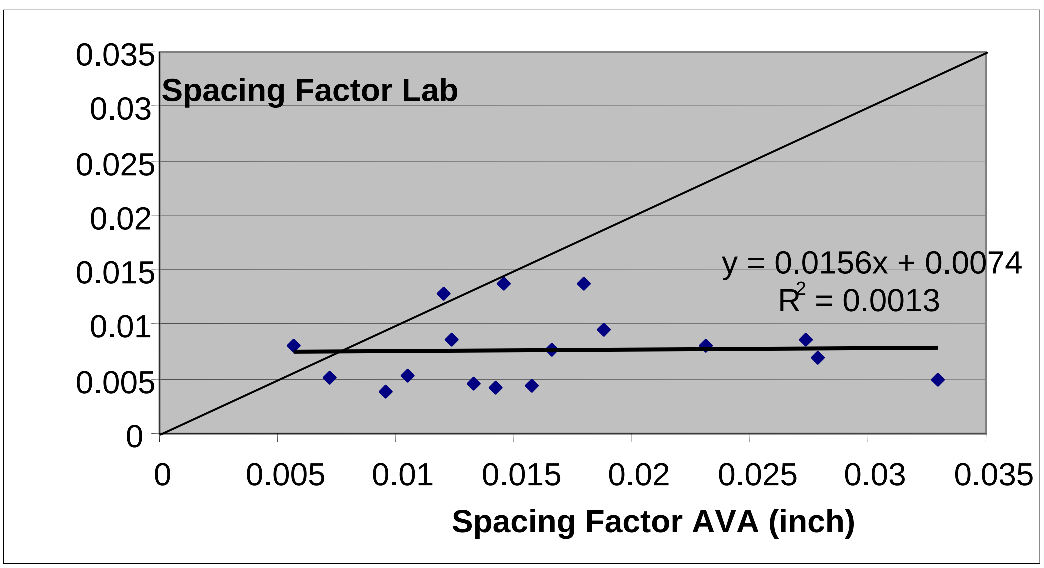

Figure 27. Comparison of Spacing Factor Measured by AVA and Manual ASTM C 457 Method.

The spacing factor values measured by AVA are on the higher side when compared to the spacing factor measured by ASTM C 457, and from the trend line in Figure 27 it can be seen that they are independent of the values calculated from the manual ASTM C 457 method.