Improving Variability and Precision of Air-Void Analyzer (AVA) Test Results and Developing Rational Specification Limits

National Concrete Pavement Technology Center

Phase I Report
June 2008

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16. Abstract
Since air-void analyzer (AVA) was introduced in the 1990s, various studies have been conducted in the United States to apply this technology. Many concerns are raised on (a) the variation of the AVA tests, (b) the relationship between AVA and other standard measurements, and (c) AVA specification limits. The application of AVA tests in concrete practice is therefore very challenging. The goals of the present research project are to reduce variability and improve precision of AVA test results and to develop rational specification limits for controlling concrete freezing and thawing (F-T) damage using the AVA test parameters.

This project consists of three phases:

- Phase 1—Literature search and analysis of existing AVA data (June 2007–August 2008)
- Phase 2—AVA testing procedure and specification modification
- Phase 3—Field study of AVA and specification refinement

In the present research report, the major activities and findings of the Phase 1 study are presented, and the major tasks for the Phase 2 study are recommended.

The major activities of the Phase 1 study included the following: performing a literature search, collecting and reviewing available AVA data, completing a statistical analysis on collected AVA data, and carrying out some AVA trial tests in lab. The results indicate that AVA is a time- and cost-effective tool for concrete quality control. However, robustness of the AVA equipment, test procedures, and resulting interoperations need further improvement for a proper implementation of the AVA technology in concrete practice.

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IMPROVING VARIABILITY AND PRECISION OF AIR-VOID ANALYZER (AVA) TEST RESULTS AND DEVELOPING RATIONAL SPECIFICATION LIMITS

Phase 1 Report
June 2008

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- Jennifer Distlehorst (Kansas Department of Transportation)
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- Larry Roberts (CTLGroup)
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EXECUTIVE SUMMARY

Since the air-void analyzer (AVA) was introduced in the 1990s, various studies have been conducted in the United States to apply this technology. Many concerns have also been raised regarding (a) the variability of the AVA tests, (b) the relationship between AVA and other standard measurements, and (c) AVA specification limits. Therefore, the application of AVA tests in concrete practice becomes very challenging.

The goals of the present research project are to reduce variability and improve precision of AVA test results and to develop rational specification limits for controlling concrete freezing and thawing (F-T) damage using the AVA test parameters. This project consists of three phases:

- Phase 1: Literature search and analysis of existing AVA data (June 2007–August 2008)
- Phase 2: AVA testing procedure and specification modification
- Phase 3: Field study of AVA and specification refinement

In the present research report, the major activities and findings of the Phase 1 study are presented, and the major tasks for the Phase 2 study are recommended.

The major activities of the Phase 1 study included the following:

1. Conducting a project Technical Advisory Committee (TAC) meeting
2. Performing a literature search
3. Collecting and reviewing available AVA data
4. Completing a statistical analysis on collected AVA data
5. Carrying out some AVA trial tests in lab

The AVA test data were collected from the Missouri, Kansas, and Michigan Departments of Transportation (DOTs) and from the "Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements" (MCO) project conducted by the National Concrete Pavement Technology Center (CP Tech Center).

Major Findings

From the first project TAC meeting, the following findings can be drawn:

- The problems associated with AVA tests are as follows: (a) AVA tests sometimes reject good concrete, (b) AVA results are not closely repeatable, and (c) AVA results do not always correlate with C457.
- The variables contributing to inconsistency of AVA test results include (a) equipment (such as inappropriate column size, stir energy, and test time for pavement concrete mixtures), (b) AVA blue fluid (such as viscosity change from shipment to shipment, over time, and with environmental temperatures), and (c) test procedure (such as sequence of test operation, mortar extraction in sampling, testing duration, and testing conditions [such as sample temperature, vibration of the test table, etc.])
- The suggestions for improving the AVA test precision include (a) conducting a

systematic study (with a given test matrix) to examine the reliability of the AVA equipment and the test procedure, (b) further studying the relationship between parameters measured by the AVA test method and other test methods, (c) improving the test procedure and establishing rational specification limits, and (d) having another well-designed round-robin AVA test to find out the reliable values of variations due to the equipment and its operation.

From the literature survey, the following findings can be drawn:

- AVA reports the content, spacing factor, and specific surface of small air voids in concrete, which are more important for the durability of concrete under a cold weather environment.
- The AVA test may be beneficial as a quality control tool for concrete mixtures incorporating various supplementary cementitious materials, additives, and/or admixtures; and for special mixtures such as short mixing time, low slump, pumped concrete; and for the mixtures exposed to extreme environmental conditions (e.g., very hot or very cold).
- The critical problems associated with the existing AVA test include (a) robustness of the test method and equipment, (b) nonstandard test procedure and acceptance criteria, (c) large variations in the test results, and (d) inconsistent relationships with other test results.
- The possible causes of variation in AVA test results can be classified as (a) variations due to test operation (such as sampling technique, removal of air from syringes, test timing, equipment cleanness, and test duration), (b) variations due to features of the AVA device (such as viscosity of the blue fluid, stirring energy (rpm), drilling model, sensitivity of the device to environmental disturbance and mixture proportions), and (c) variations due to concrete material production and construction (such as concrete mixing time, transportation time, placement method and temperature, vibration and finishing methods).

From the literature review, the following findings can be drawn:

- The total air content measured from AVA was generally lower than that measured by C231 or C457 test methods.
- The high air content didn't always ensure a low spacing factor. That is, the relationship between air content and spacing factor didn't always exist.
- MCO project data demonstrated a very good relationship between the content of small air void (≤ 300 μm) and spacing factor measured by AVA (R^2=0.82).
- The air content measured from AVA appeared to be unimportant and might not need to be reported. Instead, the frequency of small spacing factor (0.005–0.015 in.) may control the quality of concrete.
- When the criterion of the spacing factor of 0.008 in. (200 μm) was applied, the accepting/rejection agreement between C457 and AVA test methods was only about 50%.

From statistical analyses of the collected data, the following findings can be drawn:

- Although the coefficients of variation (CVs) of AVA measurements were often relatively high, the differences in CVs between AVA, C231, and C457 measurements were smaller than 15%. Therefore, the AVA variability might be considered acceptable when compared to C231 and C457 variability.
- Based on the statistical analysis, if 5% air content from gravimetric or C231 measurements is considered acceptable for fresh concrete, 2.3% or 3.0% total air content from AVA measurements shall also be considered as acceptable, respectively.
- AVA spacing factor of 0.012 in. is corresponding to the AVA total air content of 3%, C231 air content of 5%, and C457 spacing factor of 0.008 in.
- The acceptance criteria should be ≤ 0.012 in. for AVA and ≤ 0.005 in. for C457 spacing factor measurements so as to have a concrete durability factor of ≥ 85%.
- Ambient temperature changes had a significant effect on AVA measurements. Aggregate-to-cement ratio a/c had much more significant effects on air-void spacing factor and specific surface than on total air content.

From the AVA trial tests, the following findings can be drawn:

- The CVs in the AVA measurements resulting from a single operator (i.e., same mixture proportion, different batching, and same test device) were high. The high variations might be attributed to the effect of different batches produced in the lab, which should be further examined in the future.
- The CVs in the AVA measurements resulting from multiple operators, who used the same AVA device and the same test procedure and tested three samples from a given batch made with the same mixture proportion as others, were low. This suggests that implementation of a properly specified AVA test procedure can significantly reduce the variation of AVA measurements in concrete practice.
- AVA measurements of concrete mixtures made with different water-to-cement ratio (w/c) showed different variations. Therefore, use of different stirring energy may minimize the variations of samples with different flowability. More repeated tests of samples with different w/c need to be performed to verify this finding.
- There is a close relationship between the blue fluid viscosity and air-void parameters (air content, spacing factor, and specific surface). The blue fluid viscosity ranged from 0.075 Pas to 0.130 Pas provided the highest air content and lowest spacing factor measurement. This range may be used in the AVA test specification to control precision of AVA measurements.

Recommendations for Further Research

Based on the results of the Phase 1 study, the following major tasks are recommended for the Phase 2 study in order to reach the goal of this project:

- Investigate and improve robustness of AVA device.
- Systematically evaluate the American Association of State Highway and Transportation Officials (AASHTO) AVA test procedure.
- Further investigate the relationships between AVA measurements and freeze-thaw (F-

T) durability factors and develop rational acceptance criteria for AVA measurements.
- Conduct a well-designed AVA round-robin test to verify the findings obtained from the above tasks.

The Phase 2 proposal will be developed and submitted to the funding agencies in a separate document.

1. INTRODUCTION

1.1 Background

In cold climate regions, many concrete pavement deteriorations are associated with freezing and thawing (F-T) cycling and repeated applications of deicing chemicals. Properly entrained air (i.e., well-sized, well-distributed and sufficient amount air voids) is essential for the concrete. Many engineers have agreed that it is the well-spaced air voids, rather than the total air voids that play the vital role in improving the concrete frost resistance. A great deal of work has been done in characterizing concrete air-void systems—measuring not only content but also the spacing factor and specific surface of the air voids. However, much of the work has been performed on hardened concrete. Although supplying valuable information, the measurements of the air voids in hardened concrete are unable to provide on-time information for field concrete quality control. Clearly, it is too late to correct any air-entraining problems after the concrete has hardened.

Unfortunately, the test methods for assessing the spacing factor and surface area of the air voids in fresh concrete were not available until the1990s, when an air-void analyzer (AVA) was developed. Different from all existing test methods, which measure only air content of fresh concrete, the AVA device offers the ability to measure the air content, specific surface, and spacing factor in fresh concrete within 25–30 minutes. With this information, adjustments can be made in the concrete batching process to ensure that proper air-void structure is achieved in the concrete.

In 1999, the Federal Highway Administration (FHWA) tested the AVA technology on projects in nine states. Since then, various studies and field trials have been conducted in the United States to apply the AVA technology into concrete research and practice. Some results have shown that the AVA test data are well correlated with ASTM C 457 data in terms of air-void spacing factor, while others have indicated no clear relationship between these two test data. Although the AVA test procedures have been developed and accepted by many users, the environmental and construction conditions (such as temperature and vibration) during concrete production and placement often make the test difficult to repeat, and therefore brings into question its ability to be a routine quality control procedure. The AVA device captures only the air voids smaller than 3 mm (0.12 in.). There is a time delay between the sample preparation, testing, and data recording. This may result in a loss of air. These significant influences on the test precision make the test results questionable when compared with those obtained from hardened concrete. In addition, limited research has been performed to study the relationship between the air-void system parameters (total air content and spacing factor) obtained from AVA tests and the concrete F-T durability. Although the commonly accepted rules of thumb for a good air-void system include air content of 6% and a spacing factor less than 0.008 in. (200 µm), some studies have shown that concrete test results from the AVA not meeting the accepted criteria may still be resistant to a certain frost action. All of the above problems make the establishment of a rational specification limit for concrete quality control especially challenging. It is urgent to solve these problems and provide engineers with rational test procedures and specifications for controlling the fresh concrete air-void system.

1.2 Goals and Objectives

The goals of the present research are to reduce variability and improve precision of AVA test results and to develop rational specification limits for controlling concrete F-T damage using the AVA test parameters. The specific objectives of this research are as follows:

- To identify problems related to use of AVA device and causes of the variations in AVA test results (such as variability due to the test equipment, materials, weather, and construction conditions)
- To standardize the AVA test procedure and improve precision of AVA test results
- To examine the relationships between the parameters obtained from AVA tests and those from commonly used hardened air tests and durability tests
- To develop rational specification limits for controlling concrete F-T damage using the AVA test parameters

1.3 Approach and Scope

This research project consists of three phases:

- Phase 1—Literature Search and Existing Data Analysis. The first phase was designed to review and synthesize the existing AVA test data from literature and the National Concrete Pavement Technology Center's (CP Tech Center's) "Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements" (MCO) project. Data were also collected from the TAC members. It was designed to identify the factors that affect AVA test procedures, variation and repeatability of AVA measurements, existing specification limits, and the relationships between AVA and other hardened or durability test results. Phase 1 started with a kickoff meeting on June 11, 2007, and will be completed in August 2008.
- Phase 2—Testing Procedure and Specification Modification. In the second phase, researchers will conduct systematic experiments in laboratory to study the factors that influence the precision and repeatability of AVA tests. The experimental results will be used to verify the findings obtained from Phase 1 study as well as to modify, calibrate, and/or validate the test procedures. As a result, modified test procedures may be developed to ensure a proper precision, and repeatability of the AVA test will be obtained under a large range of materials and test conditions.
- Phase 3—Field study and Specification Refinement. In the third phase, researchers will conduct a series of field tests performed based on the proposed specifications obtained from the Phase 2 study. These field tests will be conducted along with the National CP Tech Center's concrete mobile lab at 10 or more different paving sites. The test results will be used to further verify the findings and recommendations obtained from Phase 2. The specifications developed in the Phase 2 study will be re-evaluated and refined based on the information obtained from Phase 3.

1.4 Overview of Phase I Study

The project started with a kickoff meeting at the Marriott Hotel, Kansas City, Missouri, on June 11–12, 2007. The approach that the research team started with was designed to get users together to share data and discuss their experience with the AVA machine. Valuable inputs on the problems associated with AVA tests, variables contributing to inconsistency of AVA test results, and potential research topics were provided by the attendees at the meeting. Broad discussions were held that addressed specific issues on the AVA equipment and test procedures. These inputs and discussions greatly helped the research team in determining the direction and developing the research activities of this project.

After the kickoff meeting, the research team conducted a literature review on the use of AVA in concrete labs and construction sites. This work was focused on examining the critical factors that affect AVA test results (such as mixture properties, time of sampling/testing, and testing conditions), specification limits, and results of the comparative tests (such as hardened air-void properties or freeze-thaw results).

In addition to the literature search, four sets of AVA test data were also collected from Missouri, Kansas, Michigan, and Iowa through the Technical Advisory Committee (TAC) members of this project. These data were compiled, and statistical analysis was applied. Based on the available data, relationships between the air-void parameters measured by AVA tests and other tests (such as ASTM C231 and C457) were examined. The agreement in the acceptance/rejection criteria provided by existing AVA and C457 specifications was investigated.

The literature search showed that although many agencies purchased AVA devices, limited AVA test results were published. Although the AVA data we collected from TAC members were interesting, some related information (such as test conditions and mix proportion) was not presented in the files, which made the in-depth data analysis difficult. Therefore, the research team conducted some AVA trail tests in lab to study the repeatability of the commonly used AVA test method, effect of dry and wet mixtures, and effect of viscosity of AVA blue fluid on AVA test results.

The research team believes that the results of the Phase 1 research activities listed above have confirmed the needs for, potential application of, and existing problems with AVA tests. Consequently, the specific objectives for Phase 2 were further clarified and the plan for Phase 2 of the project was developed.

In the following sections, the major activities and findings of the Phase 1 study are presented, and the major tasks for the Phase 2 study are recommended.

2. PROJECT TAC MEETING

The project kickoff meeting was held at the Marriott Hotel, Kansas City, Missouri, on June 11–12, 2007. All research team members and Technical Advisory Committee (TAC) members attended the meeting. The TAC members are as follows:

- Dave Amos, Missouri Department of Transportation
- Jennifer Distlehorst, Kansas Department of Transportation
- Jeff Elliot, TTL Associates
- Geoff Kurgan, Federal Highway Administration
- Larry Roberts (by phone), CTL Group
- Peter Taylor (by phone), CP Tech Center
- Brett Trautman, Missouri Department of Transportation

At the meeting, all TAC members presented their experiences with AVA tests. Many presenters studied the relationships and acceptance/rejection agreements between AVA, ASTM C457, and F-T test results. Some research projects show good relationships/agreements but some show no relationships/agreements. The meeting attendees believed that this was partially related to the large variation of the AVA test results. Therefore, discussion centered on problems with the AVA, possible factors affecting inconsistent results, and suggestions on improving the AVA test.

The problems associated with AVA tests discussed at the meeting include the following:

- AVA tests sometimes reject good concrete.
- Results are not closely repeatable.
- Results do not always correlate with ASTM 457, probably due to the variability in both AVA and 457 results.

The variables contributing to inconsistency of AVA test results may include the following:

- Equipment—It is possible that the AVA equipment might be developed based on the limited tests of European concrete mixes. The slumps of these concrete mixtures might be different from that of pavement concrete. As a result, the design of the column size and selections of the AVA fluid, stir energy, and test time were based on the limited concrete mixtures, rather than on the US pavement concrete mixtures. The equipment-related issues may be associated with the large variation of AVA test results. Recently, some users purchased the new version of AVA devices (AVA 3000 model). However, the improvement in the new machine, compared to the old one, is not clear.
- Fluid used for AVA tests—For a given piece of equipment, variation of AVA test results may also be caused by properties (such as density and viscosity) of AVA fluid. The users were not sure if there are variations in the AVA fluid viscosity from shipment to shipment and within the same container over time and how the fluid temperature affects its viscosity. Currently, AVA fluid temperature is not listed as an input of AVA tests. Physically, air bubbles move faster in a fluid with low viscosity.

It is not clear whether and how this physical phenomenon could affect the AVA test results.

- Test procedure—The AVA test procedure has been studied by FHWA and Kansas DOT, and a draft specification, the Standard Test Method for Air-Void characteristics of Freshly Mixed Concrete by Buoyancy Change, is under development through the American Association of State Highway and Transportation Officials (AASHTO). Depending upon the operator's ability and knowledge of the test procedure, many AVA operators do not follow the test procedure closely, which may be the major cause of the variation in AVA test results. Other variations may result due to (1) the number of air bubbles destroyed when mortar extraction is applied, (2) the tap water used in the test (or should the de-aired water or distilled water be used in the test?) and (3) the short test time (25 minutes) as controlled by the computer program in the AVA device. It is questionable if there are still bubbles in the tested mortar and/or in the fluid when the AVA test times out, and if other parameters, rather than the AVA spacing factor or surface number, should be reported from the test.
- Testing conditions—Since the environmental temperature can affect sample temperature and AVA blue fluid temperature, it will influence AVA test results. Some operators have observed that some vibration of the test table on which an AVA device is placed would also disturb the amount and the rate of rising air bubbles.

The TAC members suggested the following in order to improve the AVA test:

- Looking into the items discussed and questions raised at the meeting
- Conducting a systematic study (with a given test matrix) to examine the reliability of the AVA equipment and the test procedure
- Further studying the relationship between parameters measured by the AVA test method and other test methods
- Improving the test procedure and establishing rational specification limits

In addition, several TAC members suggested having another round robin with a number of machines and experienced operators. As a part of the testing, the operators could rotate after each test and run the next machine. A statistician could look at the data for significance and also compare results of one operator versus another to see if one gets higher values. More details (such as using a steel plate for the vibration of the concrete to make sure the consolidation was uniform, using the same vibrator to extract mortar sample and the same blue fluid for the test, and ensuring all operators follow the same test procedure) have been laid out in order to control operator variations.

3. LITERATURE STUDY

Air entrainment is recommended for nearly all concretes, principally for the concrete exposed to F-T cycling and deicing chemicals. Besides enhancing concrete F-T and scaling resistances, entrained air also improves flowability and reduces bleeding and segregation of fresh concrete. In addition, use of air-entraining agents has some positive effects on expansion associated deteriorations, such as sulfate attack and alkali-silica reaction. It is agreed upon that properly entrained air (with certain amount, size, and space) is essential to improve concrete durability. It is important to check the air structure of fresh concrete regularly for quality control purposes.

As mentioned previously, a great deal of research has been done on the hardened concrete air system. However, research on the fresh concrete air system had been minimal until the 1990s, when the AVA device was developed. The present literature survey concentrated on the fresh concrete air system, and it covered the following items:

- Factors affecting concrete air system
- Measurements of air voids in fresh concrete
- AVA experience in the U.S.
- Major findings from the existing AVA research

These literature survey results are briefly summarized in the following sections.

3.1 Factors Affecting Concrete Air System

The concrete air-void system or structure is comprised of three elements—air content, spacing factor, and specific surface. Air content is the total volume of the air in concrete; spacing factor indicates the number and the size distribution of air voids; and specific surface is an indirect measurement of air-void size. Many engineers and researchers agree that a properly entrained air- void system, rather than the total air content alone, plays the vital role in improving the concrete frost resistance.

There are various factors that may affect the air system in concrete:

- Portland cement (content, fineness, alkali content, contaminants)
- Supplementary cementitious materials (content, fineness, chemistry)
- Admixtures (type, dosage) and their interactions with other ingredients
- Aggregate (content, type, size, sand gradation)
- Water (chemistry, type such as recycled/gray water)
- Concrete mix design (w/c, slump)
- Construction (mixing such as procedure and energy, transportation and delivery, retempering, and placement methods [such as pumping or shotcrete, vibration, finishing, and ambient temperature])

3.2 Measurements of Air Voids in Fresh Concrete

For a long time, only air content has been measured as a quality control tool for fresh concrete. There are three commonly used methods to measure air content:

- Pressure Method (ASTM C231)—This test is determined based on the relationship between pressure and volume. The test apparatus is shown in Figure 1a.
- Volumetric Method (ASTM C173)—In this test, air content is directly measured by an apparatus equipped with an air meter. The test apparatus is shown in Figure 1b.
- Gravimetric Method (ASTM C138)—In this test, air content is calculated based on the difference between the theoretical weight/volume of concrete and the produced weight/volume of concrete.

A major problem with the measurements of air content in fresh concrete is that the air content has little or no correlation with the characteristics (spacing factor and size distribution) of the air pores in hardened concrete. That is, control of air content only does not guarantee the achievement of the demanded service life of the concrete.

Many attempts have been made for measuring other air structure parameters, such as spacing factor and specific surface of fresh concrete. One of the attempts is to use laser scan to examine ice formed in voids of fresh concrete frozen with liquid nitrogen (Hansen 1991). This test method is feasible for lab study but it is expensive and time-consuming for field application.

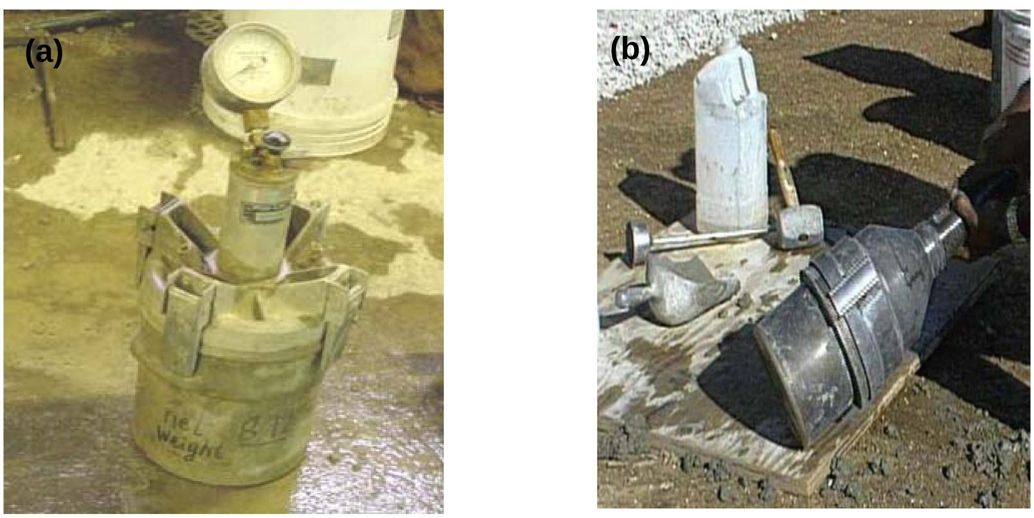


Figure 1. Devices for air content measurement of fresh concrete—(a) ASTM C231 and (b) ASTM C173

In recent times, AVA has increasingly been used for measuring the air-void structure parameters in fresh concrete. The equipment is shown in Figure 2. AVA was developed by Dansk Beton Teknik (DBT) under BRITE/EURAM project in the early 1990s (Magura 1996). The AVA procedure is also referred to as the Danish Air Test in North America (Aarre 1998). Since then it has become a standard test in Europe and has been implemented by many researchers, admixture and ready mix manufacturers, and contractors in Denmark, Sweden, Iceland, Germany, Belgium, Czech Republic, Switzerland, Italy, and Spain (AASHTO TIG 2003).

Advantages of using AVA have been recognized rapidly. The test primarily measures the entrained air (less than 1 mm) which is known to be effective in frost resistance. It not only gives the total air content but also determines the size and distribution of air bubbles, provided by the spacing factor and specific surface of the air-void system in fresh concrete. Sampling can be done just after placing, vibrating, and finishing. This means the air-void structure is determined at the very initial stage of the actual concrete pavement. The equipment is portable enough to perform the test in the lab and on-site in the field, and the whole procedure takes around 30 minutes.

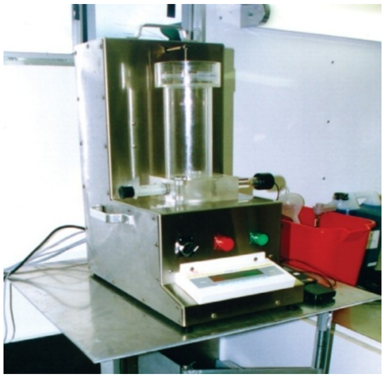


Figure 2. Air-void analyzer

3.3 AVA Experience in the United States

In the United States, AVA studies have been conducted in the last two decades. The first AVA unit was purchased by Federal Highway Administration (FHWA) in 1993. FHWA tested various concrete mixes using AVA and compared the findings with ASTM C457 (Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete) results. Several other agencies and companies (e.g., DOTs of CA, KS, IA, NC, and WI; Master Builders; WR Grace; and CTLGroup) have also been reported to own and use the equipment. However, today, limited published data are available. The following sections summarize the available information collected from published reports and conference presentations.

3.3.1 FHWA Experience

FHWA published the results of its first study in 1996 (Magura 1996). The air contents obtained from the AVA, C231, and C457 were compared. The results can be summarized as follows:

- There was a good correlation between the air contents obtained from the C457 and C231 (Figure 3a).
- AVA was found to measure the air content lower compared to the pressure meter (Figure 3b).

- The correlations between the spacing factors and the specific surfaces provided by the AVA analyzer and the C457 method were poor. AVA reported lower spacing factors and higher specific surfaces (Figures 3c and 3d).

3.3.2 Kansas Experience

Kansas DOT led in developing AVA specifications by investing significant resources on AVA studies and passing the lead to FHWA by 2006. Kansas DOT established a relationship between the Durability Factor (ASTM C 666–Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing) and the spacing factor obtained from both C457 and AVA (Wojakowski 2008). The trends were found to be similar (Figures 4a and 4b). Although the findings are promising, more data points are needed to confirm this relationship. In addition, the relationship between the AVA spacing factor and the air content (provided by the contractor) was found to be affected by the concrete materials (Figure 5a). The correlation between the AVA and C457 spacing factors were also found to be high in this study. This correlation was further confirmed in a subsequent study in 2007 (Figure 5b) (Distlehorst 2007).

Kansas DOT has decided to use AVA for the prequalification of the concrete mixture in the laboratory, and verification and monitoring of project concrete in the field. Furthermore, Kansas DOT has established a minimum air content of 5% based on a maximum spacing factor of 0.25 mm (0.01 in.).

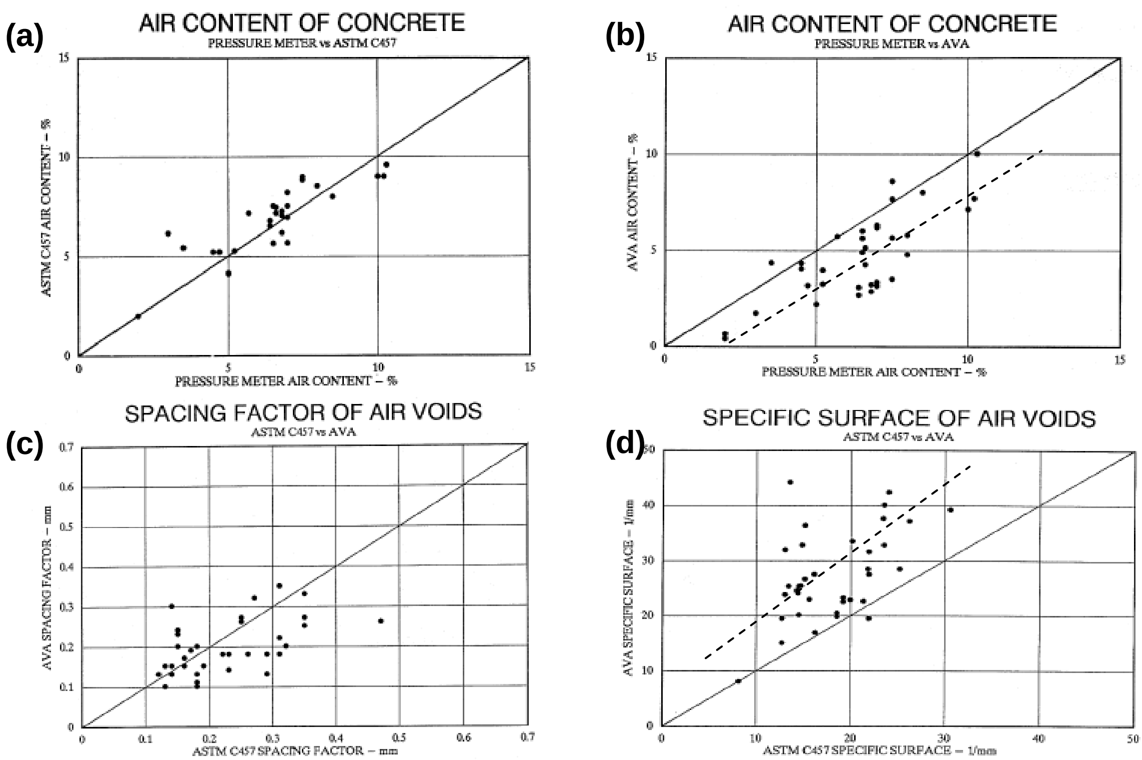


Figure 3. FHWA study on AVA—relationships between results from different test methods (a) C457 and C231 air contents; (b) AVA and C231 air contents; (c) AVA and C457 spacing factors; and (d) AVA and C457 specific surfaces

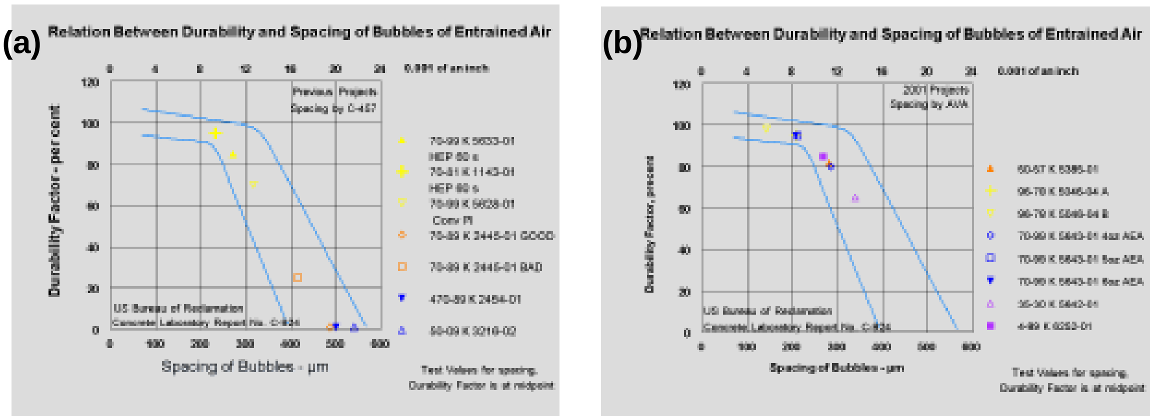


Figure 4. Kansas study—correlation of durability factor and spacing factor (a) C457 spacing factor and (b) AVA spacing factor

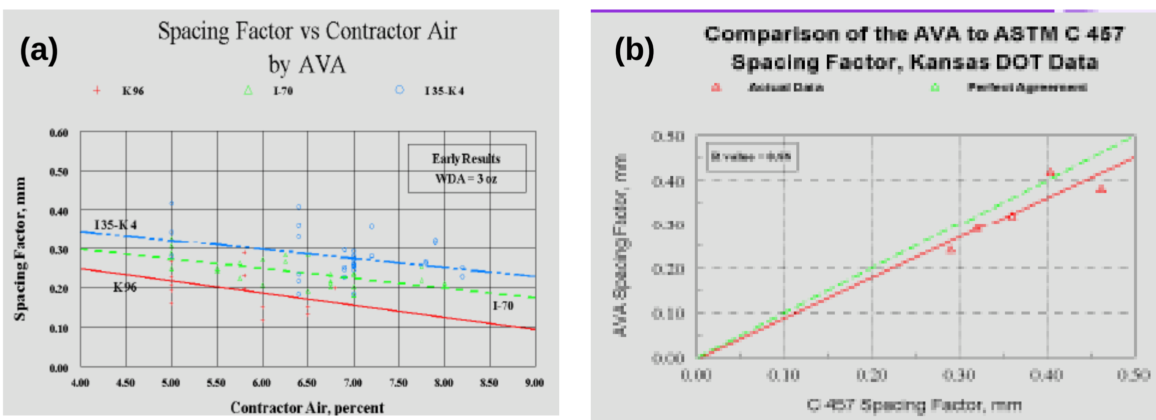


Figure 5. Kansas study—correlation of AVA and other air-void measurements (a) AVA spacing factor versus C231 air content and (b) AVA versus C457 spacing factor

In 2006, a round-robin test was performed to develop a precision statement for determining the air-void characteristics of fresh concrete using AVA (Distlehorst and Kurgan 2007). The event included 19 AVA devices, and seven concrete mixtures were tested. All the results showed that the concrete met the Kansas DOT specification for spacing factor. The single-operator and multi-machine standard deviations were found to be 0.0185 mm (0.000729 in.) and 0.0256 mm (0.001010 in.), respectively. Therefore, results of two properly conducted tests by the same operator are not expected to differ by more than 0.0524 mm (0.002062 in.) and the results of two properly conducted tests on different machines on the same material are not expected to differ by more than 0.0725 mm (0.002855 in.).

3.3.3 Michigan Experience

A Michigan AVA study aimed to produce more durable concrete and to identify material incompatibilities using AVA (Elliot 2007). Seven contractor members of the Michigan Concrete Paving Association (MCPA) purchased an AVA and hired TTL Associates to perform field testing. For this purpose, a laboratory trailer was constructed to perform on-site testing. Only two operators used the AVA; over 200 tests were carried out on more than 30 projects. The AVA was generally successful in identifying the deficiencies with the air-void system and correcting them "on-the-fly." Material incompatibilities were observed but could not be explained. Furthermore, the AVA results showed variation compared to the core data. The Michigan experience has identified the challenges regarding AVA as the following:

- The testing equipment is very sensitive to disturbance.
- The operation requires extreme care and precision.
- Availability of the testing equipment to cover all projects is questionable.
- The correlation of AVA data to hardened air (ASTM C457) data and/or durability is needed.

3.3.4 Iowa Experience

The National CP Tech Center at Iowa State University (ISU) has put considerable effort into AVA research (MCO Report 2008). AVA was utilized in field testing under the "Material and Construction Optimization for Prevention of Premature Pavement Distress in PCC Pavements" (MCO) project, which included 17 states. Figure 6 shows the effect of slipform vibration on the spacing factors: the results compare the values on the vibration and the ones between the vibration paths. Since all the data points were distributed equally around the equity line, there was no significant effect. This is probably due to the fact that AVA counts only small bubbles, excluding large entrapped voids and vibration that does not disturb small bubbles. Figure 7 shows the relationship between spacing factor and total air content as measured by ASTM C231. The correlation is not good; however, the trend shows that the spacing factor decreases as the air content increases. The results are in agreement with the findings by Pinto and Hover (2001) (Figure 8). The results also show that high air does not ensure a low spacing factor. Figure 9 shows the relationship between air content as determined by the AVA, bubble size, and spacing factor. The relationship is poor if the larger diameter air bubbles are included (i.e., total air measured by AVA); however, it is significant if smaller air bubbles (<300 μm) are counted. AVA suggests that the effective air-void size content is 300 μm for freeze-thaw durability.

The MCO project also showed that there is a larger variation in AVA results of some concrete mixtures than others. It is unclear whether the deviation results from mixture heterogeneity or from operational variation. It was also found that 90% of the spacing factors fell into 0.004–0.015 in. range and 8% of the spacing factor values were greater than 0.015 in. (Figure 10).

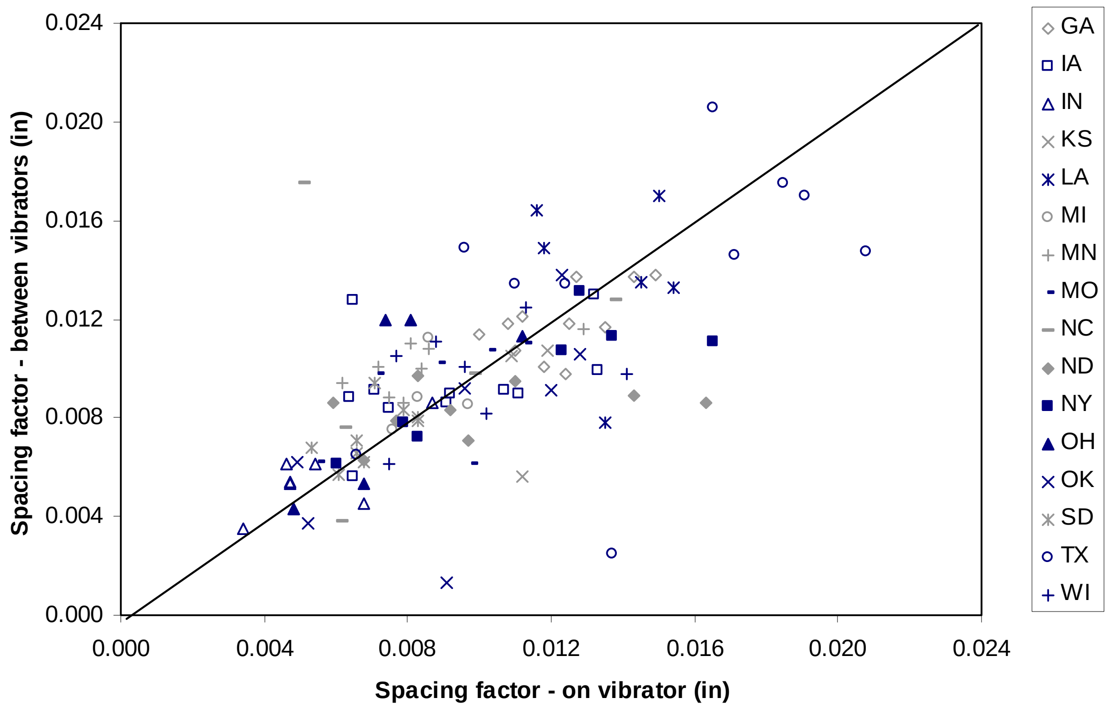


Figure 6. MCO study—spacing factors of samples between vibrators versus those on vibrators

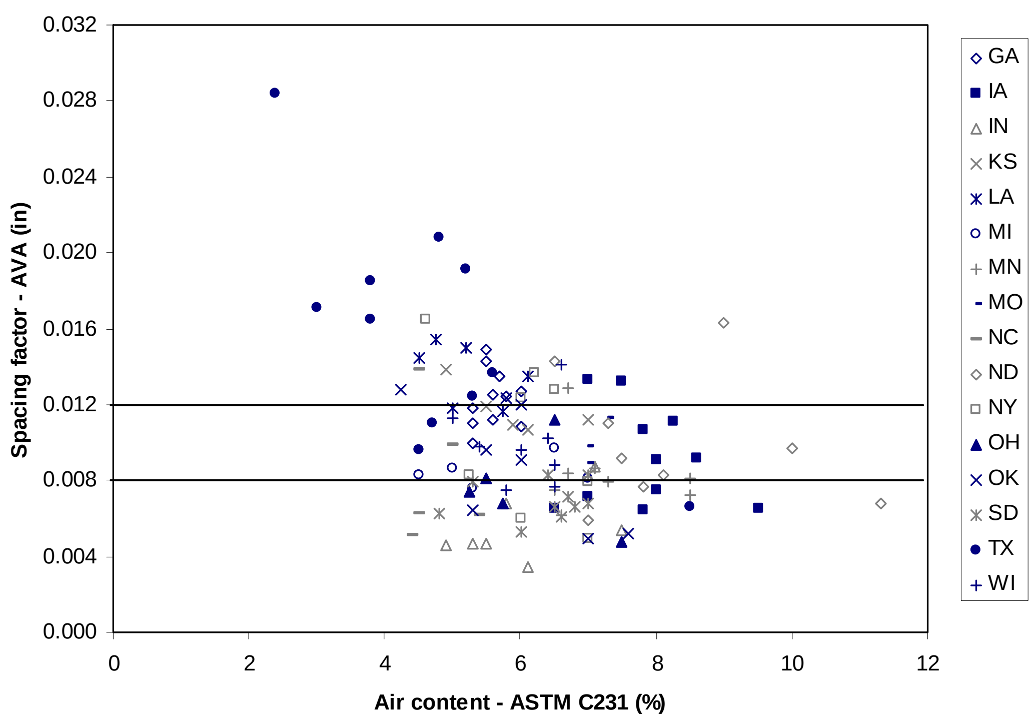


Figure 7. MCO study—spacing factor versus total air content

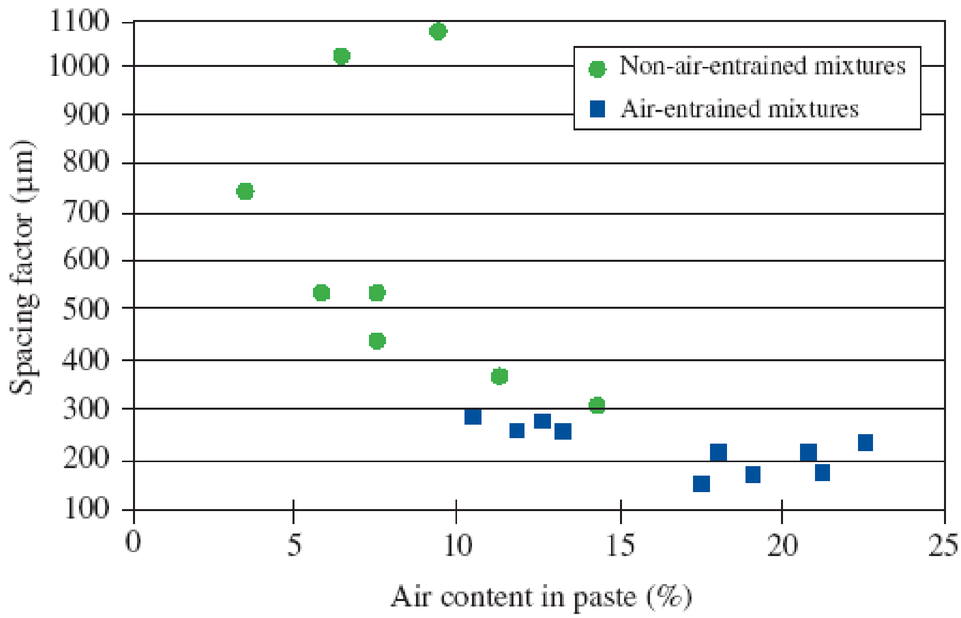


Figure 8. Spacing factor versus air content in paste

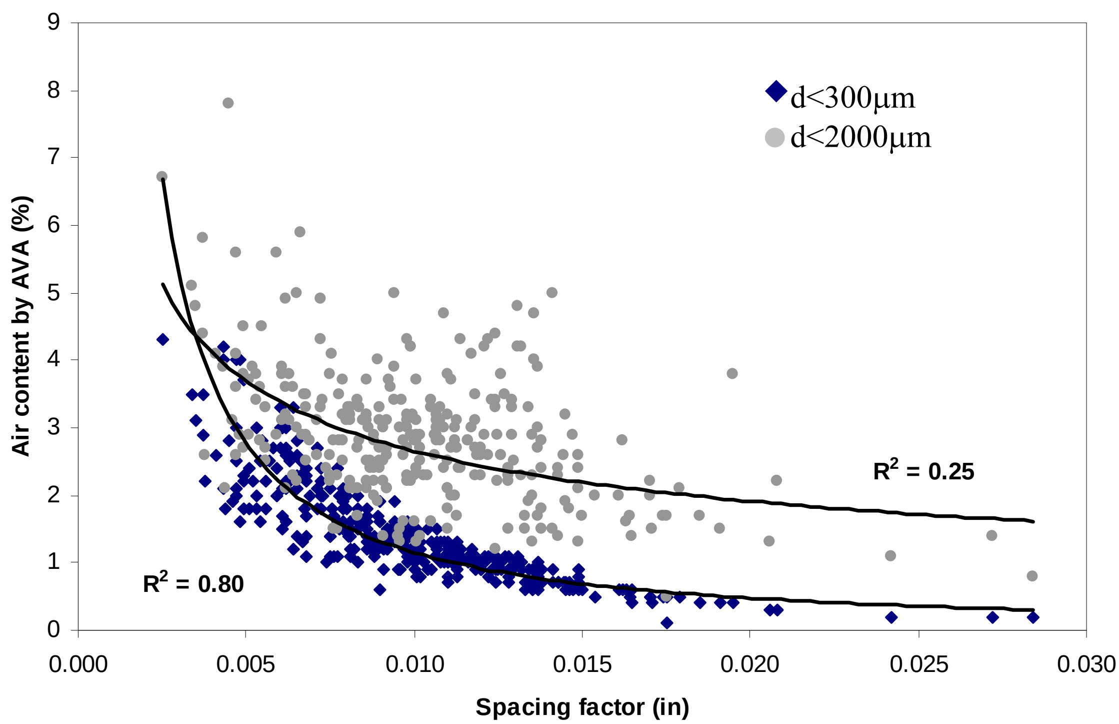


Figure 9. MCO study—relationship between AVA air content, bubble size, and spacing factor

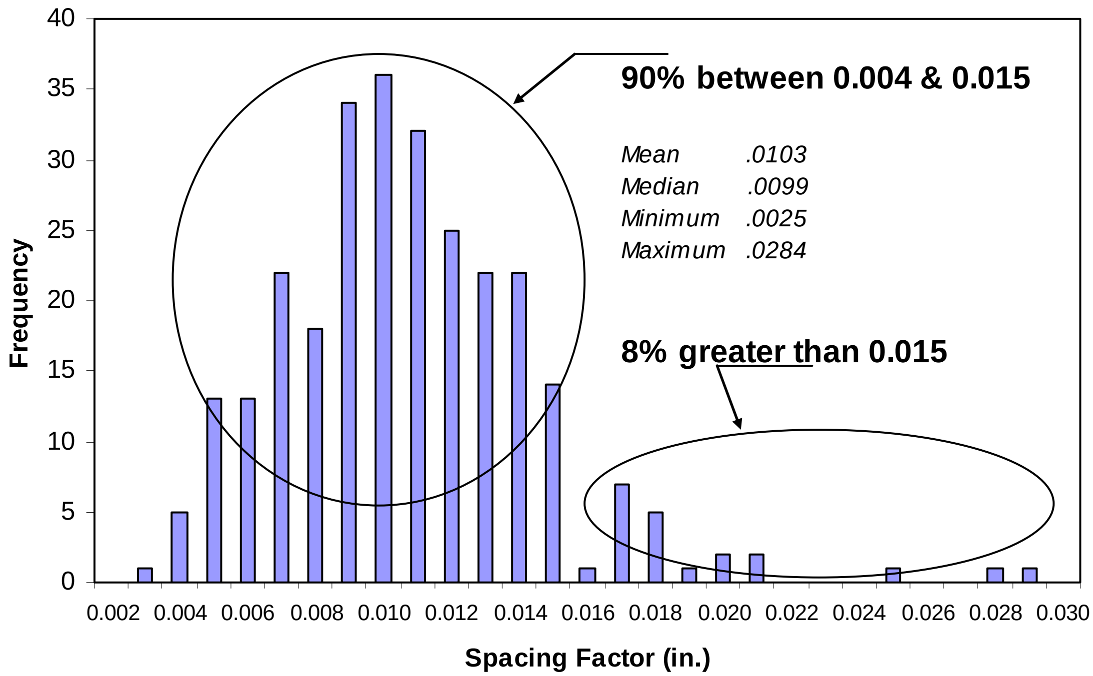


Figure 10. MCO study—distribution of AVA spacing factor

In another project at ISU (Zhang and Wang 2006), the effects of materials (i.e., fly ash, water reducer), mixing time, and mixing method on the air-void system were studied using AVA. The results showed that the water reducer increases the air content whereas the fly ash has no significant effect. It was also found that the addition of either fly ash or lignin-based water reducer decreases the spacing factor (Figure 11). Furthermore, it was concluded that the amount of large air voids decreases whereas the quantity of small size air voids increases (Figure 12). Two different procedures, which were named as one-step mixing and two-step mixing, were tested. In the one-step procedure, all materials were loaded at once and the mixing was started; in the two-step procedure, mortar was mixed initially and then coarse aggregate was added. Compared to the one-step mixing method, the two-step mixing method produced a lower spacing factor and the amount of small air voids was increased significantly (Figure 13).

3.3.5 Other Works

CTLGroup conducted an AVA study in which the spacing factor from AVA was correlated to the spacing factor from ASTM C457. If 0.200 mm (0.008 in.) spacing factor is considered as the passing criterion, the agreement between two methods was found to be 50% (Taylor 2007). The results are demonstrated in Figure 14. In a similar study conducted by W.R. Grace, the agreement between AVA and ASTM C457, depending on the same criterion, was found to be 56% (Figure 15).

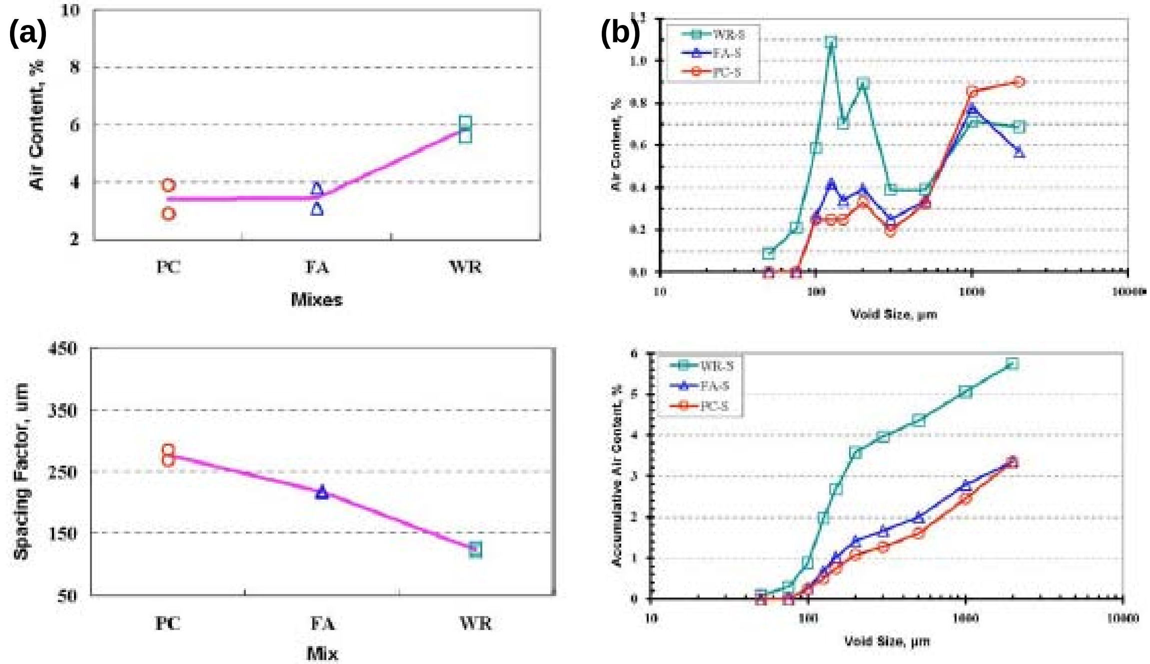


Figure 11. Other ISU study—effect of concrete materials on AVA measurements (a) air content and spacing factor (b) void size

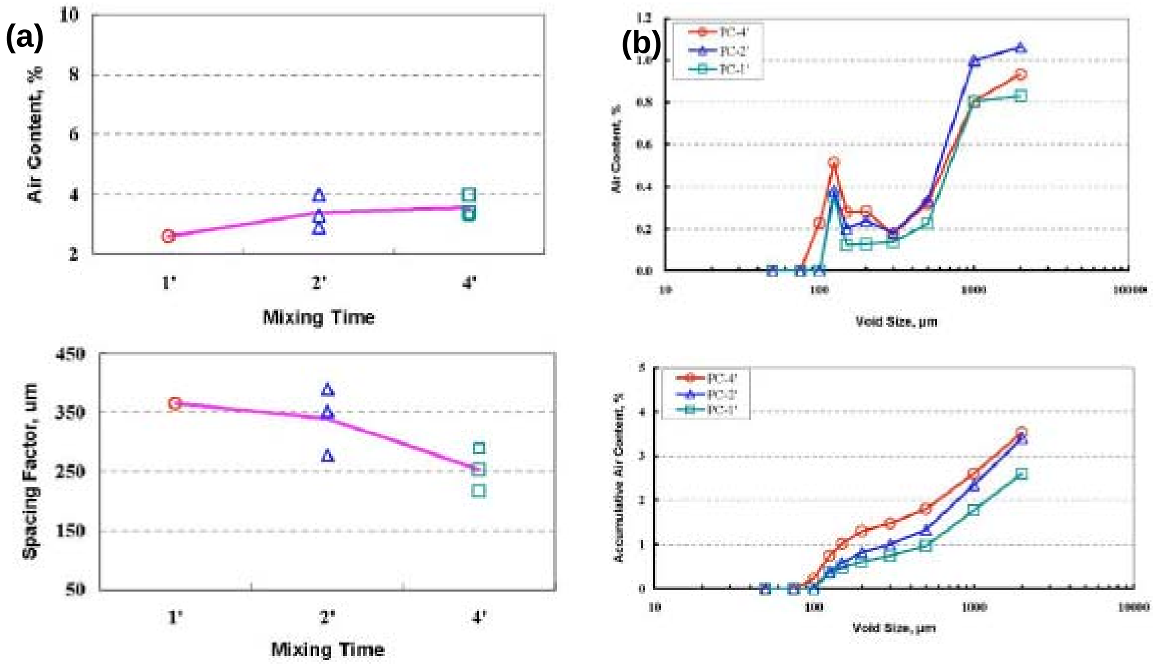


Figure 12. Other ISU study—effect of mixing time on AVA measurements (a) on air content and spacing factor (b) on void size distribution

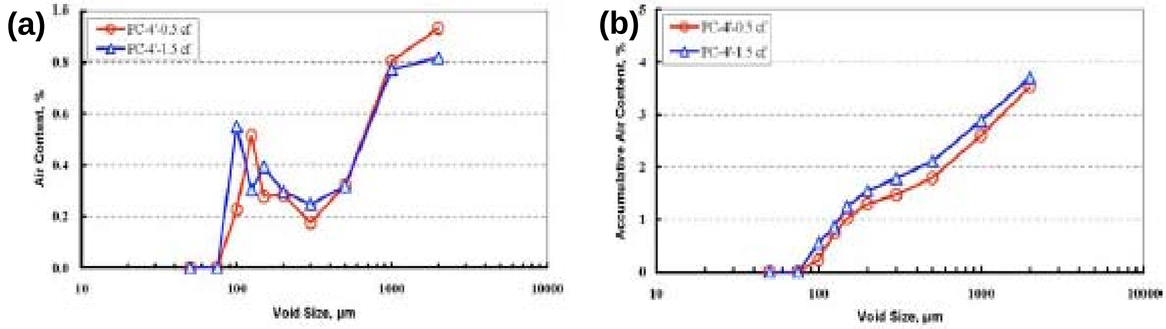


Figure 13. Other ISU study—effect of mixer on AVA measurements (a) on total air content and (b) on accumulative air content

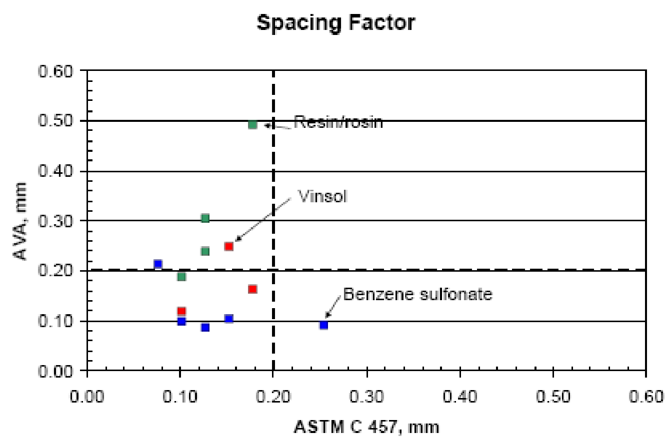


Figure 14. CTLGroup study—acceptance/rejection agreement in spacing factors measured by AVA and C457 (Acceptance criteria: spacing factor ≤ 0.008 in.)

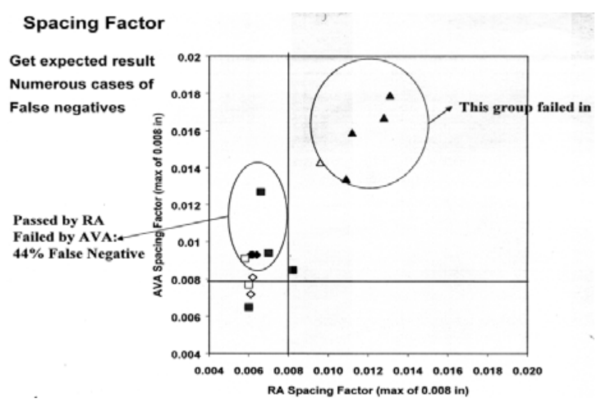


Figure 15. W.R. Grace study—acceptance/rejection agreement in spacing factors measured by AVA and C457 (Acceptance criteria: spacing factor ≤ 0.008 in.)

3.4 Major Findings from the Existing AVA Research

The major findings from the present literature survey on the existing AVA research can be summarized as follows.

3.4.1 Needs for AVA

It is widely recognized that a properly entrained air system protects concrete against deleterious effects of frost action, such as cracking due to F-T cycles and scaling. For quality control purposes concrete air content should be determined in advance when it is in a fresh state. Conventional methods—namely, ASTM C231 and C173—provide only total air content of fresh concrete. However, it is known that total air may not ensure proper air-void spacing and size for concrete to have desirable F-T resistant in some cases. AVA provides the critical air parameter of fresh concrete (the spacing factor). Unlike total air, spacing factor ensures sufficient, small air voids rather than large air voids in concrete. Using AVA, a field engineer can identify the air system problems related to material and mix proportion, incompatible materials, or construction and environmental conditions.

3.4.2 Potential Applications of AVA

The AVA test may be particularly beneficial as a quality control tool for concrete mixtures, especially sandy mixtures, with a short mixing time; mixtures with low slump and various supplementary cementitious materials, additives, and/or admixtures; and mixtures exposed to extreme environmental conditions (very hot or very cold) and construction conditions (such as pumping).

3.4.3 Existing Problems with AVA

AVA is being used by a significant number of parties; however, limited results have been published. Depending on the available literature, some areas that need examination for further improvement include the following:

- Robustness of the test method and equipment
- Nonstandard test procedure and acceptance criteria
- Reportedly large variations in the test results
- Inconsistent relationship with other test results

3.4.4 Possible Causes of Variation in AVA Tests

The problems with AVA tests are mainly related to the reproducibility and precision of the test method. Potential causes of the variation observed in testing might be from various sources such as the following:

- Operator variations
  - Sampling technique
  - Removal of air from syringes

    - Timing of test start vs. sample introduction to device
    - Leaving water in cylinder and in funnel introducing dissolved air
    - Cleanness of equipment
    - Test duration
- Equipment variations
    - Viscosity variation in blue fluid
    - Stirrer RPM
    - Drill model and action
    - Environmental disturbance to device during testing
- Batch material variations
    - Change in concrete material and mixture proportions
    - Incompatibility
    - Air-void coalescence
- Construction variations
    - Mixing time
    - Transportation time
    - Placement method and temperature
    - Vibration and finishing

3.4.5 Relationships between Air-Void Parameters and between the Parameters Measured by AVA and Other Tests

The following relationships were observed from the literature review:

- The total air content measured from AVA was generally lower than that measured by C231 or C457 test method.
- Both C457 and AVA measurements indicated that the high total air content did not always ensure a low spacing factor. That is, the relationship between the total air content and spacing factor did not always exist.
- MCO project data demonstrated a very good relationship between the content of small air voids (≤ 300 μm) and spacing factor measured by AVA (R^2=0.82). This suggested that the total air content measured from AVA might not need to be reported. Instead, the frequency of small spacing factor (0.005–0.015 in.) may control the quality of concrete.
- When the criterion of the spacing factor of 0.008 in. (200 μm) was applied, the acceptance/rejection agreement between C457 and AVA test methods was about 50%. The criterion of the AVA spacing factor of 0.015 in. (375 μm) was sometimes used.

In summary, AVA is a potentially useful tool for concrete quality control. While other conventional methods measure only the total air, AVA measures the content, spacing factor, and specific surface of small air voids in concrete, which are more essential to concrete durability. AVA is a quick and practical test and can be performed both in lab and at field. However, more research is needed to assist the equipment modification and specification development. The factors that are effective on the variability of the results should be studied in detail in order to improve the reliability of AVA. Particularly, development of acceptance criteria—perhaps using an AVA index to replace AVA content and spacing factor—is beneficial for AVA users.

4. DATA COLLECTION AND GENERAL ANALYSIS

Four sets of AVA data were collected from Missouri DOT, Kansas DOT, Michigan DOT (via TTL Associates), CP Tech Center (via MCO project) and FHWA (Mobile Lab) through the project TAC members. These data were compiled, and statistical analysis was applied to find the relationships between the air-void parameters measured by AVA tests and other tests (such as ASTM C231 and C457). The agreement in the acceptance/rejection criteria provided by existing AVA C457, and AASHTO T-161 (F-T test, Method B) specifications were investigated. The results of the data analysis are presented in the following sections.

4.1 AVA Data from Missouri DOT

The data of 36 AVA tests were obtained from Missouri DOT on 14 lab-produced concrete mixtures (Lab Mixtures) and 4 field-produced concrete mixtures (Field Mixtures). ASTM C231 and ASTM C 457 tests were also performed on some of the concrete mixtures. The test results are summarized in Tables 1 and 2, and the comparisons of the air-void parameters measured from AVA and other tests are presented in Figures 16–20.

The following findings were observed from the Missouri DOT data analysis:

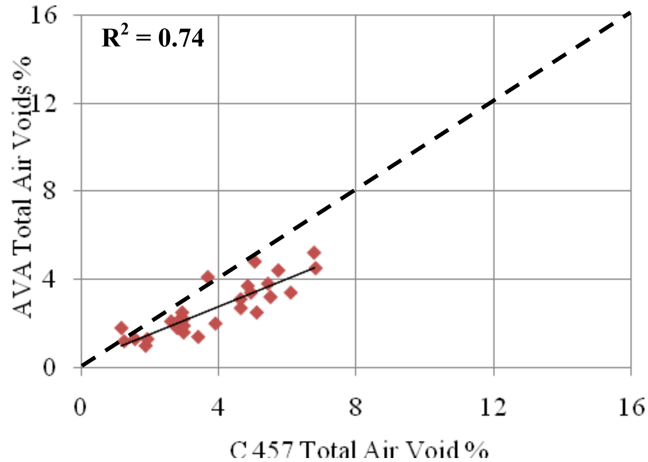
- The total air content measured from AVA was generally lower than that measured by C231 or C457 test method.
- For a given concrete mixture, AVA measurements showed larger variations in total air content and spacing factor than C457 measurements.
- When the criterion of the spacing factor of 0.008 in. (200 µm) was applied, the acceptance/rejection agreement between C457 and AVA test methods was 54%. When the criterion of the spacing factor is increased to 0.015 in. (375 µm) for AVA but kept at 0.008 in. (200 µm) for C457, the agreement increases to 94%.
- There were good relationships between the AVA lab test results (total air content and spacing factor) and C457 test results. These relationships between the AVA field test results and C457 test results were much weaker.
- If 5% air content measured from C231 and C457 is acceptable for concrete F-T durability, the 2.5%–3.0% air content measured from AVA may also be acceptable.

Table 1. Missouri data—air-void measurements of lab mixtures

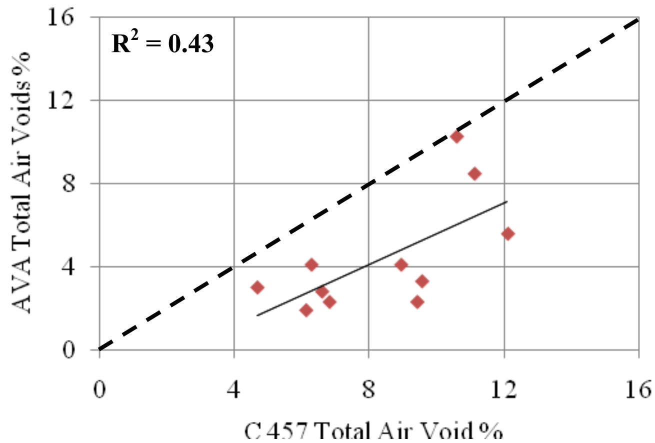
Test	ASTM C231	AVA			ASTM C457			Durability factor (ASTM C666-B)
Mix #	Air content (%)	Air content (%)	Spacing factor (in)	Specific surface (in^{-1})	Air content (%)	Spacing factor (in)	Specific surface (in^{-1})	
1	5.2	2.7	0.009	705	4.6	0.004	1104	95
		3.8	0.011	502	5.4	0.004	1021	96
		3.7	0.009	642	4.8	0.004	1120	95
2	1.5	1.3	0.006	145	1.6	0.033	230	18
		1.0	0.043	226	1.9	0.027	262	13
3	3.2	1.6	0.017	472	3.0	0.009	634	89
		2.5	0.019	337	2.9	0.008	772	93
4	6.1	2.5	0.009	762	5.1	0.004	1244	96
5	2.3	1.2	0.025	348	1.3	0.010	855	31
		1.3	0.038	226	1.9	0.010	728	91
		1.8	0.044	171	1.2	0.008	1139	95
6	6.2	4.4	0.009	536	5.7	0.005	884	94
7	3.3	2.2	0.022	310	3.0	0.008	693	40
7a	5.2	3.2	0.016	366	5.5	0.005	848	95
8	2.5	1.8	0.033	219	2.8	0.021	282	10
		1.4	0.020	397	3.4	0.024	221	15
		2.1	0.034	194	2.6	0.026	220	13
8a	3.0	2.0	0.028	247	3.9	0.019	242	-
8b	3.2	1.9	0.034	211	3.0	0.018	296	18
		2.1	0.022	298	2.8	0.015	389	18
9	6.3	4.8	0.006	794	5.0	0.004	1054	-
9b	5.0	4.1	0.009	612	3.7	0.006	798	92
		3.1	0.012	491	4.6	0.007	675	93
		3.4	0.012	495	4.9	0.007	664	92
10	7.7	4.5	0.006	860	6.8	0.003	1477	95
		5.2	0.009	561	6.8	0.003	1444	96
		3.4	0.012	494	6.1	0.003	1457	96

Table 2. Missouri data—air-void measurements of field mixtures

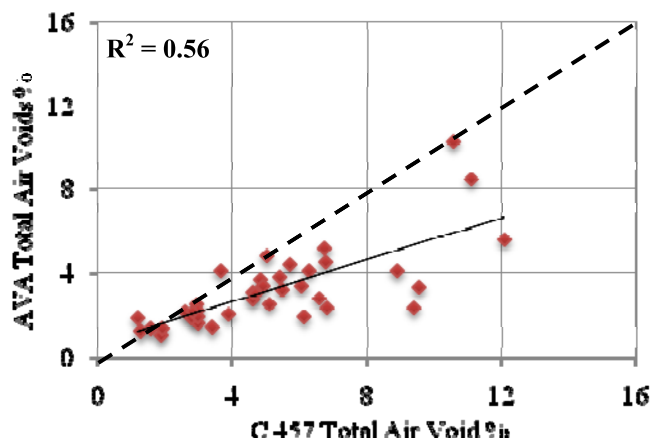
Test	ASTM C231	AVA			ASTM C457			Durability factor
Mix	Air content (%)	Air content (%)	Spacing factor (in)	Specific surface (in^{-1})	Air content (%)	Spacing factor (in)	Specific surface (in^{-1})	
Rt. 36 Macon	13.0	4.1	0.005	655	8.9	0.002	1381	95
		3.3	0.008	587	9.6	0.002	1308	94
		2.3	0.008	654	9.4	0.002	1325	95
Rt. 71 Cass	14.0	10.3	0.007	455	10.6	0.002	876	92
		8.5	0.006	512	11.1	0.002	904	89
		5.6	0.009	507	12.1	0.002	876	92
I-255 St. Louis	6.4	2.3	0.013	511	6.8	0.003	1099	42
		4.1	0.014	360	6.3	0.003	1250	47
		1.9	0.006	1227	6.1	0.003	1408	47
Rt. 63 Howell	7.2	2.8	0.006	1046	6.6	0.004	924	97
		3.0	0.006	982	4.7	0.004	1213	96



(a) Lab produced concrete results

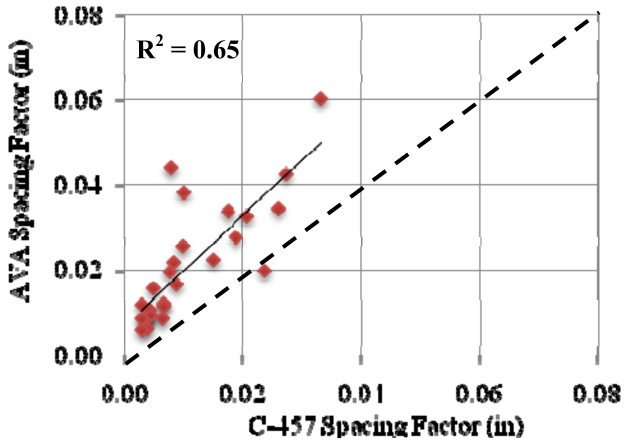


(b) Field produced concrete results

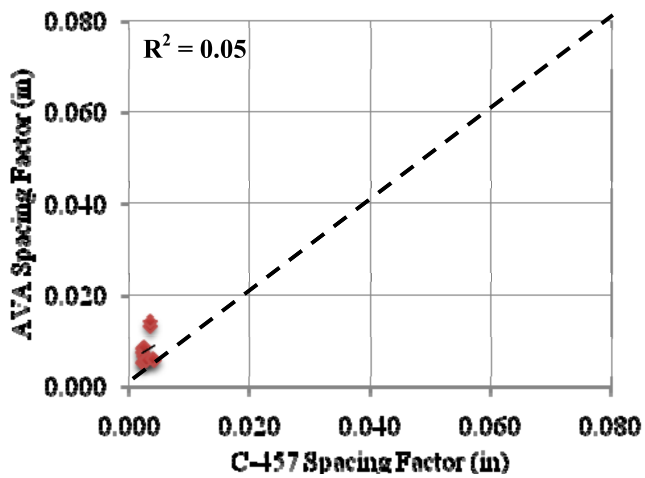


(c) All mixtures

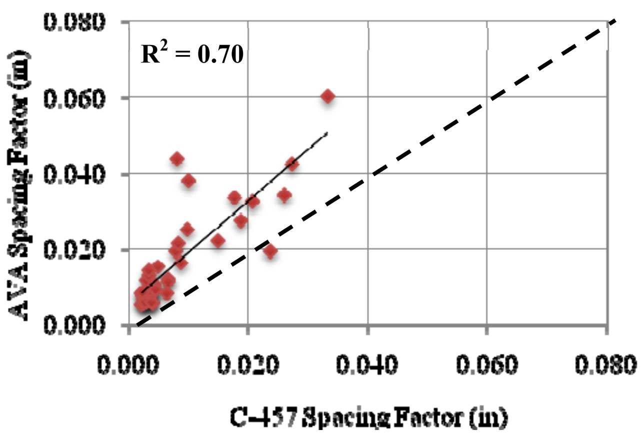
Figure 16. Missouri data—total air voids measured by AVA versus ASTM C457



Lab produced concrete results

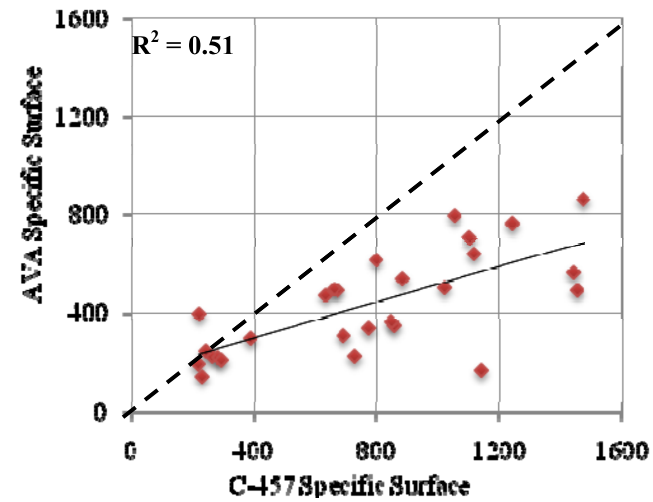


Field produced concrete results

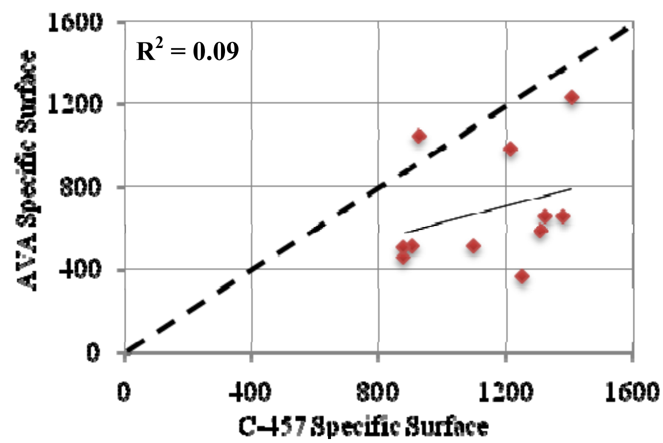


(c) All mixtures

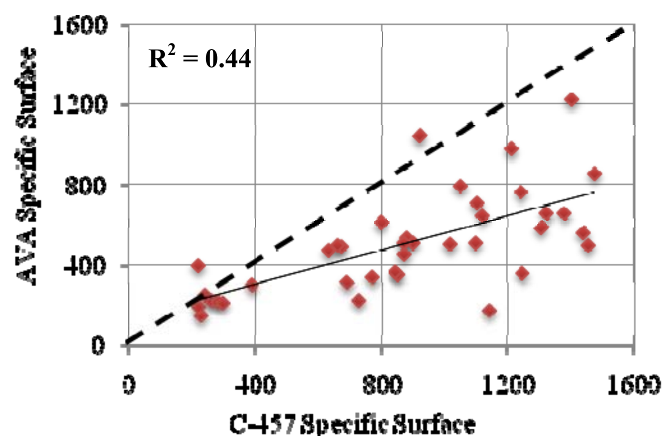
Figure 17. Missouri data—air-void spacing factor measured by AVA versus ASTM C457



(a) Lab produced concrete results

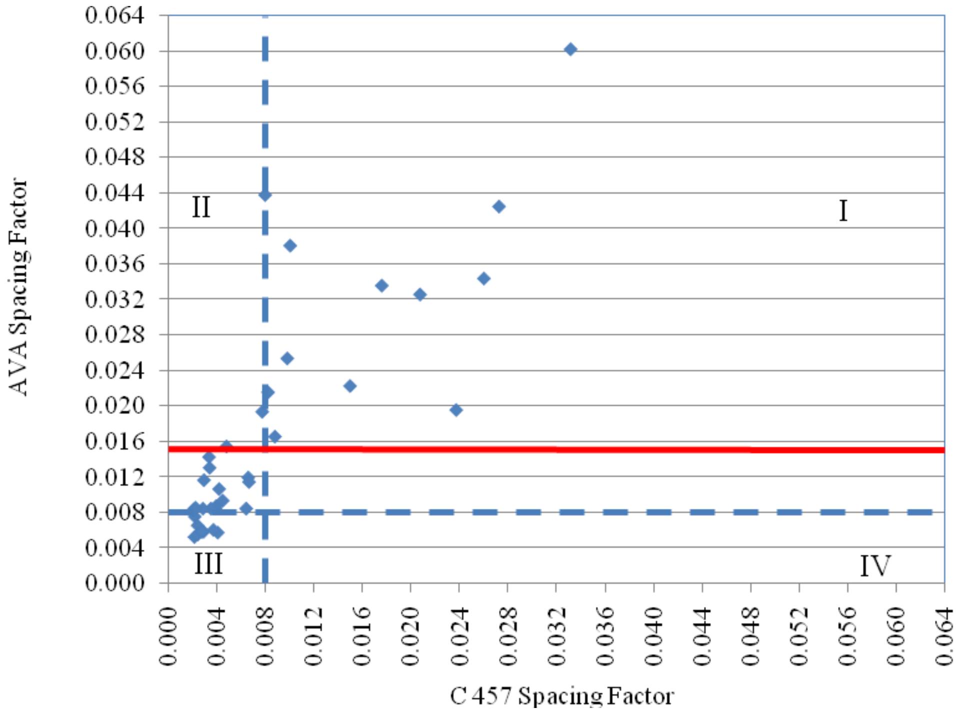


(b) Field produced concrete results



(c) All mixtures

Figure 18. Missouri data—air-void specific surface measured by AVA versus ASTM C457



No. of points (Percentage, %)

Acceptance Criterion	I	II	III	IV	Total	Agreement: I+III
SF* ≤ 0.008 For AVA & C457	12 (34%)	16 (46%)	7 (20%)	0 (0%)	35 (100%)	19 (54%)
SF ≤ 0.008 for C457 SF ≤ 0.015 for AVA	12 (34%)	2 (6%)	21 (60%)	0 (0%)	35 (100%)	33 (94%)

**SF: Spacing Factor*

Figure 19. Missouri data—acceptance/rejection agreement between AVA and C457

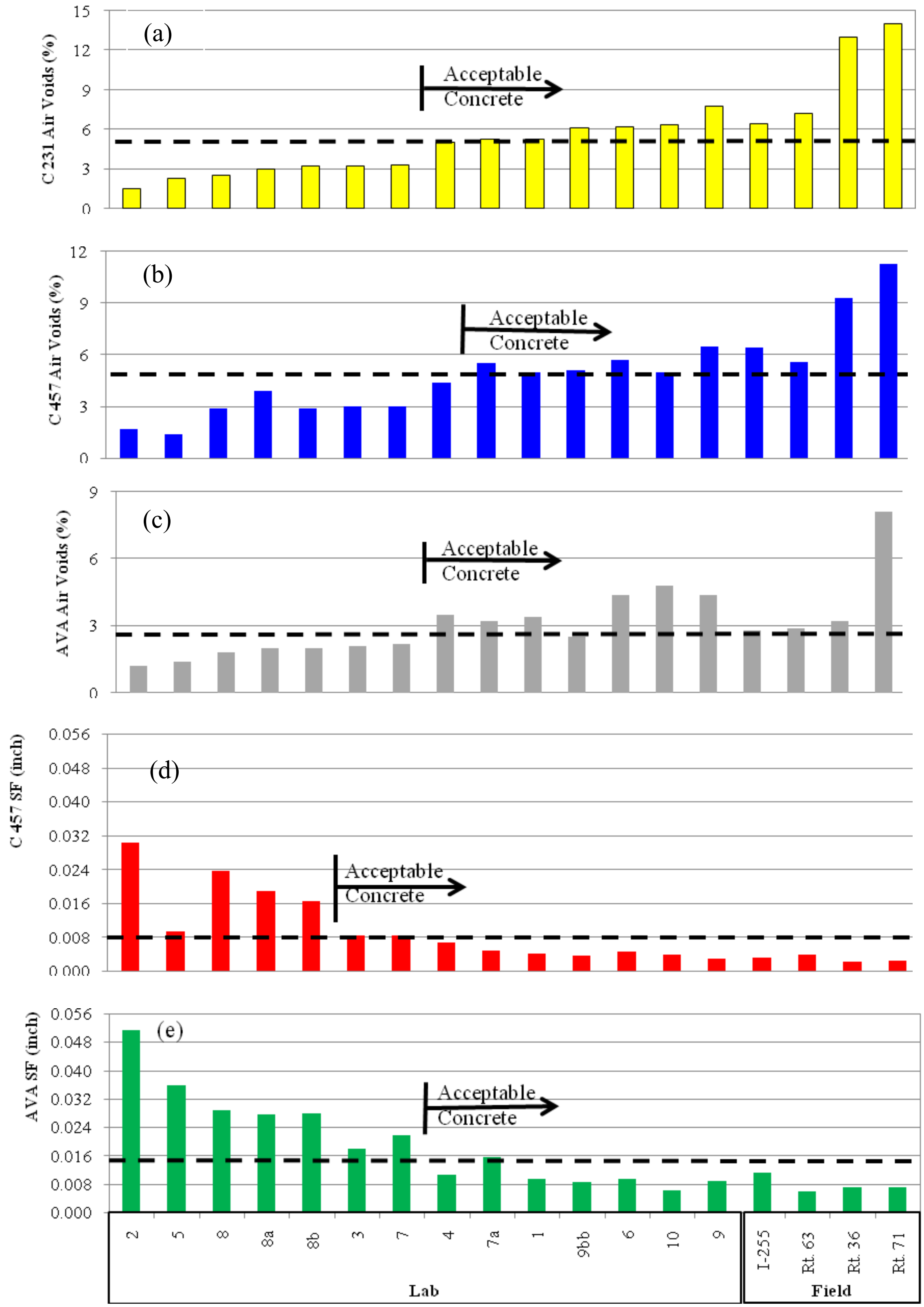


Figure 20. Missouri data—acceptance criteria for total air voids and spacing factors

4.2 AVA Data from FHWA Mobile Lab

A set of data was obtained from FHWA and it was conducted at the FHWA's Mobile Lab. These data are presented in Table 3, and further correlation analyses of the data were performed and the results are presented in Figures 21–24. Please note that only the data with a complete set of results from C231, AVA, and C457 tests are plotted in Figures 21–23.

Table 3. FHWA Mobile Lab

Location	**C231**	**Air-void analyzer (AVA)**			**Modified point count (C457)**		
	Air (%)	**Air (%)**	**SF (in.)**	**SS ($in.^{-1}$)**	**Air (%)**	**SF (in.)**	**SS ($in.^{-1}$)**
Virginia	3.3	2.2	0.009	777	4.2	0.015	410
	5.5	4.9	0.006	800	5.3	0.012	427
	5.8	4.4	0.009	516	4.3	0.009	675
	4.2	2.8	0.013	457	4.0	0.016	366
North Dakota	6.5	4.2	0.009	587	-	-	-
	6.0	4.9	0.013	359	-	-	-
Indiana	5.9	4.6	0.003	1389	-	-	-
	4.8	5.2	0.004	1266	-	-	-
	5.9	4.0	0.004	1349	-	-	-
Nebraska	5.5	4.1	0.002	2514	-	-	-
Illinois	9.0	5.5	0.004	1154	4.6	0.008	610
	6.9	3.7	0.005	1161	4.8	0.008	661
	6.6	4.1	0.007	720	7.3	0.008	586
	-	6.9	0.006	367	4.8	0.010	531
	7.2	3.5	0.006	974	11.3	0.006	358
	7.2	4.5	0.006	865	4.8	0.008	596
	6.2	3.0	0.006	986	5.4	0.017	273
	7.2	4.6	0.005	885	6.8	0.006	625
	7.2	4.9	0.006	776	8.9	0.005	561
	7.2	7.1	0.003	1000	7.3	0.008	529
	9.5	6.6	0.004	901	8.7	0.005	560
Tennessee	-	2.2	0.011	552	6.0	0.010	359
	4.8	2.2	0.015	418	6.9	0.009	376
Pennsylvania	6.6	2.5	0.012	586	5.1	0.012	413
North Carolina	3.1	1.2	0.022	410	3.1	0.020	321
	5.0	4.3	0.006	914	3.8	0.016	344
	5.0	2.7	0.013	509	3.0	0.018	338
	3.3	1.5	0.017	478	1.9	0.020	385
	3.3	0.8	0.021	530	1.2	0.017	551
	4.6	1.7	0.012	660	1.7	0.017	445
	4.6	2.1	0.015	478	2.2	0.018	401
	4.8	2.4	0.009	745	3.7	0.012	489

Table 3. ***continued***

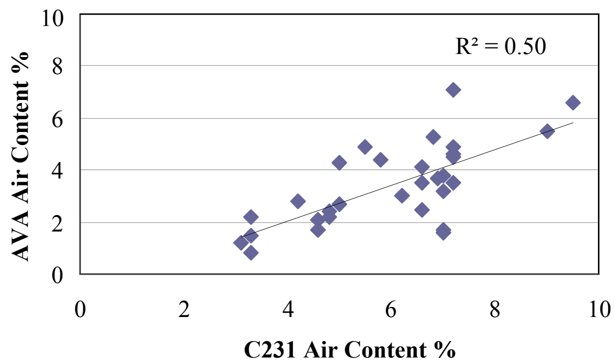
Location	C231	Air-void analyzer (AVA)			Modified point count (C457)		
	Air (%)	Air (%)	SF (in.)	SS ($in.^{-1}$)	Air (%)	SF (in.)	SS ($in.^{-1}$)
Wisconsin	7.0	1.7	0.008	936	4.8	0.011	397
	7.0	1.6	0.009	839	5.9	0.010	418
Nebraska I-80	6.6	3.5	0.016	340	5.9	0.006	687
	9.8	5.1	0.013	356	-	-	-
	6.8	5.3	0.016	279	8.0	0.006	550
	8.0	4.3	0.015	323	-	-	-
	7.0	3.8	0.019	279	5.7	0.006	781
	8.0	4.6	0.017	292	-	-	-
	7.0	3.2	0.017	338	6.8	0.006	559
	8.0	5.3	0.018	246	-	-	-
Pennsylvania (AAA Bridge Deck Comparison)	10.0	10.7	0.004	582	-	-	-
	6.8	5.9	0.008	561	-	-	-
	9.8	7.2	0.005	610	-	-	-
	6.6	4.6	0.007	739	-	-	-
	6.5	3.8	0.012	475	-	-	-
	6.0	4.0	0.009	597	-	-	-
	6.0	3.7	0.009	589	-	-	-
South Dakota US 85	5.9	3.5	0.009	650	-	-	-
	6.4	4.6	0.008	605	-	-	-
	6.6	3.0	0.009	709	-	-	-
	6.7	4.3	0.009	587	-	-	-
	5.5	4.7	0.009	546	-	-	-
	6.0	3.6	0.008	663	-	-	-
	5.8	2.7	0.010	658	-	-	-
	5.6	2.7	0.010	635	-	-	-
North Dakota I-94	6.0	3.9	0.011	468	-	-	-
	7.0	4.0	0.004	1174	-	-	-
	6.8	5.1	0.006	749	-	-	-
	6.2	6.1	0.004	945	-	-	-
	6.2	7.8	0.004	778	-	-	-

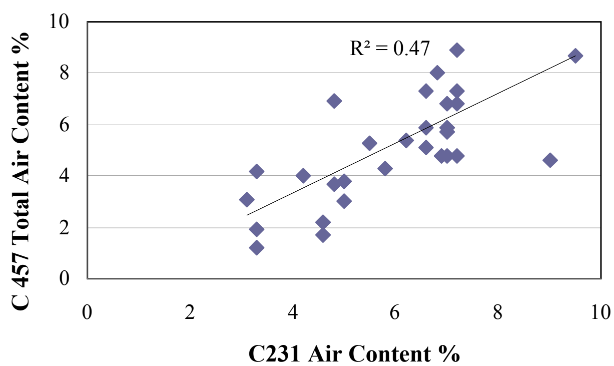
Note: The investigators were unable to identify the mixture information (such as mix proportions) of the data in the table.

The following findings were observed from the FHWA Mobile Lab data analysis:

- As reported, the variation resulting from AVA tests was higher than that from C457; both have considerable variation.
- There were weak relationships between the total air content measured with C231, AVA, and C457 tests (Figure 21).
- AVA test results showed a weak relationship while C457 showed much improved or more acceptable relationship between the spacing factor and the total air content (Figure 22).

- When the criterion of the spacing factor of 0.008 in. (200 µm) was applied, the acceptance/rejection agreement between C457 and AVA test methods was as high as 73%. When the AVA acceptance limit increased to 0.015 in. and C457 acceptance limit was kept as 0.008 in., the agreement acceptance/rejection agreement between C457 and AVA test methods did not improve although more concrete mixtures were accepted by AVA tests (Figure 23).





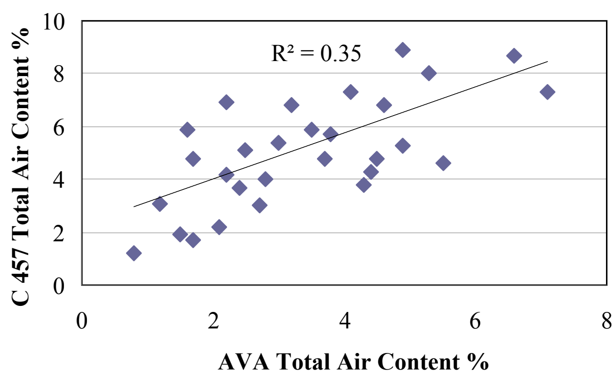


Figure 21. FHWA Mobile Lab results—air content measured with different test methods

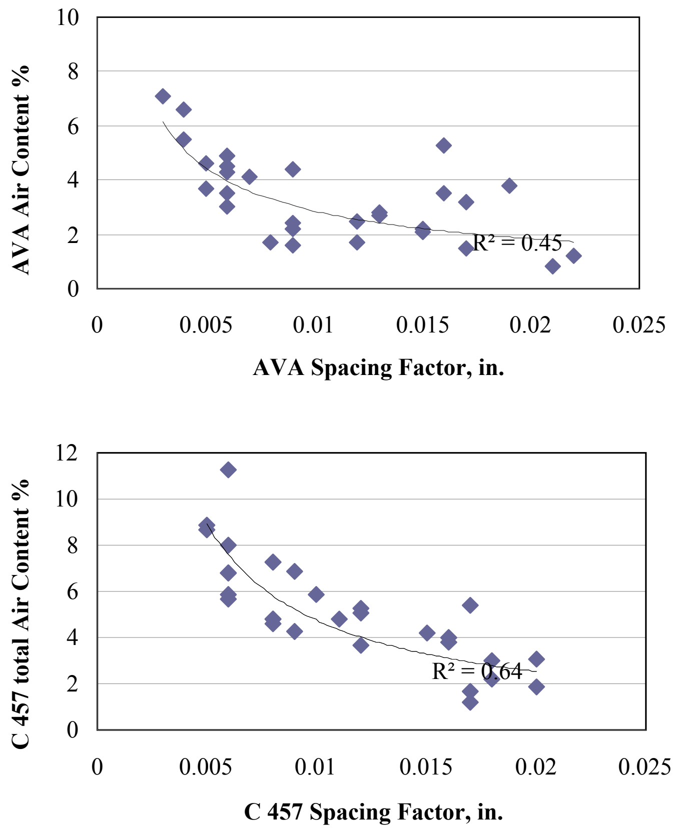
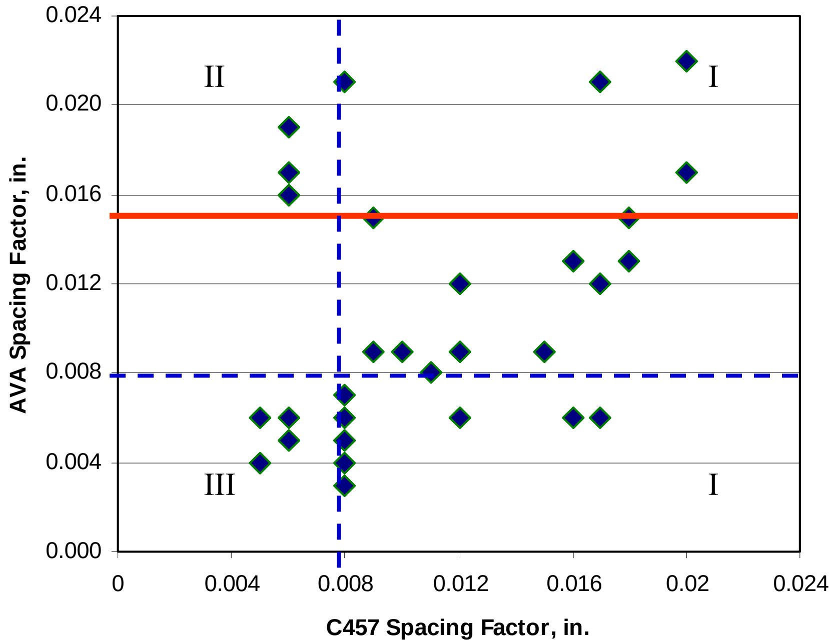


Figure 22. FHWA Mobile Lab results—relationship between air content and spacing factor obtained from different test methods



	No. of points (Percentage, %)					
Acceptance Criterion	I	II	III	IV	Total	Agreement: I+III
SF* ≤ 0.008 For AVA & C457	15 (%)	3 (%)	4 (%)	8 (%)	30 (100%)	19 (%)
SF ≤ 0.008 for C457 SF ≤ 0.015 for AVA	6 (%)	3 (%)	4 (%)	17 (%)	30 (100%)	10 (%)

**SF: Spacing Factor*

Figure 23. FHWA Mobile Lab results—acceptance/rejection agreement between AVA andC457

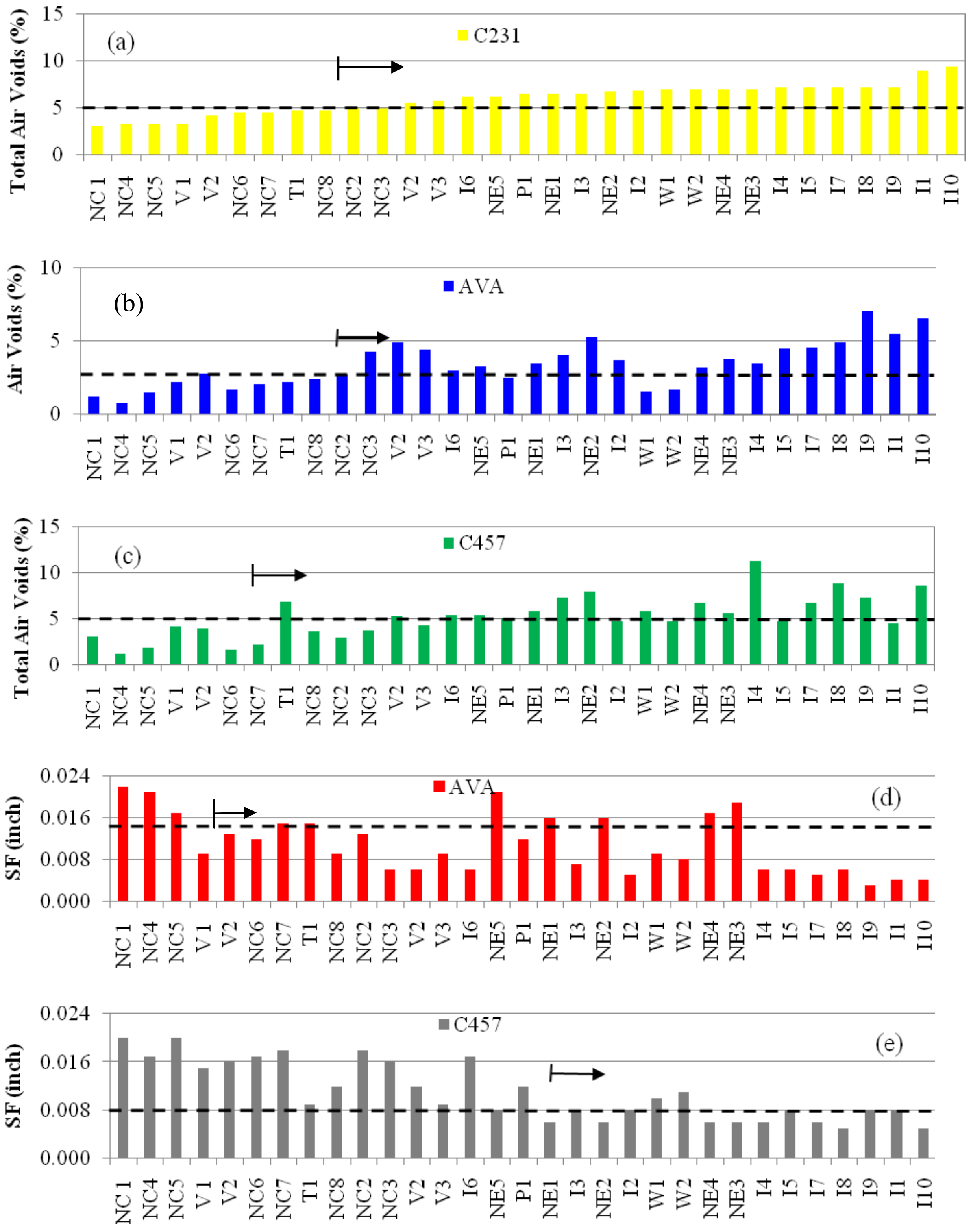


Figure 24. FHWA Mobile Lab—acceptance criteria for total air voids and spacing factors

4.3 AVA Data from Michigan DOT

The data collected from Michigan DOT consisted of two different concrete mixtures, namely 4315-1 (M1) and 4315-2 (M2). The tests were performed at the plant, laboratory and in the field. The mixture proportions are presented in Table 4. Gravimetric air content tests and AVA tests were conducted. The tests were performed over 19 days by two different technicians. M1 was tested over a period of 14 days by Technician 1 (T1) and in three more days by Technician 2 (T2). M2 was tested in two days by only T1. These test data are summarized in Tables 5 and 6. (The data of tests performed on M2 by T1 are not presented here because only gravimetric tests were performed in that data series.) The results of the data analyses are presented in Figures 25 and 26. Only the data with a complete set of results from Gravimetric and AVA tests are used in these plots.

Table 4. Proportions of concrete mixtures used in Michigan DOT's AVA tests

Constituents	M1 (4315-1) lb/yd^3	M2 (4315-2) lb/yd^3
Coarse aggregates	1843	1845
Fine aggregates	1283	1293
Water	218	218
Cement Type I	343	490
GGBF slag	147	0
Total	3834	3846

Table 5. Michigan data—air-void parameters of M2 tested by T1

	Date	Gravimetric air (%)	AVA air (%)	Spacing factor (in.)	Specific surface (in.$^{-1}$)
Proposed passing limit		5.0	2.5	0.008	600
M2 (0.35w/c)	6/23/2006	5.3	2.3	0.007	756
		6.3	3.0	0.006	733
		7.1	2.8	0.007	693
	6/24/2006	6.4	-	-	-
		5.9	-	-	-
		5.5	-	-	-
Range	Min	5.3	2.3	0.006	693
	Max	7.1	3.0	0.007	756
Average		6.1	2.7	0.007	727
STDEV		0.7	0.4	0.001	32

Note: The highlighted data are those that meet the proposed passing limit.

Table 6. Michigan data—air-void parameters of M1 tested by T1

	Date	Gravimetric air (%)	AVA air (%)	Spacing factor (in.)	Specific surface (in.$^{-1}$)
Proposed passing limit		5.0	2.5	0.008	600
M1 (0.45w/c)	5/20/2006	4.5	2.8	0.005	974
		3.6	-	-	-
		-	-	-	-
	5/27/2006	5.2	2.2	0.007	764
		5.6	2.2	0.003	1040
		5.5	4.8	0.003	1195
	6/5/2006	-	-	-	-
		7.0	3.4	0.004	1032
		-	3.1	0.008	633
	6/6/2006	4.6	3.2	0.005	1020
		5.7	2.9	`0.005	964
		5.9	2.6	0.007	689
	6/7/2006	5.7	-	-	-
		6.0	-	-	-
	6/16/2006	5.6	3.4	0.005	855
		5.2	3.3	0.006	791
	6/17/2006	6.0	-	-	-
		5.8	-	-	-
	7/22/2006	5.6	2.0	0.007	823
		5.3	-	-	-
		5.9	-	-	-
	8/19/2006	5.1	-	-	-
	8/20/2006	6.1	2.2	0.006	872
		6.0	2.4	0.008	649
		5.9	2.6	0.008	699
	8/21/2006	6.1	-	-	-
		6.0	-	-	-
		5.9	-	-	-
	8/31/2006	5.7	2.9	0.009	551
		5.6	2.2	0.007	793
		5.6	2.4	0.007	805
	9/7/2006	5.9	2.6	0.006	852
		6.5	4.3	0.004	1103
		7.3	2.6	0.007	788
	9/15/2006	4.4	2.4	0.006	907
		5.6	2.5	0.006	882
Range	Min	3.6	2.0	0.003	551
	Max	7.3	4.8	0.009	1195
Average		5.7	2.8	0.006	856
STDEV		0.7	0.7	0.002	160

Note: The highlighted data are those that meet the proposed passing limit.

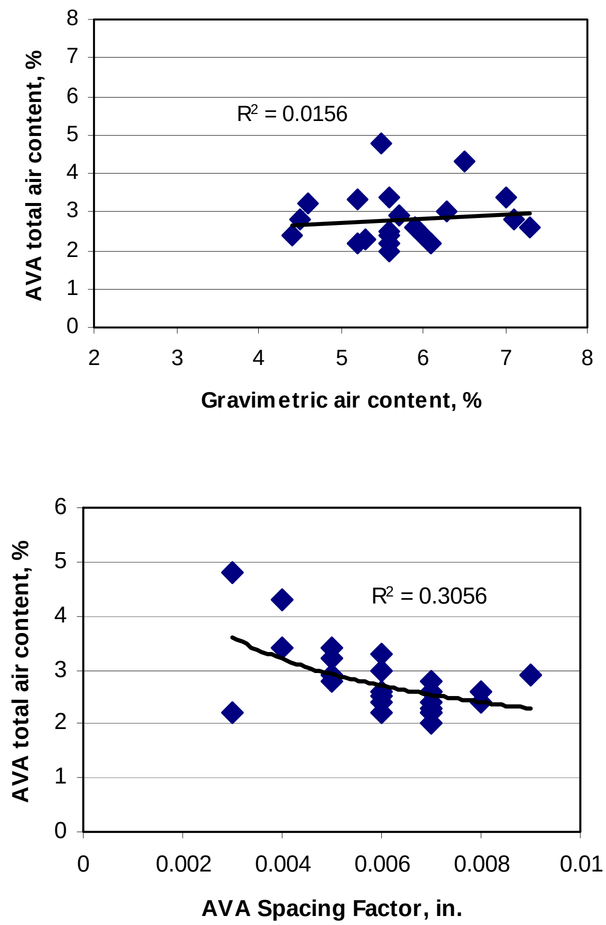


Figure 25. Michigan results—relationships between air-void parameters

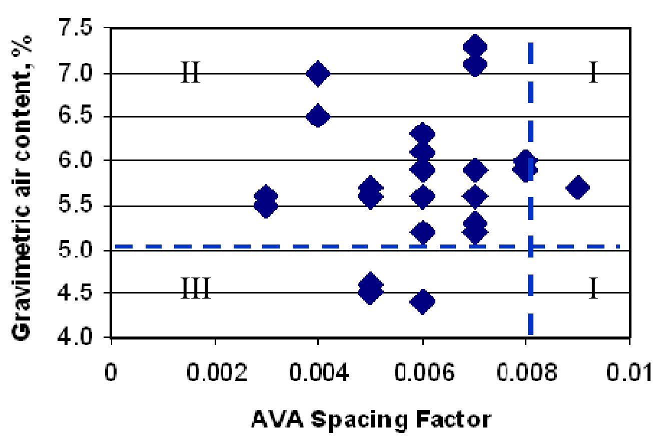


Figure 26. Michigan results—acceptance/rejection agreement between AVA spacing factor (≤ 0.008 in.) and gravimetric air content (≥ 5.0%)

The following findings were observed from the above Michigan DOT data analysis:

- There is no relationship between the total air content measured by gravimetric and AVA tests. The total air content measured from AVA was generally lower than that measured by gravimetric test method. For a concrete mix having an average gravimetric air content of 5.8%, its average AVA total air content was 2.8%.
- AVA test results showed a weak relationship between total air and spacing factor.
- If the acceptance criterion is 5.0% for gravimetric air content and 0.008 in. for AVA spacing factor, the acceptance/rejection agreement between these two test methods is over 80%.

More Michigan DOT data are presented in Tables 7 and 8, which show the effect of concrete mixture proportions (water-to-cementitious material ratios [w/cm] or water-to-cement ratio [w/c] and aggregate-to-cement ratio [a/c]) and construction conditions (i.e., temperature and vibration) on concrete air-void structure. Statistical analysis of these data was performed and the results are discussed in the following section.

Table 7. Michigan data—effect of temperature, w/cm, and vibration on AVA results

Sample No.	Gravimetric air (%)	AVA air (%)	Spacing Factor (in.)	Specific Surface ($in.^{-1}$)	Temperature (^oF)	w/cm	Paver vibration (rpm)
1	4.5	2.8	0.0051	974	47	0.474	6000
2	5.2	2.2	0.0071	764	54	0.348	6000
3	5.3	4.8	0.0032	1040	83	0.351	6200
4	6.7	4.2	0.0032	1195	84	0.524	5900
5	7.0	3.4	0.0043	1032	85	0.565	6000
6	4.6	3.2	0.0047	1020	60	0.540	6000
7	5.7	2.9	0.0050	964	75	0.510	5800
8	5.9	2.6	0.0074	689	88	0.470	6100
9	5.6	3.4	0.0054	855	61	0.520	6000
10	5.2	3.3	0.0059	791	72	0.510	5900
11	5.3	2.3	0.0074	756	64	0.541	6000
12	6.3	3.0	0.0067	733	72	0.538	5900
13	7.1	2.8	0.0073	693	72	0.521	5900
14	5.6	2.0	0.0072	823	68	0.520	6000
15	5.8	2.6	0.0057	927	75	0.510	5900
16	5.5	2.2	0.0063	872	62	0.541	5900
17	7.4	2.4	0.0084	649	65	0.540	5800
18	5.7	2.6	0.0075	699	70	0.554	6000
19	5.7	2.9	0.0090	551	60	0.566	5900
20	5.6	2.2	0.0071	793	71	0.577	5800
21	5.6	2.4	0.0067	805	74	0.572	6000
22	5.9	2.6	0.0061	852	54	0.543	6000
23	6.5	4.3	0.0035	1103	74	0.541	5900
24	7.3	2.6	0.0065	788	80	0.539	6000
25	4.4	2.4	0.0059	907	60	0.568	5900
26	5.6	2.5	0.0061	882	72	0.551	6000

Table 8. Michigan data—effect of a/c and w/cm on AVA measurements

C231 air (%)	AVA air (%)	AVA SF (in.)	AVA SS ($in.^{-1}$)	C457 air (%)	C457 SF (in.)	C457 SS ($in.^{-1}$)	A/C	w/cm
5.2	3.4	0.0093	616	5.0	0.0040	1081	5.15	0.45
1.5	1.2	0.0514	186	1.7	0.0303	246	5.13	0.46
3.2	2.1	0.0180	405	2.9	0.0083	703	5.15	0.45
6.1	2.5	0.0085	762	5.1	0.0035	1244	5.07	0.48
2.3	1.4	0.0358	248	1.5	0.0093	908	5.16	0.45
6.2	4.4	0.0094	536	5.7	0.0045	884	5.15	0.45
3.3	2.2	0.0216	310	3.0	0.0083	693	5.28	0.40
5.2	3.2	0.0155	366	5.5	0.0048	848	5.28	0.40
2.5	1.8	0.0289	270	2.9	0.0236	241	5.41	0.35
3.2	2.0	0.0280	254	2.9	0.0163	343	5.41	0.35
5.0	3.5	0.0107	533	4.4	0.0066	713	5.15	0.45
7.7	4.4	0.0087	638	6.5	0.0029	1459	5.15	0.45
13.0	3.2	0.0071	632	9.3	0.0022	1338	4.75	0.42
14.0	8.1	0.0069	491	11.3	0.0024	885	5.61	0.43
6.4	2.8	0.0111	699	6.4	0.0032	1252	4.17	0.39
7.2	2.9	0.0060	1014	5.6	0.0039	1068	4.00	0.43

4.4 AVA Data from MCO Project

The MCO project (2008) conducted by the CP Tech Center included AVA tests of concrete samples located either before or behind paver or on or between vibration path pavers through 17 state projects. The MCO project provided the most complete data sets, including information on concrete mix design, and all general fresh and hardened concrete properties. The fresh concrete air content was also measured with the C231 test method and the air structure of some corresponding concrete cores was examined using rapid air test methods. The major findings from the MCO AVA study have been summarized in the literature review section of this report. The data presented in Tables 9–12 were retrieved and compiled with those collected from Missouri, Kansas, and Michigan DOTs for the further statistical analysis.

Table 9. MCO data—AVA and C457 spacing factors

Sample No.	Project ID	Spacing factor (in.)	
		AVA	**C457**
1	70-21K 6794-01	0.012	0.006
2	70-21K 6794-01	0.013	0.005
3	70-21K 6794-01	0.010	0.006
4	77-81K 9182-01	0.015	0.008
5	77-81K 9182-01	0.016	0.009
6	77-81K 9182-01	0.005	0.007
7	U054-060 K7410-01	0.017	0.007
8	U054-060 K7410-01	0.010	0.006
9	U054-060 K7410-01	0.014	0.008
10	U054-060 K7410-01	0.014	0.008
11	U054-060 K7410-01	0.015	0.006
12	69-6 K-7412-01	0.008	0.008
13	135-87 K-6780-01	0.009	0.009
14	56-05 K-8615-01	0.006	0.007
15	54-8 K-8001-02	0.006	0.005
16	69-61 K-1591-01	0.009	0.008
17	69-54K-7413-01	0.007	0.007
18	35-105 K-6391-01	0.016	0.014
19	35-105 K-6391-01	0.007	0.010
20	89 U-1840-01	0.005	0.005
21	85 K 8307-01	0.000	0.000
22	85 K 8307-01	0.000	0.003
23	69-54 K-7890-01	0.006	0.005
24	69-6 K-7412-01	0.006	0.005
25	69-54 K-7890-01	0.008	0.004
26	85 K 8307-01	0.008	0.005
27	50-57 K-5385-01	0.011	0.013
28	50-57 K-5385-01	0.009	0.011
29	50-57 K-5385-01	0.013	0.014
30	2001 Study	0.015	0.018
31	70-89 K-2442-01	0.016	0.016

Table 10. MCO data—effect of sampling location on C231 air content

Date	Sample ID	C231 total air voids (%) ahead of paver	C231 total air voids (%) after paver
27-Sep-06	SD1	6.5	5.8
16-Aug-06	NY1	6.5	6.5
24-May-06	GA1	5.6	4.9
30-Mar-06	LA1	5.8	3.8
2-Nov-05	IN1	7.8	5.6
2-Sep-05	MN1	7.1	5.1
21-Jun-05	ND1	6.6	4.9
28-Jun-05	ND2	11.3	8.0
7-Jun-05	IA1	8.5	6.0
9-Jun-05	IA2	8.7	6.2
13-Jun-05	IA3	8.7	6.0
29-Apr-05	TX1	5.2	3.5
5-May-05	TX2	2.4	2.5
11-Nov-04	NC1	4.5	3.6
27-Oct-04	WI1	6.4	4.7
27-Sep-04	MI1	6.5	6.0
1-Sep-04	KS1	5.9	7.4
8-Sep-04	KS1	5.5	5.2

Table 11. MCO data—effect of sampling location (before and behind paver) on AVA results.

State	Location	AVA					Size distribution (%)									
		Air content in concrete (%)	Air content in paste (%)	Air content in putty (%)	Spacing factor (in.)	Specific surface (in.$^{-1}$)	50 µm	75 µm	100 µm	125 µm	150 µm	200 µm	300 µm	500 µm	1000 µm	2000 µm
OK	Before	3.5	14.6	12.7	0.007	787	0	0	15	18	9	7	3	10	19	20
							0	0	15	33	42	49	52	61	80	100
	After	3.9	16.0	13.8	0.005	978	4	4	14	21	7	6	3	7	18	18
							4	7	21	42	49	55	58	65	82	100
MI	Before	3.3	14.9	13.0	0.008	645	0	0	0	27	4	6	13	1	27	23
							0	0	0	27	31	37	49	50	77	100
	After	3.2	12.8	11.4	0.009	650	0	0	17	14	10	7	5	8	19	19
							0	0	17	31	42	49	54	62	81	100
SD	Before	5.3	20.9	17.3	0.006	726	0	0	3	19	14	14	8	7	14	21
							0	0	3	22	36	50	58	65	79	100
	After	3.2	12.2	10.8	0.007	861	0	0	0	26	17	22	8	8	10	9
							0	0	0	26	43	65	74	82	92	100
GA	Before	4.3	17.0	14.6	0.010	511	0	0	11	2	10	7	8	14	31	19
							0	0	11	13	22	30	37	51	81	100
	After	3.1	11.8	10.6	0.011	541	0	0	0	10	6	11	9	16	33	14
							0	0	0	10	17	28	37	53	86	100
LA	Before	4.3	18.9	15.9	0.007	658	0	0	12	12	6	9	5	10	26	21
							0	0	12	23	30	39	43	53	80	100
	After	2.8	12.2	10.9	0.008	739	0	0	6	20	14	8	7	6	21	17
							0	0	6	27	41	49	56	62	83	100

Table 12. MCO data—effect of sampling location on C231 and AVA test results

Sample date / State	Flow (%)	Slump (in.)	C231 air (%) ahead of paver	C231 air (%) behind paver	Sample locations	AVA air in concrete (%)	AVA SF (in.)	w/c
27-Sep-06 / SD	88	1.0	6.5	5.8	Ahead	4.3	0.007	0.38
					On vib.	3.3	0.007	
					Btw vib.	4.2	0.007	
16-Aug-06 / NY	100	1.3	6.5	6.5	Ahead	4.1	0.005	0.53
					Btw vib.	3.2	0.008	
24-May-06 / GA	82	0.5	5.6	4.9	Ahead	4.3	0.012	0.41
					On vib.	2.9	0.013	
					Btw vib.	2.7	0.012	
30-Mar-06 / LA	80	1.0	5.8	3.8	On vib.	2.8	0.012	0.51
					Btw vib.	1.7	0.016	
2-Nov-05 / IN	83	1.0	7.8	5.6	Btw vib.	2.6	0.009	0.36
21-Jun-05 /ND	78	1.5	6.6	4.9	Btw vib.	1.7	0.017	0.34
28-Jun-05 / ND	93	2.0	11.3	8.0	Btw vib.	3.8	0.006	0.36
					On vib.	3.5	0.007	
29-Apr-05 / TX	113	2.5	5.2	3.5	On vib.	1.8	0.019	0.50
					Btw vib.	2.1	0.017	
5-May-05 / TX	117	1.8	2.4	2.5	On vib.	0.8	0.028	0.50
					Btw vib.	1.5	0.027	
11-Nov-04 / NC	94	1.6	4.5	3.6	On vib.	3.1	0.006	0.50
					Btw vib.	2.9	0.008	
27-Oct-04 / WI	70	1.3	6.4	4.7	On vib.	1.4	0.010	0.42
					Btw vib.	2.1	0.008	

The major findings from the MCO AVA study can be recaptured as follows:

- ASTM C231 yields higher air content values than AVA, and there is little/no relationship between the air content values measured by these two test methods.
- There is no relationship between the C231 air content and AVA spacing factor. This implies that high C231 air content may not ensure the proper spacing factor for concrete F-T durability.
- There is no relationship between the AVA spacing factor and total air content; however, the test results show a strong relationship (R^2=0.82) between the AVA spacing factor and content of small air voids (≤ 300μm).
- Sampling locations had a significant effect on the air content measured by C231, but had little/no effect on the air content measured by AVA, which indicates that small air bubbles are stable under vibration while bigger ones (mostly entrapped) are removed.
- The frequency of small spacing factor (0.005–0.015 in.) may control the quality of concrete.

4.5 AVA Data from ISU

Additional data were collected from a paper, "Investigation into the Effect of Materials and Mixing Procedures on Air-Void Characteristics of Fresh Concrete Using Air-Void Analyzer (AVA)," by Zhang and Wang (2006), which is published in the *Journal of ASTM International*. The study was carried out at ISU. The data are presented in Table 13. These test data were used later for a statistical analysis.

Table 13. Additional data—effect of mixture, mixing method, and mixer on AVA measurements

No.	Mixture	Mixing method	Mixer type	C231 air (%)	AVA air (%)	AVA SF (in.)	AVA SS (in.$^{-1}$)
1	PC	S	0.5	6.0	2.9	0.0113	533
2	PC	S	0.5	4.8	3.9	0.0106	516
3	PC	4	0.5	5.9	3.3	0.0114	516
4	PC	4	0.5	6.7	3.4	0.0100	582
5	PC	4	0.5	6.0	4.0	0.0085	632
6	PC	2	0.5	4.8	3.3	0.0139	422
7	PC	2	0.5	5.1	2.9	0.0153	394
8	PC	2	0.5	5.7	4.0	0.0109	490
9	PC	1	0.5	3.7	2.6	0.0144	450
10	PC	M4	0.5	5.7	4.8	0.0080	617
11	PC	M4	0.5	6.2	5.1	0.0064	757
12	PC	M4	0.5	7.1	4.7	0.0059	836
13	PC	4	1.5	4.8	3.9	0.0082	655
14	PC	2	1.5	4.7	3.2	0.0109	549
15	PC	1	1.5	4.2	3.0	0.0122	505
16	FA	S	0.5	5.3	3.8	0.0085	648
17	FA	S	0.5	5.3	3.1	0.0086	699
18	FA	2	0.5	4.6	3.6	0.0105	533
19	FA	2	0.5	5.2	4.2	0.0100	526
20	FA	4	0.5	6.6	4.1	0.0075	711
21	FA	4	0.5	7.3	5.0	0.0083	645
22	WR	S	0.5	8.3	5.6	0.0048	968
23	WR	S	0.5	8.4	6.1	0.0050	892
24	WR	2	0.5	10.4	9.5	0.0038	759
25	WR	2	0.5	8.5	9.0	0.0039	795
26	WR	4	0.5	10.6	8.2	0.0039	859
27	WR	4	0.5	10.4	7.9	0.0041	851

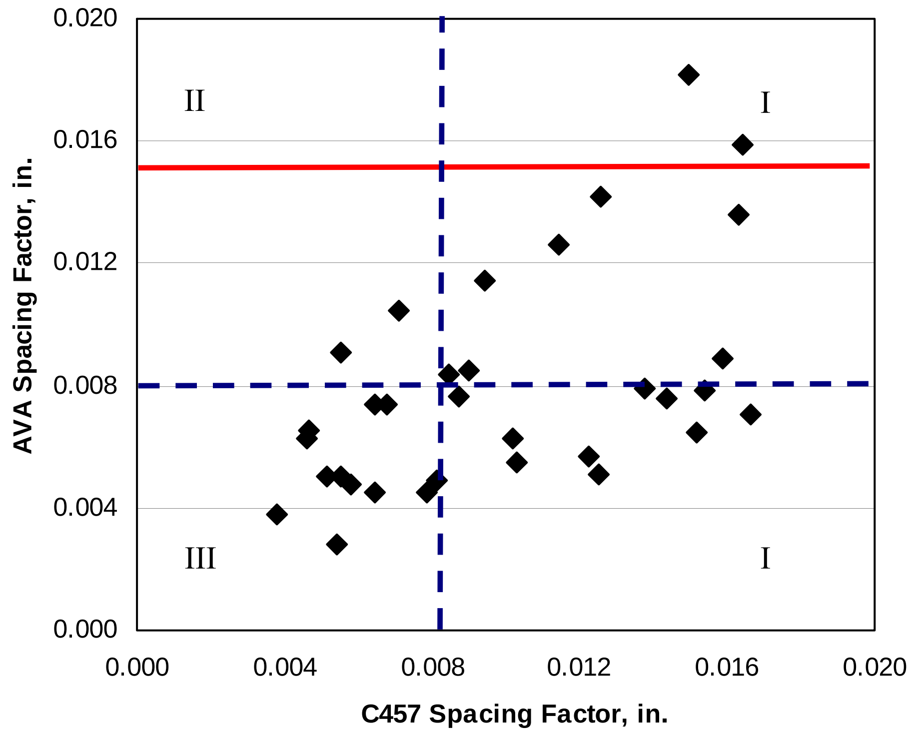
4.6 AVA Data from the Kansas DOT

The Kansas DOT is the most experienced state agency in using the AVA equipment. Currently, there are six AVA devices used by the Kansas DOT. Many AVA test data have been presented in reports and papers. Table 14 presents the data recently collected by the Kansas DOT to correlate the specific surface values obtained from AVA and C457 tests. Figure 27 shows the correlation between spacing factor values obtained from two different methods. Regardless of the weak correlations, if the spacing factor of 0.008 in. is used as the acceptance criterion for both AVA and C457 tests, the agreement between the tests is 64%. If the acceptance criterion is increased to 0.015 in. for AVA and kept at 0.008 in. for the C457 test, the agreement decreases to 48%. This is inconsistent with findings from other AVA research results.

The Kansas DOT has also provided the present research team with 990 AVA raw output files of the AVA tests conducted from 2001 to 2005. The research team went through these data. It was found that the spacing factor correlates to small air content better than it correlates to large air content (see Figure 28). This finding is in agreement with the CP Tech Center's MCO study.

Table 14. Kansas DOT data—correlation between AVA and ASTM C457 results

Sample No.	Project No.	Date	Sample ID	ASTM C231 Air (%)	AVA SF (mm)	AVA SS (mm^{-1})	ASTM C457 SF (mm)	ASTM C457 SS (mm^{-1})
1	69-6 K-7412-01	07/29/05	12+845	5.5	0.215	32.1	0.212	17.7
2	135-87 K-6780-01	08/01/05	19+870	5.5	0.228	23.1	0.216	23.4
3	56-05 K-8615-01	08/12/05	10th&Col	7.5	0.164	16.4	0.187	13.0
4	54-8 K-8001-02	08/19/05	1+805	6.8	0.140	27.4	0.128	26.8
5	69-61 K-1591-01	10/13/05	26+200	6.4	0.222	32.5	0.195	26.9
6	69-54K-7413-01	10/27/05	28+796	6.3	0.172	30.8	0.187	29.9
7	50-57 K-5385-01	04/19/01	13+675	-	0.290	-	0.320	-
8	50-57 K-5385-01	04/19/01	13+676	-	0.240	-	0.290	-
9	50-57 K-5385-01	04/19/01	12+550	-	0.320	-	0.360	-
10	2001 Study	-	-	-	0.380	-	0.462	-
11	70-89 K-2442-01	2001	-	-	0.417	-	0.404	-
12	35-105 K-6391-01	5/05	13+620	-	0.415	-	0.345	-
13	35-105 K-6391-01	5/05	13+365	-	0.181	-	0.265	-
14	89 U-1840-01	11/10/05	6th and Gage	7.0	0.131	39.4	0.128	-
15	69-54 K-7890-01	04/18/06	99+025	6.9	0.147	34.2	0.121	24.5
16	69-6 K-7412-01	04/17/06	23+645	5.7	0.164	28.6	0.115	45.8
17	69-54 K-7890-01	05/31/06	97+494	7.0	0.199	28.7	0.114	40.9
18	85 K 8307-01	06/29/06	10+414	6.5	0.206	-	0.124	21.4
19	70-21K 6794-01	07/20/06	22+178	6.3	0.311	-	0.144	34.3
20	70-21K 6794-01	07/20/06	21+837	6.5	0.318	-	0.130	39.4
21	70-21K 6794-01	07/20/06	21+237	7.2	0.259	-	0.160	29.6
22	77-81K 9182-01	07/26/06	40+310	6.0	0.391	-	0.200	20.5
23	77-81K 9182-01	07/28/06	46+490	6.0	0.404	-	0.226	18.7
24	77-81K 9182-01	08/02/06	-	7.0	0.118	-	0.166	29.7
25	U054-060 K7410-01	08/03/06	22+335	-	0.422	16.9	0.179	27.8
26	"	08/09/06	22+448	-	0.261	26.9	0.140	33.9
27	"	08/09/06	22+600	-	0.349	17.1	0.201	15.2
28	"	08/09/06	22+780	-	0.365	20.8	0.193	23.4
29	"	08/11/06	23+015	-	0.385	20.7	0.164	27.2
30	AVA Round Robin	2006	06-0396-R	7.8	0.097	-	0.097	-
31	"	2006	06-0398-R	-	0.137	-	0.072	-
32	"	2006	06-400-R	-	0.140	-	0.231	-
33	"	2006	06-401-R	-	0.117	-	0.159	-



Acceptance Criterion	I	II	III	IV	Total	Agreement: I+III
	No. of points (Percentage, %)					
SF* ≤ 0.008 For AVA & C457	9 (27%)	2 (6%)	12 (36%)	10 (30%)	33 (100%)	21 (64%)
SF ≤ 0.008 for C457 SF ≤ 0.015 for AVA	2 (6%)	0 (0%)	14 (42%)	17 (52%)	33 (100%)	16 (48%)

** Spacing Factor*

Figure 27. Kansas DOT results—acceptance/rejection agreement between AVA and C457 spacing factors

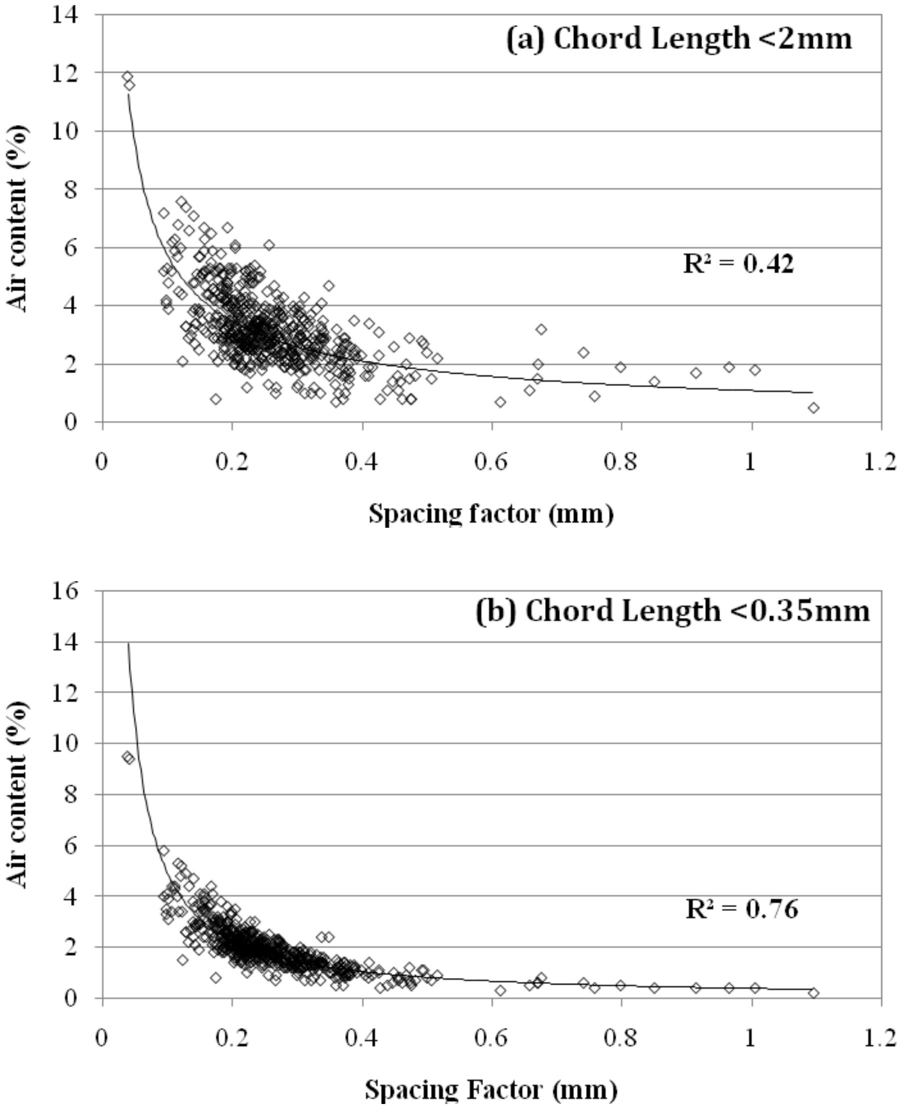


Figure 28. Kansas DOT data—relationship between AVA spacing factor and air content max bubble size (a) large (b) small

5. STATISTICAL ANALYSIS OF COLLECTED DATA

Statistical analyses were performed on the compiled data from Missouri, Kansas, and Michigan DOTs, FHWA Mobile Lab and MCO project. The analyses contained two parts: (1) a further determination of the overall relationships between AVA and other standardized test methods (such as ASTM C231, C457, C138, and F-T durability tests), and (2) an examination of the significance of different factors (such as different operators, different w/cm, and different viscosity of blue fluid) on AVA measurements.

5.1 Determining the Relationship between AVA and Other Test Methods

This investigation was conducted in three steps:

1. Studying the consistency between the available data
2. Testing equal variance of the data
3. Establishing linear regression models

5.1.1 Relationship between Air Content Values Measured by AVA, C231, and C457

Based on the analysis of all collected data, Figure 29 shows the relationships between the air contents measured by AVA, C231, and C457. As discussed before, the figure illustrates that the order of air content measured by these three test methods, from high to low, is C231, C457, and AVA test methods. This is because C231 measures all the air voids in fresh concrete, including entrapped air; C457 measures the air content of hardened concrete, which is generally well consolidated; while AVA measures the air voids less than 3mm (0.12 in.) in diameter.

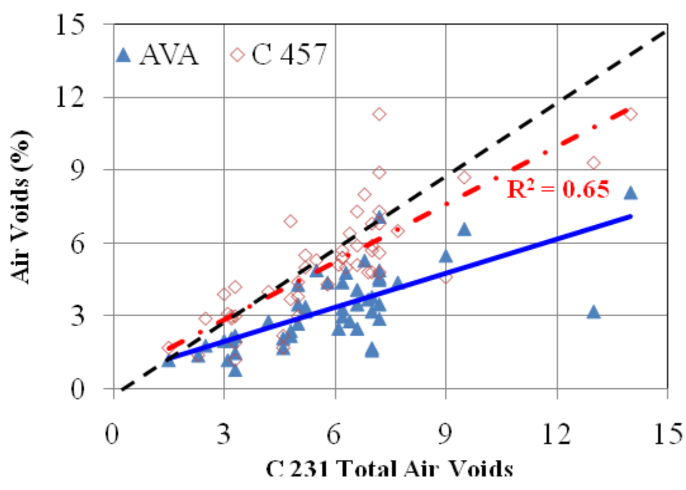


Figure 29. Statistical analysis—total air content measured by different test methods

Using the Spearman's rank correlation (Spearman's ρ) test in the statistical software JMP 6.2, the equal variances between AVA, C231, and C457 were tested, and the results are shown in Table 16. The Spearman's rank correlation test is generally used when two variables (such as air voids measured by two methods) are related to the same nominal variable (such as air voids measured from the same mixture). In the present study, Spearman's rank correlation test was conducted to examine whether two air-void measurements used for a given mixture had the same variance or not. If the probability of the test, Prob>|ρ|, is less than 0.05, it is assumed that the two air-void measurements statistically have different variances. These results in Table 15 are strong evidence that AVA, C231, and C457 had different variances. The coefficient of variation (CV) is 48% for AVA, 37% for C231, and 45% for C457 test methods. The high CV of AVA is partially due to the non-standardized test method. Nevertheless, the differences in CVs may be considered as insignificant if they are less than 15%. Therefore, the AVA variability, could be considered acceptable when compared to C231 and C457.

Table 15. Equal variance test between AVA, C231, and C457 air content

	Spearman's ρ	Prob>|ρ|	STDEV (%)		Mean (%)		CV (%)	
AVA – C231	-0.3282	0.0043	C231 2.3	AVA 1.8	C231 6.0	AVA 3.7	C231 37	AVA 48
AVA – C457	-0.4107	0.0037	C457 2.3	AVA 1.6	C457 5.1	AVA 3.3	C457 45	AVA 48

Using JMP 6.2, the following linear regression equations are obtained from the air content data studied:

AVA Air = -0.33 + 0.68 C231 Air (R^2=0.67, P-value=0.0001) (1)
AVA Air = 0.787 + 0.498 C457 Air (R^2=0.50, P-value=0.0001) (2)
C457 Air = 0.27 + 0.836 C231 Air (R^2=0.63, P-value=0.0001) (3)

It should be noted that Equation 1 resulted from all data sets that had both AVA and C231 total air contents. It is slightly different from the linear relationship shown in Figure 29, which resulted from data sets that contained AVA, C231, and C457 total air contents. Based on the linear regression Equations 1 and 2 and Figure 27, if 5% air content from C231 measurements is used as an acceptance criterion for fresh concrete, approximately 3% total air content from AVA measurements shall also be considered as acceptable for concrete.

Similar statistical analyses were performed for the Michigan test data to compare AVA test results with gravimetric test results. CV values were found as 24% and 14% for AVA and the gravimetric test method, respectively. The linear regression shows that

AVA Air = 0.455 Gravimetric Air (R^2=0.01, P-value=0.0001) (4)

As a result, if 5% air content from gravimetric measurements is used as an acceptance criterion for fresh concrete, 2.3% total air content from AVA measurements can also be considered acceptable.

5.1.2 Relationship between Air Content and Spacing Factors

Based on the analysis of all collected data, Figure 30 shows the relationship between the AVA total air content and spacing factor. As discussed before, the figure illustrates that AVA total air content decreases non-linearly with spacing factor. The CV value was 50% for the total air content and 74% for the spacing factor measurements. The linear regression gives the following equation:

AVA Air = 5.04 - 151.1 AVA SF + 3053.6 AVA SF^2 (R^2=0.35, P-value=0.0001) (5)

According to Equation 5, AVA spacing factor of 0.012 in. may be used as an acceptance criterion for concrete to have AVA total air content of approximately 3% or C231 air content of 5%.

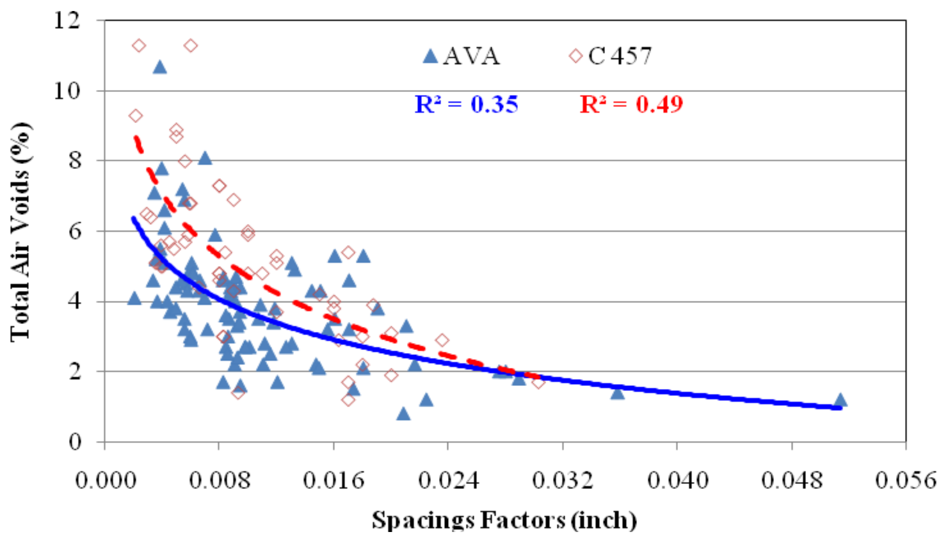


Figure 30. Statistical analysis—relationship between AVA total air and spacing factor

Similar analyses were performed for the test data resulting from the C457 test method. The CV value was 50 % for the total air content and 64% for the spacing factor measurements. The linear regression shows:

C457 Air = 7.98 - 303.1 C457 SF + 8474.2 C457 SF^2 (R^2=0.49, P-value=0.0001) (6)

5.1.3 Relationship between AVA and C457 Spacing Factor

The relationship between AVA and C457 spacing factors were based on data collected from Missouri DOT (38 data points), FHWA Mobile Lab (33 data points), and MCO project (31 data points).

The consistency between AVA and C457 spacing factors was first determined according to the level (%) of agreement made by different test methods in accepting or rejecting the concrete. The results are presented in Figure 31 and Table 16. It is noted in Figure 29 that if the AVA spacing factor limit is raised from 0.008 in. to 0.015 in., a certain percentage of concrete mixtures that are unacceptable by C457 test methods become acceptable by the AVA test method. This clearly suggests that selecting a rational AVA acceptance criterion for concrete quality is very important, and more research is needed on this subject.

The equal variance analysis results are presented in Table 17. The CV value was 70% for AVA spacing factor and 62% for the C457 spacing factor measurements. Both values are high, however, the difference between AVA and C457 values is only 8%. That is, if C457 test method is acceptable, AVA test method could also be considered acceptable.

The linear regression equation for the relationship between the AVA and C457 spacing factors is given below:

$$\text{AVA SF} = 0.0041 + 0.98 \text{ C457 SF} \qquad (R^2=0.40, \text{P-value}=0.0001) \qquad (7)$$

Although this relationship is not strong, equation (7) denotes that for a given concrete mixture, the AVA generally provides slightly higher spacing factor values than the C457 test method. Based on this equation, the AVA spacing factor value will be 0.012 in. when C457 spacing factor is 0.008 in. More data points could be helpful to establish a dependable value.

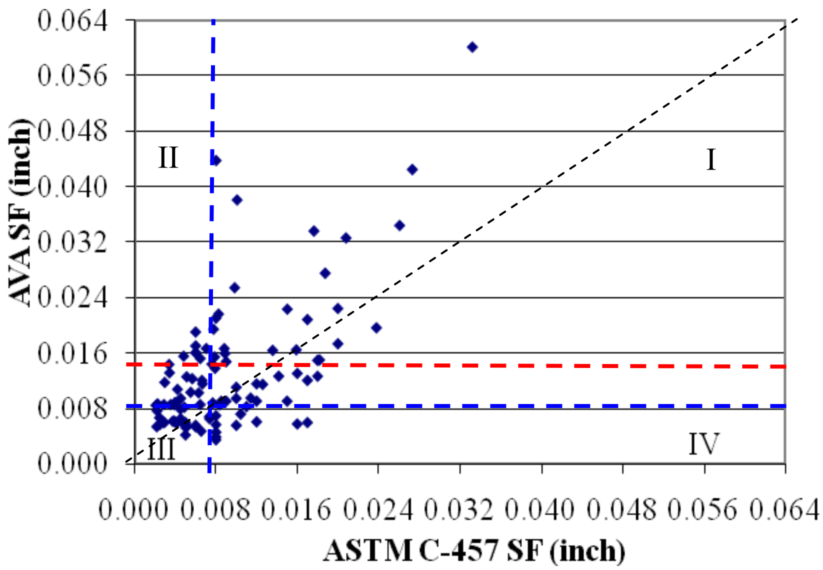


Figure 31. Statistical analysis—relationship between spacing factors measured by AVA and C457

Table 16. Acceptance/rejection agreement between AVA and C457 spacing factors

		No. of points in acceptance/rejection regions (%)					
		I (N-N)	**II (Y-N)**	**III (Y-Y)**	**IV (N-Y)**	**Total**	**Agreement (I+III)**
Acceptance Criteria	SF ≤ 0.008 For AVA & C457	37 (36%)	32 (31%)	28 (27%)	5 (5%)	102 (100%)	65 (64%)
	SF ≤ 0.012 For AVA SF ≤ 0.008 For C457	25 (25%)	16 (16%)	44 (43%)	17 (17%)	102 (100%)	69 (68%)
	SF ≤ 0.015 For AVA SF ≤ 0.008 For C457	19 (19%)	10 (10%)	50 (49%)	23 (23%)	102 (100%)	69 (68%)

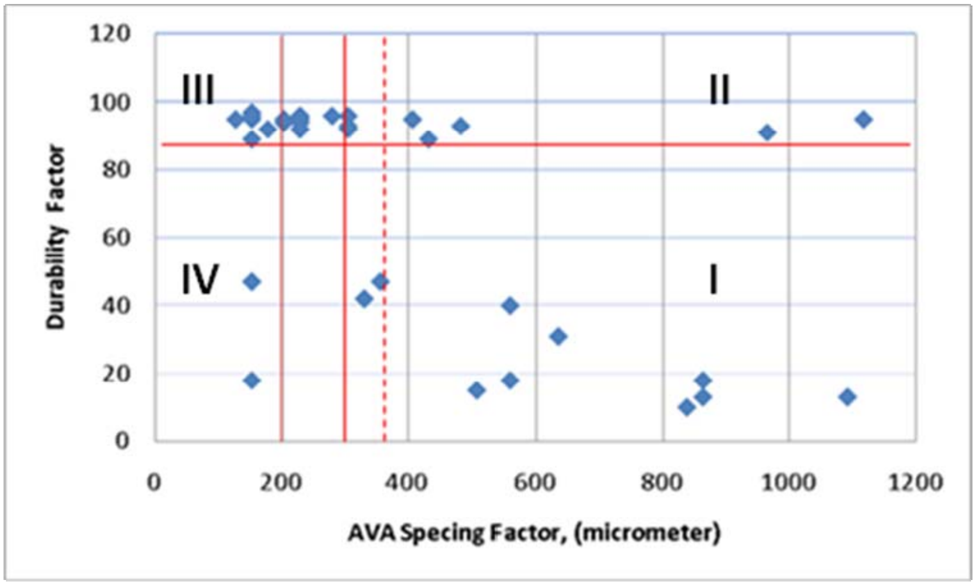
Note: N/Y-N/Y indicates C457 rejection (N)/accepting (Y)—AVA rejection (N)/acceptance (Y).

Table 17. Equal variance test between AVA and C457 spacing factors

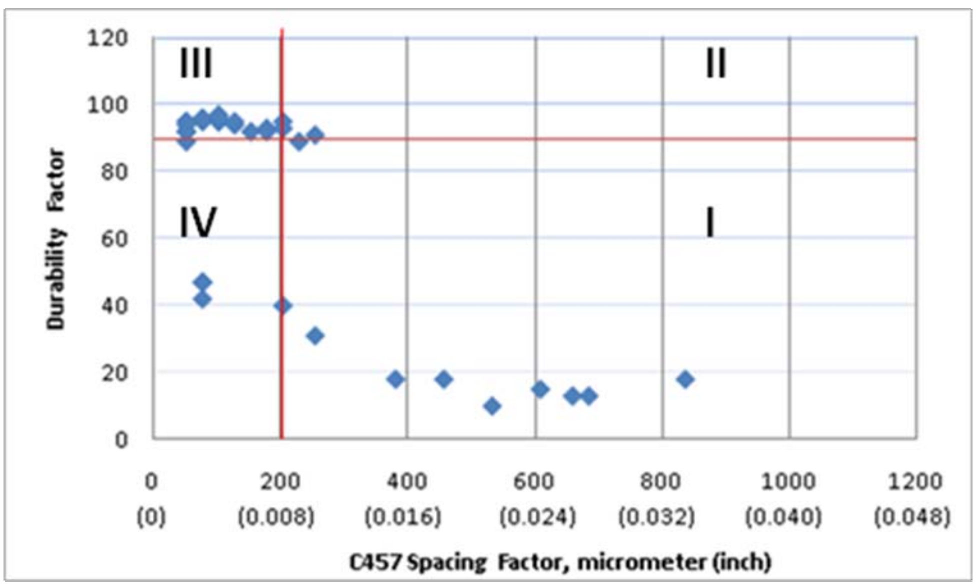
	Spearman's ρ	**Prob>|ρ|**	**STDEV (%)**		**Mean (%)**		**CV (%)**	
			C457	AVA	C457	AVA	C457	AVA
AVA – C457	0.1862	0.0709	0.006	0.009	0.010	0.013	62	70

5.1.4 Relationship between AVA Spacing Factors and F-T Durability Factors

The relationship between AVA spacing factor and F-T durability factor (from AASHTO T-161 – Method B) was investigated based on data collected from Missouri DOT (36 data points). The consistency was determined based on the level (%) of agreement of the two sets of test results in accepting or rejecting concrete. The results are presented in Figure 32 and Table 18. The acceptance criteria were ≤ 0.008 in., 0.012 in. or 0.015 in. for AVA spacing factors, ≤ 0.008 for C457 spacing factor, and ≥ 85% for F-T durability factor.



(a) Spacing factor measured from AVA



(b) Spacing factor measured from C457

Figure 32. Statistical analysis—relationship between spacing factors and F-T durability factor

Table 18. AVA and durability factor consistency

	No. of points in acceptance/rejection regions (%)					
	I (N-N)	II (Y-N)	III (Y-Y)	IV (N-Y)	Total	Agreement (I+III)
SF ≤ 0.008 in. For AVA F-T Durability factor ≥ 85%	10 (28%)	18 (50%)	6 (17%)	2 (5%)	36 (100%)	16 (45%)
SF ≤ 0.012 in. For AVA F-T Durability factor ≥ 85%	10 (28%)	5 (14%)	19 (53%)	2 (5%)	36 (100%)	29 (81%)
SF ≤ 0.015 in. For AVA F-T Durability factor ≥ 85%	8 (22%)	5 (14%)	19 (53%)	4 (11%)	36 (100%)	27 (75%)
SF ≤ 0.008 in. For C457 F-T Durability factor ≥ 85%	9 (25%)	2 (5%)	23 (64%)	2 (5%)	36 (100%)	32 (89%)

Note: N/Y-N/Y indicates F-T durability factor rejection (N)/acceptance (Y)—AVA or C457 SF rejection (N)/acceptance (Y).

As shown in Figure 32, of 36 data analyzed, 24 concrete mixtures are accepted by the F-T durability factor criterion, but only eight mixtures are accepted by the AVA 0.008 in. spacing factor criterion, including two rejected by F-T durability factor (DF) criterion. When the AVA spacing factor limit increases from 0.008 in. to 0.015 in., 23 mixtures are accepted, including 4 rejected by the F-T durability factor criterion. The relationship between the AVA spacing factor and the F-T durability factor is very poor whereas the relationship between the C457 spacing factor and the durability factor is clearer. The acceptance agreement between the C457's 0.008 in. spacing factor and the F-T durability factor is also much higher (89%) compared to AVA (45%). One of the reasons may be attributed to the large variation of AVA test results. Therefore, it is essential to study the AVA test variations and to ensure reliable AVA parameters before establishing the acceptance criteria.

The linear regression was performed to relate both AVA and C457 spacing factors with F-T durability, and the regression equations are as follows:

AVA SF = 0.032 – 0.00024 DF (R^2=0.67, P-value=0.0001) (8)
C457 SF = 0.020 – 0.00018 DF (R^2=0.66, P-value=0.0001) (9)

It is noted that R^2 values for Equations 8 and 9 are almost equal, which suggests that AVA spacing factor measurements can be used as confidently as C457 spacing factor measurement although the acceptance limits may be different. According to Equations 8 and 9, the acceptance criteria should be ≤0.012 in. for AVA and ≤0.005 in. for C457 so as to have a concrete durability factor of ≥ 85%.

5.2 Examining Significance of Different Factors that Affect AVA Measurements

5.2.1 Effect of Sampling Location

As mentioned previously, the CP Tech Center has studied the effects of sampling locations on AVA and C231 measurements through the MCO project (MCO 2008). The study showed that paver vibration had considerable effect on C231 air content measurement but had little effect on AVA air content measurement. In the present study, the AVA data have been reviewed and analyzed in a different way—the size distribution of air voids in different samples was studied. The results of the analyses are presented in Figures 33 and 34.

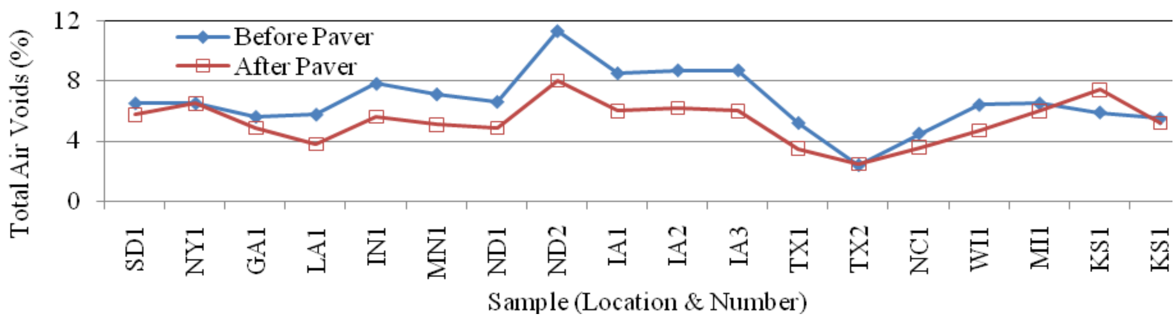
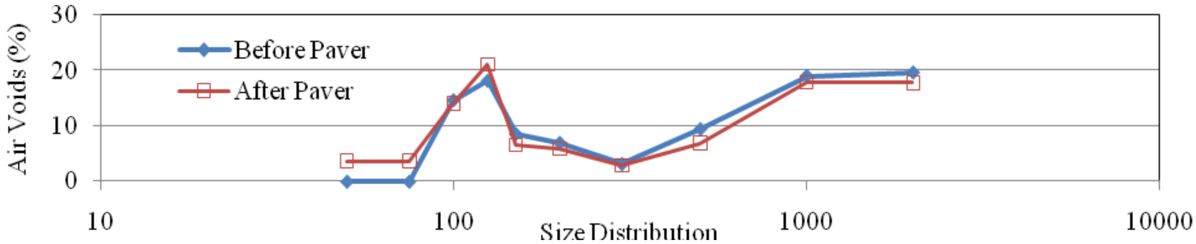
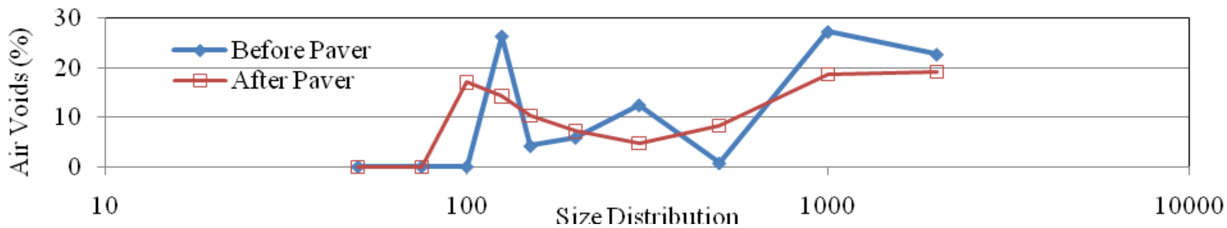


Figure 33. Statistical analysis—effect of sampling locations on C231 air content measurements

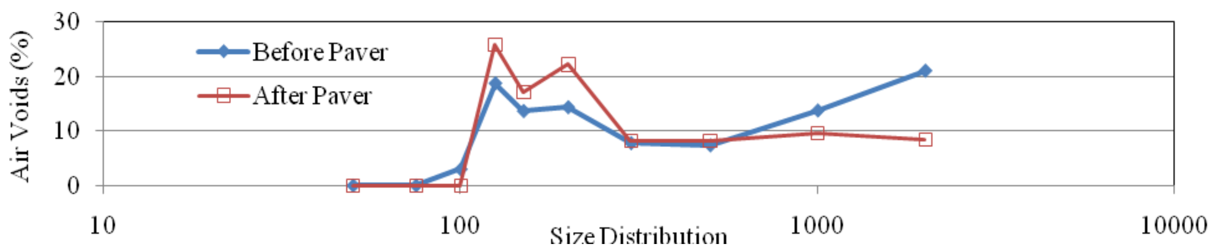
Figure 31 demonstrates that concrete mixtures sampled before paver generally had significantly higher air content as measured by the C231 test method. The AVA air-void size distribution curves (Figure 32) show that there was no clear difference in the small air content voids (≤ 300 µm) between the mixtures sampled in front of or behind the paver. However, the total content, including large air voids, (≤ 2 mm) of the samples retrieved behind the paver was generally lower than that in the samples retrieved in front of the paver. This suggests that small air voids that are more significant to concrete durability are not destroyed by normal paver vibration (5800–6200 rpm). Consequently, the air-void parameters measured from AVA, if they can be measured accurately, may be more meaningful than the parameters measured by other existing test methods.



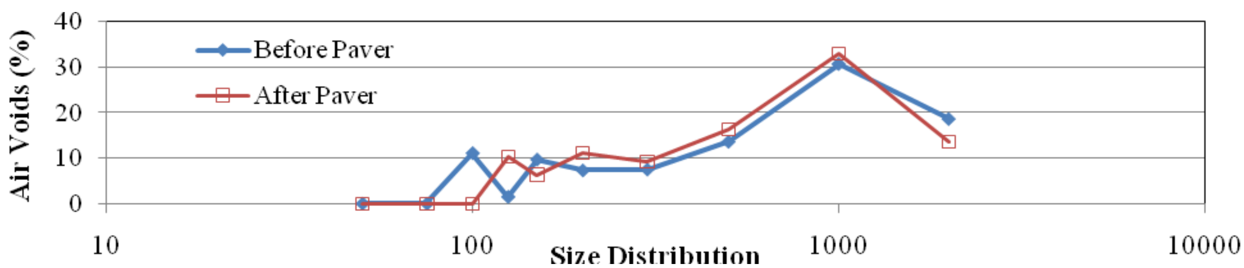
(a) Oklahoma samples



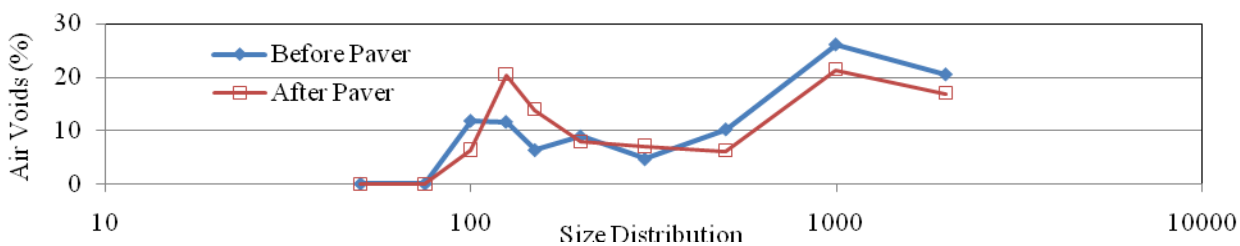
(b) Michigan samples



(c) South Dakota samples



(d) Georgia samples



(e) Louisiana samples

Figure 34. Statistical analysis—effect of sampling location on AVA air-void size distribution

5.2.2 Effect of Ambient Temperature, Concrete w/c, and Vibrator Frequency

Statistical analysis was also conducted to identify the effect of various mix design and construction factors on measurements including AVA method and others. The results are shown in Figures 35 and 36. The following observations have been made:

- Ambient temperature had the most significant effect on both gravimetric and AVA test results.
- Concrete w/c had little effect on the gravimetric air content, but it had noticeable effect on the AVA measurements.
- The vibrator frequency had significant effect on gravimetric air content, but little effect on AVA measurements.
- Concrete a/c had much more significant effect on air-void spacing factor and specific surface measured by AVA and C457 compared to its effect on total air content measured by C231, AVA, and C457.

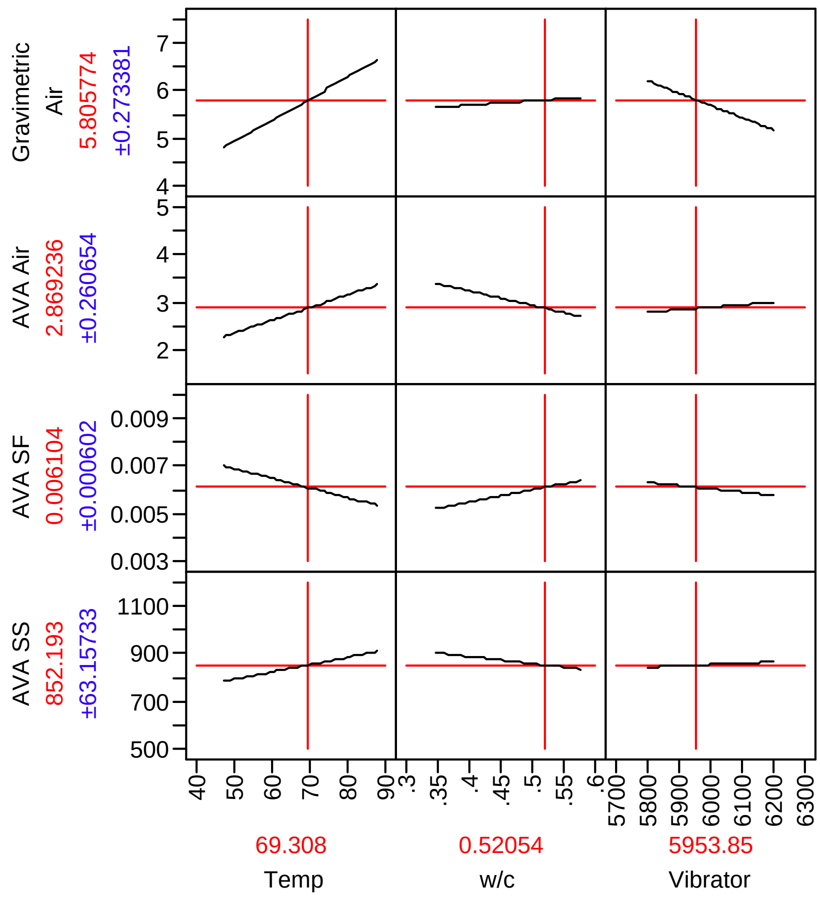
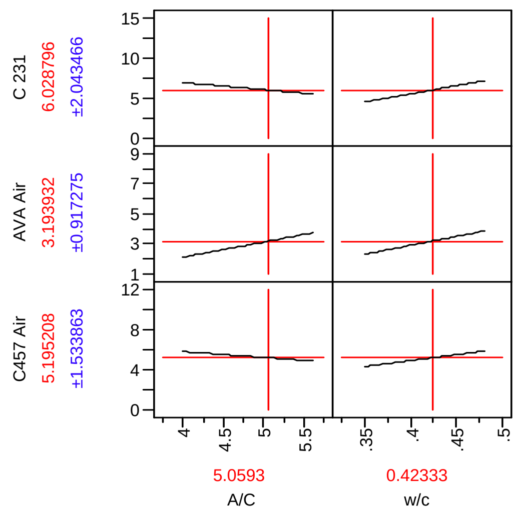
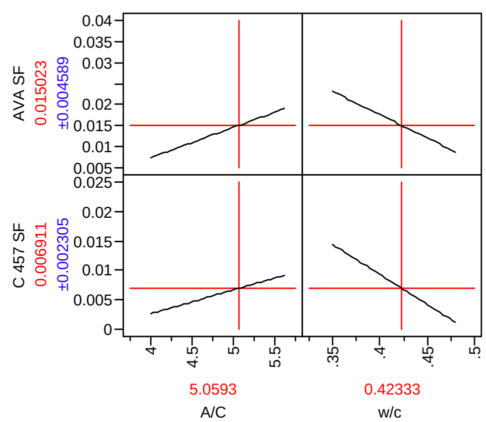


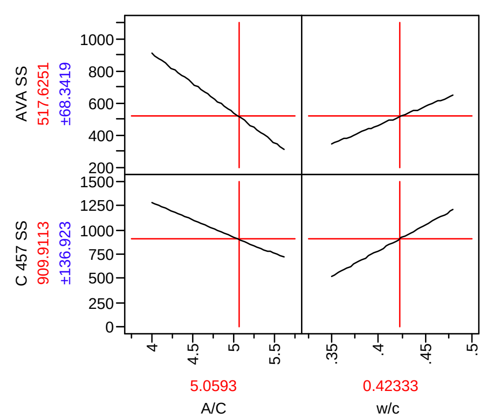
Figure 35. Statistical analysis—effects of ambient temperature, concrete w/cm, and vibrator energy effect



(a) Effect on total air content



(b) Effect on spacing factors



(c) Effect on specific surfaces

Figure 36. Statistical analysis—effect of a/c and w/cm on air-void parameters

5.2.3 Effect of Mixture Type, Mixing Method, and Mixer Type

This analysis was based on the 27 test data presented in Table 13, and the results of the analysis are presented in Table 19. As shown in the table, Restricted Maximum Likelihood (REML) variance component estimates are statistical tests used to measure variations due to random effects. In the present study, REML variance component estimates were used to measure AVA test variations caused by concrete mixture, mixing method, and mixer type. The results of the REML tests are given in terms of (1) variance ratio—the ratio of the variance of each random effect to the variance of the residual, (2) variance component—the variance of each random effect, and (3) percentage of total—the percentage of the variation associated with each random effect.

Table 19. REML variance component estimates for C231 and AVA parameters (Based on the data in Table 15)

ASTM C231 air			
Random effect	**Var ratio**	**Var component**	**Pct of total**
Mixture	10.50	4.79	78
Mixing method	1.41	0.64	10
Mixer type	0.61	0.28	5
Residual		0.46	7
Total		6.18	100
AVA air			
Random effect	**Var ratio**	**Var component**	**Pct of total**
Mixture	10.46	5.69	82
Mixing method	1.43	0.78	11
Mixer type	-0.19	-0.10	-1
Residual		0.54	8
Total		6.91	100
AVA spacing factor			
Random effect	**Var ratio**	**Var component**	**Pct of total**
Mixture	8.32	1.21×10^{-5}	58
Mixing method	4.33	6.31×10^{-6}	30
Mixer type	0.65	9.56×10^{-7}	5
Residual		1.46×10^{-6}	7
Total		2.08×10^{-5}	100
AVA specific surface			
Random effect	**Var ratio**	**Var component**	**Pct of total**
Mixture	8.95	27456.19	60
Mixing method	4.25	13036.21	28
Mixer type	0.88	2691.34	6
Residual		3066.95	6
Total		46250.68	100

The following conclusions can be made from Table 19:

- The mixture type had the most significant effect on the air-void measurements, and it contributed to 78%, 82%, 58% and 60% of the variations in C231 air content, AVA air content, spacing factor, and specific surface, respectively.
- The mixing method was the second most significant factor that caused variations in air- void parameters.
- The variations due to mixer type did not exceed 10%, as shown in Table 19 (b), (c), and (d).

6. AVA TRIAL TESTS

A total of 41 AVA trial tests were conducted at the ISU lab to study (1) the repeatability of the commonly used AVA test procedure operated by single and multiple operators, (2) effect of dry and wet mixtures (made with different w/c), and (3) effect of viscosity of AVA blue fluid on AVA test results. The following sections provide the detailed information on the test materials, method, and results.

6.1 Test Regime

Four sets of AVA tests were performed, and they can be described as follows:

- AVA variations due to single operator—a single operator measured air-void parameters using a given AVA device for eight mortar samples made with the same mixture proportion but different batches.
- AVA variations due to multiple operators—three different operators tested a given mortar mixture using the same AVA device and the same test procedure. Each operator conducted three tests (repetitions) sampled from the same batch.
- Effect of different w/cm on AVA measurements—a single operator measured air-void parameters using a given AVA device for four mixtures made with different w/c. Three samples from the same batch were tested for each mixture.
- Effect of viscosity of AVA blue fluid on AVA measurements—A single operator measured air-void parameters using a given AVA device but blue fluid with twelve different viscosities. (The different viscosities were obtained by diluting or heating a commercially used AVA blue fluid.) The mortar samples were made with a given mixture proportion but at different batches and tested with a given procedure.

6.2 Materials and Properties

6.2.1 Fine Aggregate Properties

The fine aggregate used for all AVA mortar samples was concrete sand from Hallett Materials, Ames, Iowa. It had a fineness modulus of 2.88 and gradation as listed in Table 20.

Table 20. Fine aggregate gradation

Sieve size # (mm)	#4 (4.75)	#8 (2.36)	#16 (1.18)	#30 (0.60)	#50 (0.30)	#100 (0.15)	#200 (0.08)
% Passing	97	87	69	39	9	1	0

6.2.2 Cement Properties

Type I cement from the Holcim plant at Mason City, Iowa, was used for all samples. Its Bogue compounds were C_3S = 55.08%, C_2S = 18.56%, C_3A = 10.98% and C_4AF = 6.90%, and its fineness was 399 m^2/Kg. The bulk chemical composition of the cement is given in Table 21.

Table 21. Chemical composition of Type I cement used

Composition	**CaO**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**K_2O**	**Na_2O**	**Anhydrite**
%	64.77	20.97	5.59	2.27	1.92	0.51	0.19	0.34
Composition	**SO_3**	**TiO_2**	**P_2O_5**	**SrO**	**Mn_2O_3**	**Gypsum**	**Bassanite**	
%	2.99	0.26	0.49	0.05	0.06	1.74	2.34	

6.2.3 Chemical Admixtures

Two different air-entraining admixtures, which have similar performance, were used in the trial tests and are described below. Both comply with ASTM C260, *Standard Specification for Air-Entraining Admixtures*.

1. Daravair 1400—a liquid air-entraining admixture based on a high-grade saponified rosin formulation. It is manufactured by W.R. Grace, which specified the dosage to be 1⁄2 to 3 fl oz/100 lbs (30 to 200 mL/100 kg) of cement (single and multi operator variation testing).
2. AEA-92—a liquid air-entraining admixture based on synthetic organic chemicals. It is manufactured by Euclid Concrete Admixtures, which specified the dosage to be 1⁄2 to 1 fl oz/100 lbs (30 to 60 mL/100 kg) of cement (effects of w/c and blue fluid viscosity testing).

6.2.4 Mixture Proportions

All trial test mortar mixtures had the same mixture proportion (Mix 2, in Table 22) except for the mixtures used to study the effect of different w/c on AVA measurements. The different mixture proportions are listed in Table 21.

Table 22. Mixture proportions for AVA trial tests (lb/cy)

	w/c	**Cement (lb)**	**Water (lb)**	**FA (lb)**	**AEA (ml)**
Mix 1	0.35	624	218	1383	112
Mix 2	0.43	624	268	1383	112
Mix 3	0.48	624	299	1383	112
Mix 4	0.55	624	343	1383	112

6.3 Test Procedures

6.3.1 Sample Preparation

All AVA samples were mortar samples prepared according to ASTM C305, *Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*.

6.3.2 AVA Test Procedure

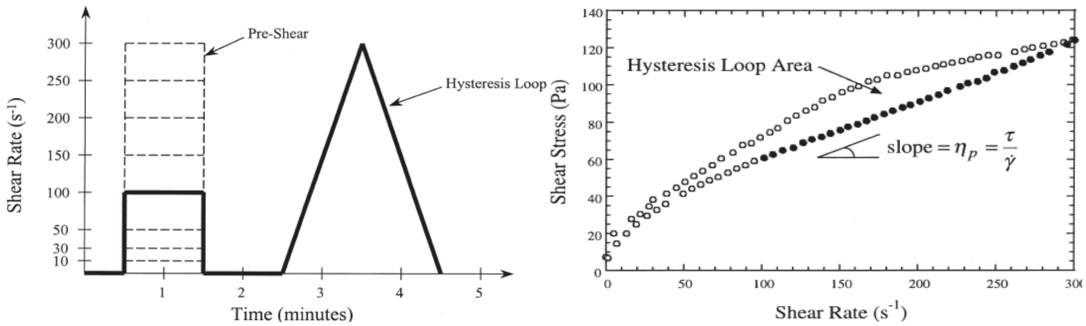
Air-void parameters were measured using AVA 2000 manufactured by Germann Instruments Incorporation, USA. The following test procedure, which is almost the same as that in the proposed AASHTO standard, was used:

1. Enter required data into the control system.
2. Place the stirrer rod flat on the bottom of the riser cylinder.
3. Insert the plastic rod through the hole on the wider side of the base of the riser cylinder.
4. Fill the riser cylinder with de-aerated water to about 15 mm (0.5 in.) above the bottom of the top collar. Use the brush to remove all bubbles from the stirrer rod, the plastic rod and the riser cylinder.
5. Fill the funnel with the amount of blue fluid as specified by the manufacturer.
6. Insert the blue liquid into the bottom of the riser cylinder using the funnel.
7. Connect the integral heating element of the riser cylinder and the temperature sensor to the control system.
8. Insert the dish into the riser cylinder collar.
9. Seat the syringe containing the sample on the reduced end of the plastic rod.
10. Move the syringe and plastic rod together through the riser cylinder base until the junction of the syringe and plastic rod is at the nearest inside edge of the riser cylinder.
11. Leave the syringe in the position. Continue withdrawing the plastic rod until the reduced end is flush with the opposite inside edge of the riser cylinder.
12. When the temperature of the analysis liquid as measured by the temperature sensor is 23°C ± 2°C (73°F ± 4°F), inject the mortar from the syringe into the riser cylinder. Immediately start the mixing and data collection.

6.3.3 Viscosity of Blue Fluid

A rheometer, manufactured by Brookfield Incorporation, USA, was used to measure the viscosity of the AVA blue fluid. The rheology test procedure was done according to Williams et al. (1999). After placing the blue fluid into the Rheometer, the specimens were left to equilibrate for 30 s and were then sheared at a constant rate for 1 min. The applied rate of pre-shear to each specimen ranged from 0 to 300 s^{-1}. The sensor was lifted and the sample was generally stirred to mitigate the formation of preferential shear planes due to particle orientation. The sample was then subjected to a controlled rate hysteresis loop where the shear rate was increased from 0 to 300 s^{-1} over 1 min and then immediately decelerated back to 0 s^{-1} over an additional 1 min. This testing program is illustrated in 37(a). The plastic viscosity, η_p, was determined from the

Bingham equation using the slope of the linear regression of the down curve of the hysteresis loop shown in (b).



(a) Viscometer test program (b) Typical hysteresis loop

Figure 37. Rheometer experimental program (Williams et al. 1999)

6.3.4 Flowability of Cement Mortars

Flowability of mortar was measured using the flow table specified in ASTM C230, *Standard Specification for Flow Table for Use in Tests of Hydraulic Cement*. The flowability of mortar was measured according to a procedure similar to ASTM C109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars.* In this test, a mortar sample was placed at the flow table and subjected to 25 drops. As the standard flow table has a limited diameter, mortars with high flow ability can flow out of the flow table before 25 drops. Therefore, a smaller number of drops were applied to these cement mortars and then the flowability was calculated according to J. Hu and K. Wang (2007).

6.4 AVA Trial Test Results and Analysis

6.4.1 Variations from a Single Operator

The results of eight tests performed by a single operator with a given AVA device are presented in Table 23. The mortar samples were made from different batches and had the same mixture proportions of Mix 2.

Table 23. AVA test results from a single operator

Sample*	Air content (%)	Spacing factor (inch)	Specific surface (inch^{-1})
1	4.1	0.0074	649
2	4.8	0.0072	615
3	3.9	0.0071	688
4	5.3	0.0049	846
5	5.5	0.0037	1078
6	4.5	0.0044	1055
7	4.7	0.0052	871
8	3.6	0.0059	859
Average	4.6	0.0057	833
Standard deviation	0.7	0.0014	175
Coefficient of variation (%)	15.0	24.0000	21

Note: All samples were made with the same mix proportion but in different batches.

The test results show that the AVA measurements produced relatively high CV values—15% for total air content, 24% for spacing factor, and 21% for specific surface. The high CV might be attributed to the effect of different batches produced in the lab, which should be further examined in future study.

6.4.2 Variations Due to Multiple Operators

Mix 2 mortar was tested by three operators (MAR, GIL and CHI) using the same AVA device. Each operator tested three mortar samples obtained from the same batch. After mixing, the batch mortar was divided into three portions. One was used immediately for an AVA test, and the other two samples were placed in a refrigerator/freezer (35ºF–38ºF) until the time of testing. The test results are presented in Table 24.

Statistical analysis was conducted on the data presented in Table 24, and the results are shown in Table 25. The variance components due to the operator for AVA air voids and AVA spacing factors in the table were $-0.151*10^{-9}$ and $-1.85*10^{-9}$, respectively, very close to zero. This suggests that the variability resulting from different operators is insignificant. This study also shows that the standard deviations of the AVA spacing factors measured by the three operators were equal and less than that specified by Kansas DOT (0.0007 in.).

Table 24. AVA results obtained by different operators

Operator	Sample	Air content (%)	Spacing factor (in.)	Specific surface (in.$^{-1}$)
	1	12.1	0.0013	1279
MAR	2	14.0	0.0012	1205
	3	11.9	0.0012	1431
Average		12.7	0.0012	1305
Standard deviation		1.2	0.0001	115
Coefficient of variation (%)		10.0	8.0000	9
	1	12.5	0.0011	1155
GIL	2	13.3	0.0013	1010
	3	14.1	0.0011	1250
Average		13.3	0.0012	1138
Standard deviation		0.8	0.0001	121
Coefficient of variation (%)		6.0	8.0000	11
	1	12.9	0.0012	1234
CHI	2	13.5	0.0013	992
	3	13.3	0.0011	1347
Average		13.2	0.0012	1191
Standard deviation		0.3	0.0001	181
Coefficient of variation (%)		2.0	8.0000	15

Table 25. REML variance component estimates for AVA results from different operators

	AVA air voids		
Random effect	Variance ratio	Variance component,	Pct of total
Operator	-0.332518	-0.151×10^{-9}	-50
Residual (equipment)		0.454×10^{-9}	150
Total		0.303×10^{-9}	100
	AVA spacing factors		
Random effect	Variance ratio	Variance component	Pct of total
Operator	-0.208333	-1.852×10^{-9}	-26
Residual (equipment)		8.89×10^{-9}	126
Total		7.03×10^{-9}	100
	(c) AVA specific surfaces		
Random effect	Variance ratio	Variance component	Pct of total
Operator	0.0249216	504.89	2
Residual (equipment)		20259.11	98
Total		20764.00	100

6.4.3 Effect of Different w/c on AVA Measurements

AVA tests were performed by a single operator for four mixtures made with different w/c. Two samples from the same batch were tested for each mixture. Flowability of the mixtures was also measured. The results are shown in Figures 38 and 39.

Table 26. Effect of different w/c on AVA measurements

Mix	w/c	Flow (%)	Sample	Air content (%)	Spacing factor (in.)	Specific surface (in.$^{-1}$)
			1	7.6	0.0017	1378
1	0.35	107	2	5.4	0.0024	1362
			Average	6.5	0.0021	1370
			1	12.0	0.0013	1295
2	0.43	126	2	14.0	0.0012	1205
			Average	13.0	0.0013	1250
			1	14.5	0.0012	1122
3	0.48	166	2	15.2	0.0014	953
			Average	14.9	0.0013	1038
			1	9.3	0.0021	1006
4	0.55	190	2	8.4	0.0024	990
			Average	8.9	0.0023	998

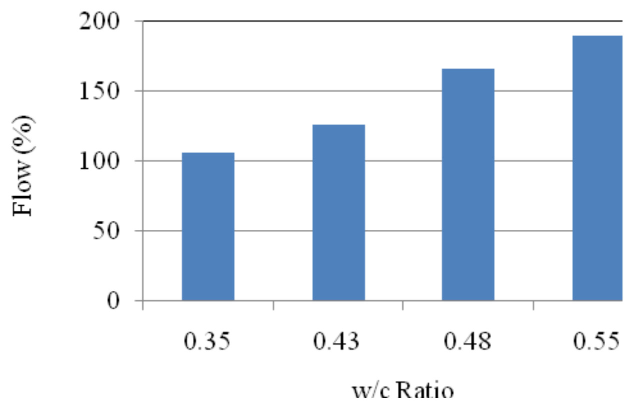
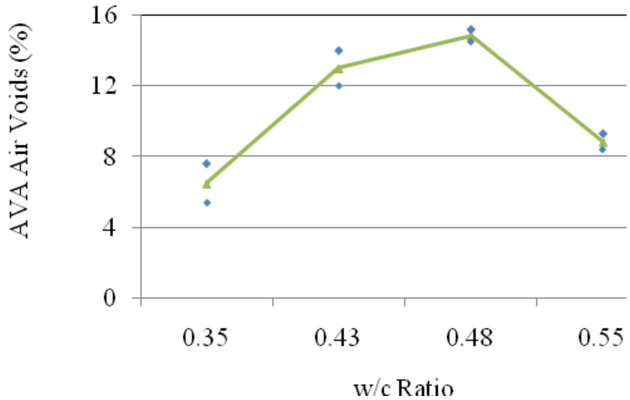
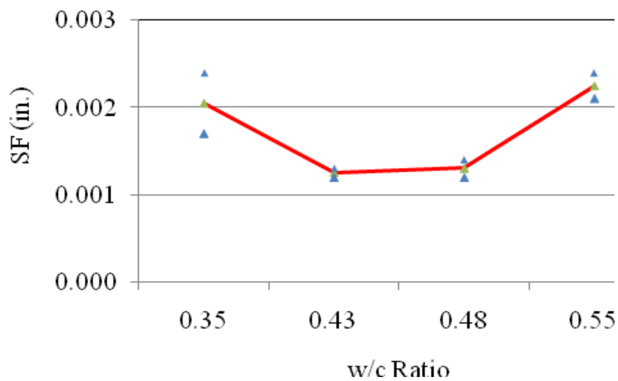


Figure 38. Effect of different w/c on flowability

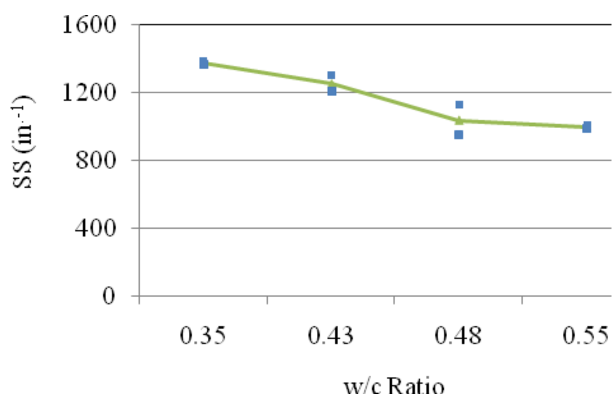
As expected, the flowability of the mortar mixtures increased with w/c. The AVA total air content increased and the spacing factor decreased when mortar w/c increased from 0.35 to 0.48. However, the opposite trend occurred when the mortar w/c increased from 0.48 to 0.55. This is probably because high amounts of large air voids were produced in the high w/c mixture, which were not captured by the AVA. It was also noted that the variation in the air content and the spacing factor measurements of the three samples from the same batch, tested by the same operator, was high for the low w/c mixture (w/c=0.35) and slightly high for the high w/c mixture (w/c=0.55).



(a) Total air content



(b) Spacing factor



(c) AVA specific surfaces

Figure 39. Effect of w/c on AVA measurements

Statistical analysis was conducted to study the variance of AVA measurements of samples with different w/c, and the results are presented in Table 27. As observed in the table, the P-values of AVA air content and spacing factor measurements were 0.0307 and 0.0273, respectively; smaller than 0.05, which indicates that the w/c was a significant factor that affects the AVA measurements. AVA measurements of concrete mixtures with different w/c may have different variations. Additional testing with different w/c is needed to verify this finding.

Table 27. Variance of AVA measurements of samples with different w/c

		Total air content			
Source	DF	Sum of squares	Mean square	F ratio	Prob > F
w/c	3	164.49	54.83	7.00	0.0307
Error	5	39.15	7.83		
C. Total	8	203.64			
		Spacing factors			
Source	DF	Sum of squares	Mean square	F ratio	Prob > F
w/c	3	2.147×10^{-6}	7.16×10^{-7}	7.43	0.0273
Error	5	4.817×10^{-7}	9.63×10^{-8}		
C. Total	8	2.629×10^{-6}			
		Specific surfaces			
Source	DF	Sum of squares	Mean square	F ratio	Prob > F
w/c	3	184142.22	61380.7	13.33	0.0080
Error	5	23014.67	4602.9		
C. Total	8	207156.89			

6.4.4 Effect of Viscosity of Blue Fluid on AVA Measurements

The blue fluid used in AVA tests is the medium that transfers air bubbles from the tested sample to water without being broken: it prevents the air bubbles in mortar from being dispersed. Viscosity of the blue fluid may have significant effects on the AVA test results. A series of tests were carried out to investigate the viscosity effect.

Different viscosities of the blue fluid were obtained with three methods:

- Heating the blue fluid at 40°C (104°F) in the oven for one, three, and seven days (the new fluids are labeled as V-H1,V-H3, or V-H7)
- Heating or cooling the blue fluid from room temperature to 60°F, 80°F, 90°F, and 100°F (within about three min) just before the testing (the new fluids are labeled as V-T60, V-T80, V-T90, or V-T100)
- Diluting the blue fluid with water, The new fluids are labeled as V100, V75, V50, V25 or V0 as they have 100%, 75%, 50%, 25%, or 0% of the original blue fluid in their solutions. V100 or V-control is the original blue fluid without water, used as a control fluid, and V0 is pure water.

Figure 40 illustrates the viscosities of the blue fluid achieved. These new fluids were used in tests of 12 mortar samples made with the same mixture proportion (Mix 2) in three different batches. Trial tests were conducted by the same operator using the same AVA device. The test results are presented in Table 28. Statistical analysis was performed on the test data and the results are given in Figure 41. (Note: Two blue fluids, V-H3 and V-H7, were excluded from the statistical analysis as they achieved very high viscosity that did not yield reliable AVA measurements.)

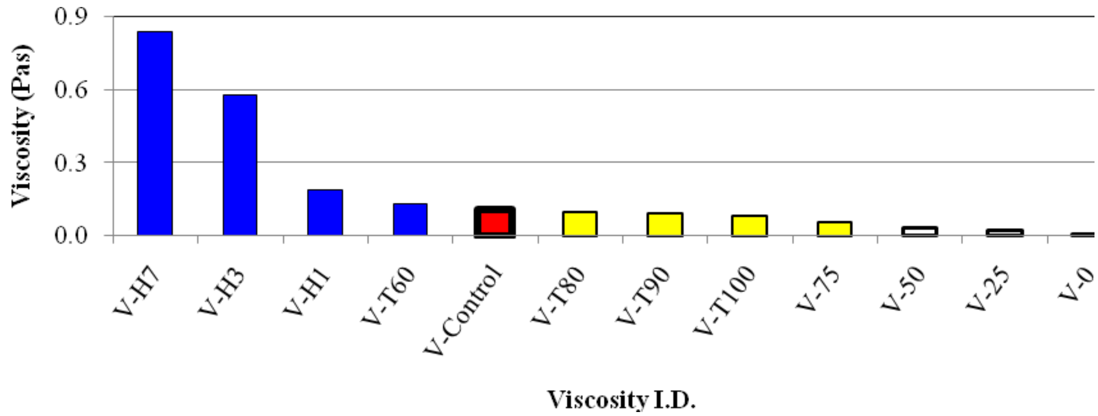
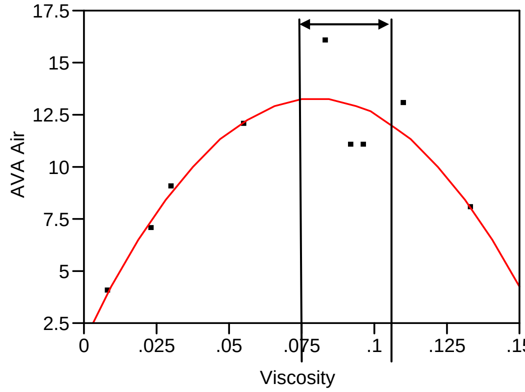


Figure 40. Viscosities of the new fluid

The results indicate that the viscosity of AVA blue fluid significantly influenced the AVA measurements and there is a close relationship between the fluid viscosity and air-void parameters, namely air content, spacing factor, and specific surface. The blue fluid viscosity ranged from 0.075 Pas to 0.130 Pas and provided the highest air content and lowest spacing factor measurement. This range may be used in the AVA test specification to control precision of AVA measurements.

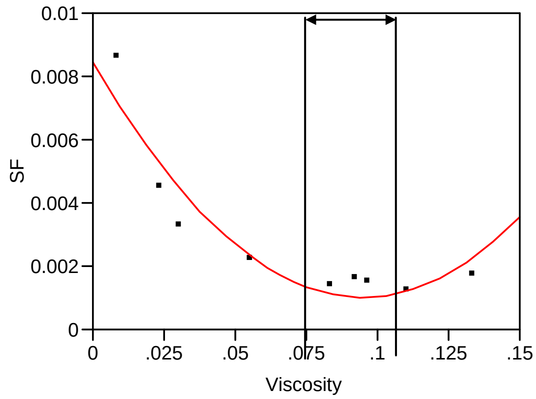
Table 28. AVA measurements using blue fluid with different viscosities

Blue fluid	Viscosity (Pas)	Air content (%)	Spacing factor (in.)	Specific surface ($in.^{-1}$)
V-H7	0.840	6	0.0020	1594
V-H3	0.580	7	0.0017	1768
V-H1	0.188	11	0.0011	1613
V-T60	0.133	8	0.0017	1351
V100 (V-Control)	0.110	13	0.0012	1205
V-T80	0.096	11	0.0015	1103
V-T90	0.092	11	0.0016	1011
V-T100	0.083	16	0.0014	800
V-75	0.055	12	0.0022	620
V-50	0.030	9	0.0033	438
V-25	0.023	7	0.0045	390
V-0	0.008	4	0.0086	305



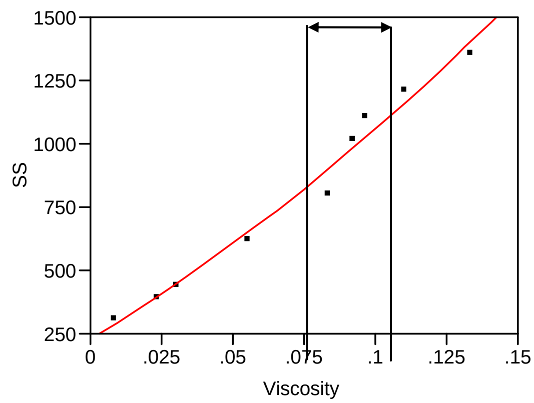
Regression equation: AVA air = 10.63 + 35.47 V - 1827.36 V^2 (R^2 = 0.83)

(a) Air content vs. viscosity



Regression equation: AVA SF = 0.004 - 0.04 V + 0.83 V^2 (R^2 = 0.89)

(b) AVA spacing factor vs. viscosity



Regression equation: AVA SS = 155 + 8903 V + 14972 V^2 (R^2 = 0.98)

(c) AVA specific surfaces vs. viscosity

Figure 41. Statistical analysis—effect of blue fluid viscosity on AVA measurements

6.5 Summary of AVA Trial Test Results

The observations made from the above AVA trial tests can be summarized as follows:

- The CVs in the AVA measurements resulting from a single operator who tested samples made with a given mixture proportion but different batches using a given AVA device were relatively high. The high variations might be attributed to the effect of multiple batching, which should be further examined.
- The CVs in the AVA measurements resulting from multiple operators who tested samples made with the same mixture proportion using the same AVA device and the same test procedure were low. This suggests that implementation of a properly specified AVA test procedure could significantly reduce the variation of AVA measurements in concrete practice.
- The AVA total air content increased and spacing factor decreased when the mortar w/c increased from 0.35 to 0.48. However, the opposite trend occurred when the mortar w/c increased from 0.48 to 0.55. This is probably because high amounts of large air voids were produced in the high w/c mixture, which were not captured by AVA.
- AVA measurements of concrete mixtures with different w/c may have different variations. As a result, different stirring energy may be required to minimize the variations of samples with different flowability. Repeated testing with different w/c is needed to verify this finding.
- The viscosity of AVA blue fluid significantly influenced the AVA measurements; there is a close relationship between the fluid viscosity and air-void parameters. The blue fluid viscosity ranged from 0.075 to 0.130 Pas provided the highest air content and lowest spacing factor measurement. This range may be used in the AVA test specification to control precision of AVA measurements.

7. SUMMARY OF FINDINGS FROM THE PHASE 1 STUDY

7.1 Project Summary

The goal of the present research is to reduce variability and improve precision of AVA test results so as to develop rational specification limits for controlling concrete F-T damage using the AVA test parameters. The entire project includes three phases:

- Phase 1: Literature search and existing data analysis
- Phase 2: Testing procedure and specification modification
- Phase 3: Field study and specification refinement

In this report, the major activities and findings of the Phase 1 study are presented.

The Phase 1 study started with a kickoff meeting at Kansas City on June 11–12, 2007. At the meeting, the project Technical Advisory Committee (TAC) members shared their experience in working with AVA tests. They discussed the problems associated with AVA tests, variables contributing to inconsistency of AVA test results, and potential research topics. Specific issues on the AVA equipment and test procedures were also addressed. These inputs and discussions greatly directed the research team in developing the research activities of this project.

A literature review was conducted in the Phase 1 study on the use of AVA in concrete labs and construction sites. This work was focused on examining the critical factors that affect AVA test results (such as mixture properties, time of sampling/testing, and testing conditions), specification limits, and results of the comparative tests (such as hardened air-void properties or freeze-thaw results).

In addition, four sets of AVA test data were collected from Missouri, Kansas, Michigan, and Iowa through the TAC members of this project. These data were compiled, and statistical analysis was applied. Based on these available data, relationships between the air-void parameters measured by AVA tests and other tests (such as ASTM C231 and C457) were examined. The agreement in the acceptance/rejection criteria provided by existing AVA and C457 specifications were investigated.

Finally, the research team also conducted some AVA trail tests in lab to study the repeatability of the commonly used AVA test method, effect of flowability of mixtures, and effect of viscosity of AVA blue fluid on AVA test results.

Based on the results of the Phase 1 study, the major tasks for the Phase 2 study are recommended.

7.2 Major Findings from the Project TAC Meeting

Several findings can be drawn from the first project TAC meeting.

The problems associated with AVA tests may include the following:

- AVA tests sometimes reject good concrete.
- Results are not closely repeatable.
- Results do not always correlate with ASTM 457, probably due to the variability in both AVA and 457 results.

The variables contributing to inconsistency of AVA test results may include the following:

- Equipment—it is possible that the current device may not have appropriate column size, AVA fluid, stir energy, and test time for testing of US pavement concrete mixtures.
- AVA blue fluid—the viscosity of the blue fluid used in AVA tests may change from shipment to shipment, over time, and with environmental temperature. It is not clear whether and how the blue fluid viscosity affects the AVA test results.
- Test Procedure—since there is no published specification for AVA tests, AVA operators may operate the test in a different way, which may be the major cause of the variation in AVA test results. Other variations may result from (1) loss of air bubbles due to the mortar extraction in sampling, (2) inducing additional bubbles into the test system when tap water is used, and (3) the short test time (25 minutes) controlled by the AVA software
- Testing Conditions—sample temperature, environmental temperature, vibration of the test table on which the AVA device stands, etc.

The suggestions for improving the AVA test accuracy include the following:

- Looking into the items discussed and questions raised at the meeting
- Conducting a systematic study (with a given test matrix) to examine the reliability of the AVA equipment and the test procedure
- Further studying the relationship between parameters measured by the AVA test method and other test methods
- Improving the test procedure and establishing rational specification limits
- Having another well-designed round-robin AVA test with a number of new AVA devices, experienced operators, and improved statistical analyses to find out the reliable values of variations due to the equipment and its operation.

7.3 Major Findings from the Literature Study

The major findings from the present literature survey on the existing AVA research can be summarized as follows:

- AVA is a potentially useful tool for concrete quality control. While other conventional methods measure only the total air, AVA measures the content, spacing factor, and specific surface of small air voids in concrete, which are more essential to concrete durability. Many agencies have purchased AVA devices but few research results have been published. One of the reasons may be related to the variability of the test results and test procedures. Therefore, further study on AVA equipment and test methods is an urgent demand.
- The AVA test may be particularly beneficial as a quality control tool for the concrete mixtures, especially sandy mixtures, with a short mixing time; the mixtures with low slump and various supplementary cementitious materials, additives, and/or admixtures, and the mixtures exposed to extreme environmental conditions (very hot or very cold) and construction conditions (such as pumping).

The critical problems associated with the existing AVA include the following:

- Robustness of the test method and equipment
- Nonstandard test procedure and acceptance criteria
- Reportedly large variations in the test results
- Inconsistent relationship with other test results

The possible causes of variation in AVA test results can be classified as follows:

- Variations due to test operation such as sampling technique, removal of air from syringe, test timing, equipment cleanness, and test duration
- Variations due to features of the AVA device such as viscosity of the blue fluid, stirring energy (RPM), drilling model, sensitivity of the device to environmental disturbance and mixture proportions
- Variations due to concrete material production and construction such as concrete mixing time, transportation time, placement method and temperature, vibration and finishing methods

The following relationships were observed from the literature review:

- The total air content measured from AVA was generally lower than that measured by C231 or C457 test method.
- Both C457 and AVA measurements indicated that the high total air content didn't always ensure a low spacing factor. That is, the relationship between the total air content and spacing factor didn't always exist.
- MCO project data demonstrated a very good relationship between the content of small air void (≤300 μm) and spacing factor measured by AVA (R^2=0.82). This suggested that the total air content measured from AVA might not need to be

- When the criterion of the spacing factor of 0.008 in. (200 µm) was applied, the acceptance/rejection agreement between C457 and AVA test methods was about 50%. The criterion of the AVA spacing factor of 0.015 in. (375 µm) was sometimes used.

7.4 Major Findings from the Collected AVA Data

The data collected from Missouri, Kansas, and Michigan DOTs and MCO project confirmed major findings obtained from the literature review. The findings observed from collected data analyses can be summarized as follows:

- The total air content measured from AVA was generally lower than that measured by C231 or C457 test method.
- Both AVA and C457 test methods showed considerable variations in their measurements. The variations resulting from AVA measurements were generally higher than those from C457 measurements.
- There was little relationship between the AVA spacing factor and total air content; however, the MCO test results showed a strong relationship (R^2=0.82) between the AVA spacing factor and content of small air voids (≤ 300 µm).
- There was a weak relationship between the AVA lab test results (such as total air content and spacing factor) and ASTM C457 test results. These relationships between the AVA field test results and ASTM C457 test results were much weaker.
- Sampling locations had a significant effect on the air content measured by C231, but had little/no effect on the air content measured by AVA, which indicates that small air bubbles are stable under vibration.
- When the criterion of the spacing factor of 0.008 in. (200 µm) was applied, the acceptance/rejection agreement between C457 and AVA test methods was often as low as 50%. When the criterion of the spacing factor increased to 0.015 in. (375 µm) for AVA but stayed at 0.008 in. (200 µm) for C457, the agreement might significantly increase but not always. More research on the AVA test acceptance criteria should be conducted.

7.5 Major Findings from the Statistical Analyses of the Collected Data

The computer software JMP 6.2 was used in the statistical analyses, and the major findings are summarized in the following section. (It shall be noted that the statistical analyses were done on the limited data collected in the Phase 1 study. The conclusions made from these analyses may not be always applicable. More analyses are necessary using well controlled data in future.)

- Although the coefficients of variations (CVs) of AVA measurements were often relatively high, the differences in CVs between AVA, C231, and C457 measurements were smaller than 15%. Therefore, the AVA variability should be considered acceptable when compared to C231 and C457 variability.
- The following regression equations were obtained based on the available data:

- AVA Air = -0.33 + 0.68 C231 Air (R^2=0.50) (1)
- AVA Air = 0.787 + 0.498 C457 Air (R^2=0.50) (2)
- C 457 Air = 0.27 + 0.836 C231 Air (R^2=0.63) (3)
- AVA Air = 0.4549 Gravimetric Air (R^2=0.01) (4)
- AVA Air = 5.04 - 151.1 AVA SF + 3053.6 AVA SF^2 (R^2=0.41) (5)
- C457 Air = 7.98 - 303.1 C457 SF + 8474.2 C457 SF^2 (R^2=0.49) (6)
- AVA SF = 0.0041 + 0.98 C457 SF (R^2=0.41) (7)
- AVA SF = 0.032 – 0.00024 DF (R^2=0.67) (8)
- C457 SF = 0.020 – 0.00018 DF (R^2=0.66) (9)

- Based on the above regression Equations 1 and 4, if 5% air content from gravimetric or C231 measurements is considered acceptable for quality control of fresh concrete, 2.3% or 3.0% total air content from AVA measurements shall also be considered acceptable, respectively.
- According to the regression Equation 5, AVA spacing factor of 0.012 in. may be used as an acceptance criterion for concrete to have AVA total air content of approximately 3% or C231 air content of 5%. Equation 6 also indicates that the AVA spacing factor value is 0.012 in. for a C457 spacing factor of 0.008 in.
- The R^2 values in Equations 8 and 9 suggest that AVA spacing factor measurements can be used as confidently as C457 spacing factor measurement although the acceptance limits may be different. According to Equations 7 and 8, the acceptance criteria should be ≤ 0.012 in. for AVA and ≤ 0.005 in. for C457 spacing factor measurements so as to have a concrete durability factor of ≥ 85%.
- In the MCO project, ambient temperature changes had the most significant effect on AVA measurements when compared with concrete w/c and vibrator frequency changes, the latter of which had the least effect on AVA measurements.
- Concrete a/c had a much more significant effect on air-void spacing factor and specific surface measured by AVA and C457 than its effect on total air content measured by C231, AVA, and C457.
- Concrete mixtures had significant effects on the air-void measurements, and they contributed to 78%, 82%, 58% and 60% of the variations in C231 air content, AVA air content, spacing factor, and specific surface, respectively. The mixing method was also a significant factor that caused variations in air-void parameters.

7.6 Major Findings from AVA Trial Tests

The observations made from the above AVA trial tests can be summarized as the following:

- The CVs in the AVA measurements resulting from a single operator, who tested samples made with a given mixture proportion but different batches using a given AVA device, were relatively high. The high variations might be attributed to the effect of different batches produced in the lab, which should be further examined in future study.
- The CVs in the AVA measurements resulting from multiple operators, who used the same AVA device and the same test procedure as others and tested three samples from a given batch made with the same mixture proportion as others, were low. This suggests that implementation of a properly specified AVA test procedure can significantly reduce the variation of AVA measurements in concrete practice.

- The trend of AVA total air content and spacing factor measured from the mortar made with different w/c indicates that AVA measurements of concrete mixtures with different w/c may have different variations. Therefore, different stirring energy may be required to minimize the variations of samples with different flowability. More tests of samples with different w/c need to be performed to verify this finding.
- There is a close relationship between the fluid viscosity and air-void parameters (i.e., air content, spacing factor, and specific surface). The blue fluid viscosity ranging from 0.075 Pas to 0.130 Pas provided the highest air content and lowest spacing factor measurement. This range may be used in the AVA test specification to control precision of AVA measurements.

8. RECOMMENDATIONS FOR PHASE 2 STUDY

The Phase 1 study has indicated that AVA is a useful tool for determining the air-void parameters in fresh concrete, and it has significant advantages over conventional air-void test methods, providing not only air content as ASTM C231 and C173 but also air-void spacing factor and specific surface as ASTM C457. AVA is also a time and cost effective tool for field concrete quality control compared with ASTM C457. However, AVA equipment and test methods need further improvement for a proper implementation in concrete practice.

As mentioned previously, the goals of the entire research project were to reduce variability and improve precision of AVA test results and to develop rational specification limits for controlling concrete F-T damage using the AVA test parameters. The Phase 2 study of the project was designed to modify the AVA test procedure and specification through a series of systematic experiments in laboratory. The experimental results will be used to modify, calibrate, and/or validate the test procedures. Based on the results of the Phase 1 study, the following major tasks are recommended for the Phase 2 study so as to reach the goal of this project:

- Investigate and improve robustness of AVA device.
- Systematically evaluate the underdeveloped AASHTO AVA test procedure.
- Further study the relationships between AVA measurements and F-T durability factors and develop rational acceptance criteria (AVA indexes) for AVA measurements.
- Conduct a well-designed round robin test to verify the findings obtained from the above-described tasks.

More detailed information on these tasks is presented below.

Task 1 includes investigating and improving the robustness of the AVA device:

- The Phase 1 study has revealed that the precision and repeatability of AVA tests is of the utmost importance for application/implementation of AVA tests. To improve AVA test precision, as the first step, the variations caused by the device itself (such as speed/energy of the AVA mortar stirrer and sensitivity of the AVA to environmental temperature and vibration) and by the device-controlled test procedures (such as energy used in vibratory cage during sampling, blue fluid viscosity and test time) should be minimized. Although the effect of AVA blue fluid viscosity on AVA measurements has been investigated in the Phase 1 study, many other factors, such as sensitivity of AVA to environmental temperature and vibration, energy used in vibratory cage during sampling, column size, test time, differences between old and new machines (AVA 2000 and AVA 3000), have not been studied. The research team is now proposing to work with AVA device supplier, Germann Instrument, and to investigate these factors through a well-controlled laboratory study. It is expected that the results of this study can be used to improve robustness of the next generation of AVA devices.

Task 2 includes systematically evaluating the underdeveloped AASHTO AVA test procedure:

- The objective of this study is to improve precision of the AVA test procedure. A systematic test matrix will be designed to consider effects of mixture composition, production, construction condition, operators, and test sequences to AVA measurements. The experimental results will be used to verify the findings obtained from the Phase 1 study as well as to modify, calibrate, and/or validate the test procedures. Consequently, modified test procedures may be developed to ensure a proper precision and repeatability of AVA tests.

Task 3 includes further study of the relationships between AVA measurements and F-T durability factors and developing rational acceptance criteria for AVA measurements:

- The Phase 1 study has indicated that there are significant variations in air-void measurements of both AVA and C457 test methods, although the variation of AVA tests is slightly higher than that of the C457 test method. Statistically, there are some relationships between AVA spacing factor, C457 spacing factor, and F-T durability. These relationships may be improved when the variations of AVA tests are reduced through the study of the first two tasks proposed for Phase 2. Considering that the main purpose of using AVA is to control concrete F-T durability, it is proposed that the focus of the Phase 2 study will be on the relationships between AVA parameters and F-T durability factors. The AVA parameters will include not only the total air content, spacing factor, and specific surface but also the small air or micro air (≤ 300 μm) content and spacing factor frequency (see Figure 10). These newly proposed AVA parameters (such as micro air content and spacing factor frequency) may be used as AVA indexes for development of rational specification limits for controlling concrete F-T damage. The concrete samples in the systematic test matrix designed for the previous task will also be used for F-T tests. In-depth statistical analyses will be conducted to analyze all the test results. Based on the results of this study, recommendations will be provided for the AASHTO AVA specification modification.

Task 4 includes conducting a well-designed AVA round robin test to verify the findings obtained from the above tasks:

- Two AVA round robin tests were conducted in Iowa (2003) and Kansas (2006), respectively. It seems that no report has been published on the first AVA round robin test in Iowa. The results from the second AVA round robin test in Kansas have been reported by Kansas DOT. As discussed at the first TAC meeting of this Phase 1 project, these results appeared unsatisfactory because of the variety of variations resulting from the AVA devices, inexperienced operators, operation procedures, etc. Several TAC members of the Phase 1 project have suggested having another round robin test with a number of machines and experienced operators. As a part of the testing, the operators could rotate after each test and run the next machine. A statistical analysis will be conducted to examine the data for significance and also compare results of one operator versus another. The research team also believes that a well-designed AVA round robin test is necessary for obtaining valuable information on AVA device and test variations. The test results can be used for the test precision development in the AVA specification and to verify the findings obtained from the other tasks of this Phase 2 study.

The Phase 2 proposal will be developed and submitted to the funding agencies in a separate document.

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