A "FRESH" PERSPECTIVE ON MEASURING AIR IN CONCRETE

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ABSTRACT

This paper discusses Federal Highway Administration's (FHWA) recent experience with a new piece of testing equipment called the Air Void Analyzer (AVA). This device allows the concrete practitioner to measure not only the air content of fresh concrete, but also its air void spacing factor and specific surface in about half an hour. FHWA's Mobile Concrete Laboratory has employed the use of the AVA on numerous bridge and pavement projects throughout the United States with encouraging results. Use of the AVA promises to significantly improve the freeze-thaw durability of concrete placed in the United States.

KEY WORDS

Air Void Analyzer, Air Content, Air Test Method, Air Voids, Freeze-Thaw Durability, Spacing Factor,

INTRODUCTION

The transportation community is facing a financial crisis. According to a 2002 report released by the U.S. Department of Transportation, $106.9 billion per year is required to improve highways and bridges.[1] An additional $75.9 billion per year is required to maintain these highways and bridges. The current highway program, however, only allocates $64.6 billion per year toward the improvement and maintenance of highways and bridges. These numbers show the growing backlog of required repair or replacement on our existing system. In order to minimize the impact of maintenance and repair in the future, there is a need to construct more durable structures. Many agencies have looked at ways of increasing the design life of pavements to 50 years or more, and bridges to 100 years. To reach these goals, it is critical that new structures be properly designed and constructed using high quality materials and efficient construction techniques.

To improve concrete's quality, better and more rapid test methods are needed for measuring concrete's in-place properties. These improved tests need to provide relevant information in a timely manner, so that decisions about the material's quality can be made at the job site. Timely test information will allow the contractor to make real time adjustments to the production process, and minimize the risk of inferior concrete without adequate durability being placed. One new tool that can provide this proactive information about fresh concrete is the air void analyzer (AVA) described in this paper.

BACKGROUND

Hydraulic cement concrete used in bridges, pavements and other highway infrastructure must resist deterioration caused by environmental factors, and it must be durable. In most parts of the United States damage caused by freezing and thawing is a serious durability problem for concrete structures. The damage is greatly exacerbated in pavements and bridge decks by the use of deicing salts, and often results in severe surface scaling.

The mechanisms causing freezing and thawing damage are fairly well understood. Fortunately, hydraulic cement concrete made with good quality aggregates, a low water-cementitious materials ratio, a proper air void system, and proper curing before being exposed to severe freezing and thawing will be highly resistant to frost and salt scaling damage. The air void system protects the paste portion of the concrete by providing relief from hydraulic pressures generated as a result of freezing and migrating water in the paste. Developing the proper air void system is an important factor in the development of durable concrete.[2]

Researchers believe that the pressure developed by water as it expands during freezing depends upon the distance the water must travel to the nearest air void. The voids must be spaced close enough to relieve the pressure. Thus smaller, closely spaced voids provide more protection than larger, more distant void spacing. Figure 1 illustrates the concept.

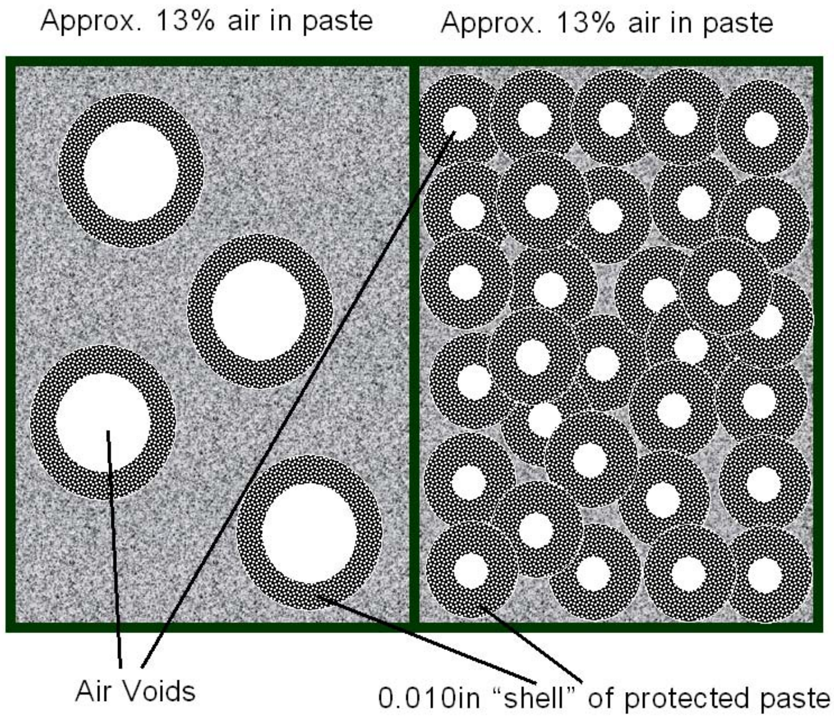

Fig. 1 Influence of Bubble Size On Volume of Paste Protected (per Hover)

ASTM C 457 states that the maximum value of the spacing factor for moderate exposure is usually taken to be 0.008 in. The spacing factor is the average maximum distance from any point in the cement paste to the edge of the nearest air void. The minimum specific surface (surface area per unit volume), is generally targeted at 600 sq in./cu in. of air void volume. The specific surface is an indirect way of expressing the bubble size.[3]

Commonly used field test methods are only capable of measuring the total air content (volume of air), not void size or spacing. As a result, air content recommendations, used in mixture design, are given in terms of total air content requirements based on exposure conditions and maximum aggregate size. An air volume in concrete between 4 and 8% is generally assumed to yield a satisfactory air void system, with sufficiently small and closely spaced air bubbles to protect the concrete. On most jobs, spacing and void size are left to chance, and are often not known.

Microscopic examination (ASTM C 457) of the concrete to measure air parameters directly can only be performed after the concrete has hardened, and is typically only performed if durability problems have occurred. The approach of only measuring air content (volume of air) has worked well in the past, but with higher requirements for durability, and with changing materials used in concrete, the approach may not be adequate for today’s transportation structures.

Air is incorporated into concrete during the mixing process. Unless chemical air entraining admixtures are used to stabilize the bubble system, air will only exist in larger voids that are less effective than smaller voids in protecting the concrete. Air-entraining admixtures stabilize the system of smaller voids; however, the performance of any given air-entraining agent is affected by a host of factors during the production, transportation and placing of concrete. These factors are discusses in significant detail in Portland Cement Association's Design and Control of Concrete Mixtures.[3]

In an attempt to ensure that concrete used in the construction of pavements and bridges will resist freeze-thaw related damage, the inspecting agency, concrete supplier and contractor must test the concrete being used in the highway project and make necessary changes in the production process to create the proper air void system in the concrete structure. As noted above, commonly used fresh concrete test methods can only measure the total volume of air in concrete, and provide no information about the size and spacing of the air void system. Table 1 lists the currently available air test methods including the Air Void Analyzer (AVA), the property measured, principle used and property reported. Only the AVA and microscopic examination provide information on the spacing factor and specific surface.

Table 1 Tests Methods Commonly Used to Determine the Air Content of Concrete

Test Method		Title	Property Measured	Principle Used	Property Reported
ASTM	AASHTO				
C 231	T 152	Air Content of Freshly Mixed Concrete by the Pressure Method	Pressure change of known volume of air	Gas pressure/ volume	Total air content of concrete sample
C 173	T 196	Air Content of Freshly Mixed Concrete by the Volumetric Method	Volume loss when air is released from sample	Volume loss	Total air content of concrete sample
C 138	T 121	Density, Yield, and Air Content (Gravimetric) of Concrete	Density	Actual and theoretical density compared	Total air content of concrete sample
N/A	T 199	Chase air indicator	Volume loss when air is released from mortar sample	Volume loss	Total air content in mortar/concrete
N/A	N/A	Fresh Concrete Air Void Analyzer	Time rate of air loss from mortar sample	Stoke's Law	Bubble size & spacing, "entrained"air content
C 457	N/A	Microscopically Determination of Parameters of the Air-Void System in Hardened Concrete	Linear measurement or point tally	Statistics	Specific surface, average spacing factor total air content

In view of the uncertainty in knowing if we have a satisfactory air void system, the shortcomings of currently used test methods, and the increasing emphasis on durability, new test methods are needed to measure the air void characteristics of fresh concrete.

A FRESH PERSPECTIVE

In the mid 1980's, researchers in Europe were challenged to improve quality assurance in concrete construction by innovative testing of still plastic concrete. As a part of the BRITE/EURAM research program, Dansk Beton Teknik A/S (DBT) and its partners were tasked with developing a method of qualitative and quantitative determination of the air void structure in fresh concrete. The team's efforts resulted in the development and evaluation of the fresh concrete air void analyzer (AVA). This device can characterize the air void structure (volume, size and spacing) of fresh concrete. Extensive work was performed to validate the AVA by comparing its results with those obtained using the ASTM C 457 microscopical methods.[4] This comparison was very favorable, indicating that the specific surface and spacing factor data from the AVA and ASTM C 457 were within a 95% confidence limit. The slope of the regression line was close to 1, indicating good correlation between test methods.[5] Consequently, it was concluded that the AVA can be used as a quality control tool to ensure the desired air void structure is being produced.

The clear advantage of the AVA is its ability to characterize the air void structure of fresh concrete in less than 30 minutes. With this information, adjustments can be made in the production process during concrete placement to rectify any problems with the air void system, resulting in lesser amounts of deficient concrete being placed. Examples of changes made during the production process that have impacted fresh concrete air void characteristics include; 1) varying mixing time, 2) changing admixture types, dosage rates, or dosing order, and 3) modifying the moisture condition of the aggregates.

Since 1995, the AVA has been used commercially in a number of European countries (Denmark, Sweden, Iceland, Germany, Belgium, Czech Republic, Switzerland, Italy and Spain) as well as in North America and the Far East. Many of the users of the AVA are contractors, admixture manufacturers, research organizations, ready mix producers, and state highway agencies. The FHWA has been actively promoting this technology since 1993. Recently, several state highway agencies have purchased the equipment as well.

HOW DOES THE AVA WORK?

The AVA test is performed on a fresh sample of concrete mortar. The sample can be extracted from a cylinder or beam test specimen, or any in-place horizontal concrete surface such as a pavement or bridge deck. The sample of mortar is extracted using a 20 ml syringe, vibrated into the fresh concrete with a percussion drill (see Figure 2).

Fig. 2 Extracting an AVA Sample from the Pavement Surface

The extracted mortar sample is injected into the bottom of the AVA testing device, a temperature conditioned riser column assembly that contains a layer of analysis liquid under a column of water (see Figure 3). Immediately after injection, a magnetic stirring rod mixes the mortar sample thoroughly with the analysis liquid. Air bubbles in the sample then rise through the liquids towards a buoyancy recorder (inverted petri dish) at the top of the assembly. The analysis liquid has specific properties that ensure the air void system in the fresh mortar is released into it without any modification or distortion. The properties of the liquid allow the air bubbles to retain their original size and prevent coalescence and disintegration of the bubbles. The rate of rise of the bubbles through the liquids is a function of their size, according to Stokes Law. Larger bubbles rise faster than smaller bubbles. The viscosity of the analysis liquid is also such that the rise of the bubbles of varying size is slowed sufficiently to provide a measurable time separation between them before they reach the petri dish. Due to the limitations of the test method, all air bubbles of an average diameter greater than 0.12 in., considered to be entrapped air, are excluded from the results. The change in buoyancy is recorded as a function of time, and based on known batch proportions, the program calculates a “gradation” of air bubbles. From this data the specific surface, average spacing factor and total air content of the concrete are calculated following procedures similar to those used in ASTM C 457.[6] The entire test takes from 20-40 minutes to conduct depending on the fineness of the air void structure. This total time includes sampling the fresh concrete, entering mix proportion data into the AVA software, preparing the sample for injection into the riser column, and running the actual test. The AVA test report includes the total volume of air less than 0.12 in. in average diameter (entrained air), spacing factor and specific surface. Figure 4 shows an example report.

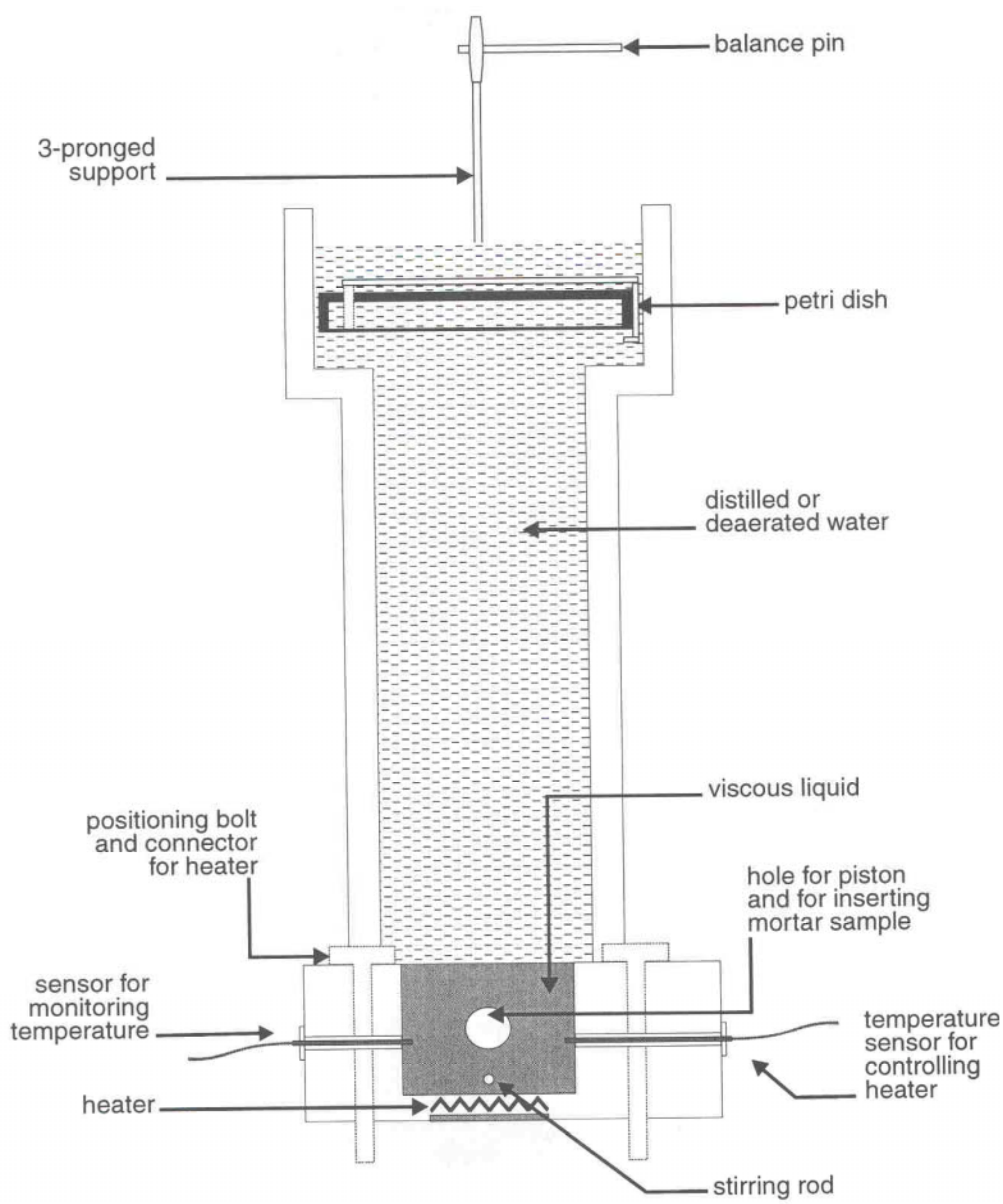

Fig. 3 Schematic of the AVA Test Setup

Measurement of 2002-07-25 13:14

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Sampler         : FHWA
Ordered by      : FHWA
Sample location: Pavement
Case number     : 0205 NC
Sample number   : 02
Mortar <6mm     : 51.1 %          Paste          : 27.9 %
Expected air % :  5.0 %           Sample volume : 20.0 cm3
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Analysis

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Start:0.00g  +5sec:0.10g  +30sec:0.53g  Temp:70.5°F
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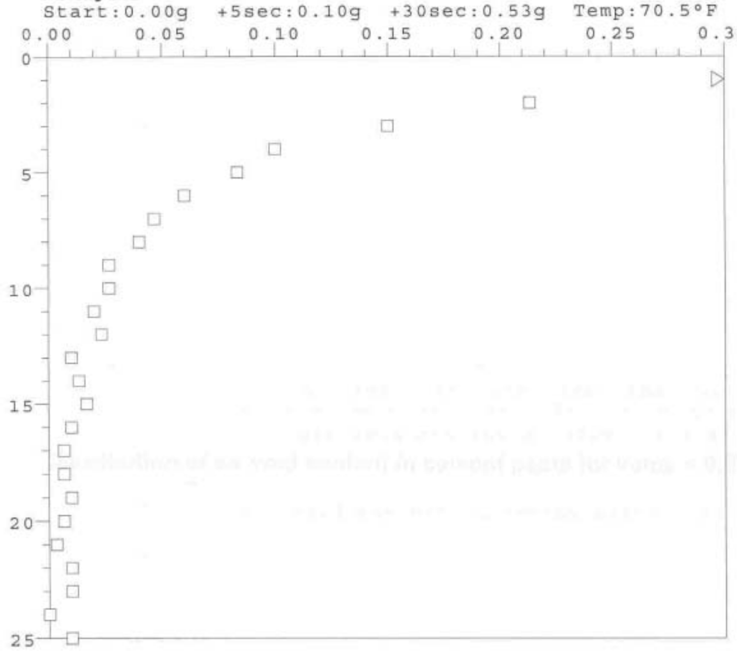

Diff	-15	Min	+15	T/°F
69.7	0.63	0.70	0.76	72.3
21.3	0.87	0.91	0.95	72.5
15.0	1.03	1.06	1.09	72.7
10.0	1.14	1.16	1.18	72.9
8.3	1.23	1.24	1.26	72.9
6.0	1.29	1.30	1.32	73.0
4.7	1.34	1.35	1.36	73.2
4.0	1.38	1.39	1.40	73.4
2.7	1.41	1.42	1.42	73.4
2.7	1.44	1.44	1.45	73.6
2.0	1.46	1.46	1.47	73.8
2.3	1.48	1.49	1.49	73.9
1.0	1.49	1.50	1.50	73.9
1.3	1.51	1.51	1.51	74.1
1.7	1.52	1.53	1.53	74.1
1.0	1.53	1.54	1.54	74.3
0.7	1.54	1.55	1.54	74.3
0.7	1.55	1.55	1.55	74.3
1.0	1.56	1.56	1.56	74.5
0.7	1.57	1.56	1.57	74.5
0.3	1.57	1.57	1.57	74.5
1.0	1.58	1.58	1.58	74.7
1.0	1.59	1.59	1.59	74.7
0.0	1.59	1.59	1.59	74.7
1.0	1.60	1.60	1.60	74.8

Results (adjusted to correlate with ASTM C457)

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Chord length      : < 0.079in.    < 0.014in.
Air-% concrete    :   4.3 %          2.9 %
Air-% paste       : 15.4 %          10.5 %
Air-% putty       : 13.3 %           9.1 %
Specific surface : 914 in.-1
Spacing factor    : 0.0057 in.
```

Fig. 4 Example AVA Test Report

FHWA EXPERIENCE WITH THE AVA

The Federal Highway Administration (FHWA) first purchased an AVA test unit in 1993. The equipment was used on a variety of projects throughout the U.S., including projects in Michigan, Wisconsin, Texas and Iowa. Magura[6] reported results of the initial trials. The report noted that total air content, as measured by the AVA, was typically 2% less than the air content measured by the pressure meter. The spacing factor was consistent with ASTM C 457 results, but the AVA tended to report smaller void sizes when compared to the ASTM C 457 examination. Nevertheless, Magura concluded that the AVA does provide information that characterizes the air void system in fresh concrete. In early 1999, FHWA upgraded the equipment to utilize improved Windows© based software supplied by DBT.

Since upgrading the equipment, FHWA has used the AVA on a variety of field projects in nine different states. Projects have included pavements, precast sheet pile, foundation elements and bridge decks. For six of these projects, accompanying hardened air content tests were also performed. Table 2 summarizes the relevant test results for these projects.

Table 2 Summary of Air Test Results from 9 Projects Since 1999

	Job Specification Limits		ASTM C 231	Air Void Analyzer		ASTM C 457 (MPC)
Test #	Vol. (%)	Sp. Fac. (in/in2)	Vol. (%)	Vol. (%)	Sp. Fac. (in/in2)	Sp. Fac. (in/in2)
1	5.5	0.008	**3.3** *	2.2	**0.009** *	**0.015** *
2	5.5	0.008	5.5	4.9	0.006	**0.012** *
3	5.5	0.008	5.8	4.4	**0.009** *	**0.009** *
4	5.5	0.008	**4.2** *	2.8	**0.013** *	**0.016** *
5	4.5	(0.008)	6.5	4.2	**0.009** *	N/A
6	4.5	(0.008)	6.0	4.9	**0.013** *	N/A
7	5.0	(0.008)	5.9	4.6	0.003	N/A
8	5.0	(0.008)	**4.8** *	5.2	0.004	N/A
9	5.0	(0.008)	5.9	4.0	0.004	N/A
10	5.0	(0.008)	5.5	4.1	0.002	N/A
11	5.5	0.010	9.0	5.5	0.004	0.008
12	5.5	0.010	6.9	3.7	0.005	0.008
13	5.5	0.010	6.6	4.1	0.007	0.008
14	5.5	0.010	N/A	6.9	0.006	0.010
15	5.5	0.010	7.2	3.5	0.006	0.006
16	5.5	0.010	7.2	4.5	0.006	0.008
17	5.5	0.010	6.2	3.0	0.006	**0.017** *
18	5.5	0.010	7.2	4.6	0.005	0.006
19	5.5	0.010	7.2	4.9	0.006	0.005
20	5.5	0.010	7.2	7.1	0.003	0.008
21	5.5	0.010	9.5	6.6	0.004	0.005
22	3.0	(0.008)	N/A	2.2	**0.011** *	**0.010** *
23	3.0	(0.008)	4.8	2.2	**0.015** *	**0.009** *
24	5.0	(0.008)	6.6	2.5	**0.012** *	**0.012** *
25	3.5	(0.008)	**3.1** *	1.2	**0.022** *	**0.020** *
26	3.5	(0.008)	5.0	4.3	0.006	**0.016** *
27	3.5	(0.008)	5.0	2.7	**0.013** *	**0.018** *
28	3.5	(0.008)	**3.3** *	1.5	**0.017** *	**0.020** *
29	3.5	(0.008)	**3.3** *	0.8	**0.021** *	**0.017** *
30	3.5	(0.008)	4.6	1.7	**0.012** *	**0.017** *
31	3.5	(0.008)	4.6	2.1	**0.015** *	**0.018** *
32	3.5	(0.008)	4.8	2.4	**0.009** *	**0.012** *
33	5.5	(0.008)	7.0	1.7	0.008	**0.011** *
34	5.5	(0.008)	7.0	1.6	**0.009** *	**0.010** *
Average Values			5.8	3.6	0.0094	0.0118
# of tests failing job spec. limits			6	N/A	16	18

Note: Sp. Fac. in parenthesis are taken from ASTM C 457, as no limit was specified in project specs
* Test result did not meet job specification limits

Data in the table show that, on average, the AVA reports an air content approximately 2% less than the pressure meter (ASTM C 231). This is similar to Magura's findings and can be accounted for by the fact that the AVA does not include large air voids in its results. The large voids, generally referred to as entrapped air, typically correspond to about 1.5 to 2.5% of the volume of concrete, depending on the aggregate size. Table

6.3.3 in ACI 211.1R illustrate the relationship between amount of entrapped air in concrete and nominal maximum aggregate size.[7]

Specific surface results (not detailed in Table 2) indicate that, on average, the AVA measures a smaller air void system than the ASTM C 457 method. The difference however is not significant, but the results agree with those reported by Magura.

The difference in observed spacing factor between the AVA and ASTM C 457 test is, on average, 0.0024 in. This average difference is relatively small, and falls well within the range of average between-lab precision for two test results reported in ASTM C 457. In fact, AVA results showed spacing factors outside generally accepted limits (upper limit taken as 0.008 in. unless otherwise noted) for 14 of the 18 samples where ASTM C 457 reported unacceptable spacing factors. In this respect, the two methods seem to measure the same thing. However, the high range in the difference in AVA and ASTM C 457 determined spacing factors (0.0037 in.) does raise concern about the accuracy of the methods. It is impossible to discern from this data set whether this variability is a result of AVA testing factors or ASTM C 457 testing factors. Recent FHWA experience with ASTM C 457 testing indicate a within and between lab variability exceeding that suggested in the test method's precision and bias statement. In one case, spacing factors for the same specimen reported by one laboratory was 80% greater than that reported by another. In light of these observations, it may be more appropriate to evaluate the AVA results using other durability indicators instead, such as laboratory freeze-thaw performance (ASTM C 666).

It is also noteworthy that in 9 of the 14 cases where the concrete did not meet generally accepted durability criteria limits based <u>both</u> upon deficient AVA and deficient ASTM C 457 spacing factor results, the concrete did meet total air volume requirements based upon pressure meter tests (ASTM C 231). This means that in approximately 65% of the cases where a deficient concrete was delivered, it was deemed adequate by the current test practice. Likewise, while pressure meter results failed to meet specified limits only 18% of the time, AVA/ASTM C 457 results did not meet recommended criteria in nearly 50% of cases. This clearly suggests a potential problem with our current test practice. Moreover, based on this limited set of data, it appears that a significant quantity of concrete with inadequate frost resistance is currently being placed in the United States. Implementing the use of the AVA can therefore significantly improve the quality of concrete placed in the United States from a freeze-thaw perspective.

Based upon this recent FHWA experience with the AVA, the main conclusion drawn in Magura's 1996 report remains valid: The AVA does provide information that characterizes the air void system in fresh concrete.

Several state highway agencies have implemented the use of the AVA. Kansas Department of Transportation has developed a specification for acceptance of highway paving concrete.[8] Also, the American Association of State Highway and Transportation Officials (AASHTO) has included the AVA as a focus technology in its 2002 Technology Implementation Group (TIG) program. The TIG has been tasked with providing leadership and technical assistance to promote implementation of the AVA technology over the next two years. More information on the TIG's activities can be found on the AASHTO website, www.aashtotig.org.

CONCLUSIONS

Current techniques for determining the air void characteristics of fresh concrete are inadequate to ensure durable, high quality concrete for long-life transportation infrastructure. FHWA field experience confirms the ability of the AVA to detect substandard air void systems with an accuracy comparable to that of ASTM C 457 results. The primary benefit of the AVA is that it measures the air content, spacing factor and specific surface of fresh concrete in about ½ hour, allowing for the timely detection of concrete that will not be resistant to freeze/thaw cycles. It allows adjustment to the production process to minimize the delivery of fresh concrete with a deficient air void structure. For the traveling public to get the durable high quality infrastructure they deserve, the AVA or similar technologies that provide real-time information about the quality of the air void structure should be implemented.

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