A ROUND ROBIN TEST ON MEASUREMENTS OF AIR VOID PARAMETERS IN HARDENED CONCRETE BY VARIOUS AUTOMATED IMAGE ANALYSES AND ASTM C 457 METHODS

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ABSTRACT

A systematic round robin study of five carefully prepared hardened concrete samples, having air contents from 2 to 10 percent was done by using four different automated image analysis techniques and the conventional ASTM C 457 method to compare the results obtained between various image analysis methods, and their variations compared to the average results from the C 457 method. The techniques used include image analysis of: (a) lapped sections of concretes as prepared for the C 457 tests, and (b) lapped sections treated with a black-and-white contrast enhancement step to highlight the air voids against the rest. All methods produced results of air void parameters that are more or less consistent with each other with expected reasonable between-method variability, and good agreements with the C 457 tests. This study demonstrates the ability and applicability of all these modern image analysis methods in rapid air void measurements of hardened concrete and particularly in rapid evaluation of freeze-thaw durability concrete at a fraction of time, with minimum operator-dependency, and with good reproducibility. All these image analysis methods have high potential for accurate assessment of air void spacing factor, the most important parameter for freeze-thaw durability, in concrete quality control and failure investigation.

INTRODUCTION

Air voids are essential for durability of concrete in a cyclic freezing and thawing environment. Accurate measurements of air void parameters are therefore necessary for evaluating performance and durability of concrete in an outdoor environment. A variety of standard methods are used for measuring: (a) the total air content in freshly placed concrete in the plastic state such as the ASTM C 173 [1] volumetric method and ASTM C 231 [2] pressure method, and (b) air void parameters (air content, void frequency, specific surface, and void spacing factor) in hardened concrete by the linear traverse and modified point count microscopical methods of ASTM C 457 [3]. A wealth of literature is available on correlations or lack of correlations between air void measurements in plastic and hardened concretes [4, 5]. Similar encyclopedic research and round robin studies have been done on repeatability, accuracy, and precision of conventional hardened air measurements (ASTM C 457) between various operators and laboratories [6, 7].

Over the last three decades, a plethora of new techniques became available, which have not only reduced the measurement time and influences of operator-dependency significantly, but also demonstrated their suitability, ease of operations, and superiority by comparing results obtained by these methods with the conventional methods, as well as their precision, accuracy, and repeatability by numerous inter and intra-laboratory comparisons [8-21]. Notable among these techniques are the Air Void Analyzer (AVA) for measuring air void parameters in plastic concrete [8, 9], automated and semi-automated image analyses methods for measuring air void parameters in hardened concrete [10-20], and CT scan for measuring air void parameters in both fresh and hardened concrete [21]. The AVA and various image analysis methods have been extensively researched and in practice by isolated researchers or agencies for two to three decades as popular alternatives recommending their potential, and need or consideration for standardization. Despite the long use in medical science, CT scan is a relatively fresh new perspective on the air void analysis. A brief description of these techniques is given below:

(a) The Air Void Analyzer (AVA), or the Danish air test, measures air void parameters in plastic concrete. The instrument, originally developed in the mid 1980s by the European firm Dansk Beton Teknik A/S (DBT) measures changes in buoyancy using a special buoyancy recorder that captures air bubbles as they rise from the concrete, through a viscous liquid and finally through water to the recorder. The viscous liquid retains the original air bubble sizes. The larger bubbles rise faster than smaller ones; therefore, monitoring the change in buoyancy as a function of time allows for determination of the air void size distribution, total air content, void spacing factor, and specific surface.

(b) A variety of automated and semi-automated image analysis methods on hardened concrete involve digital imaging of a lapped section of concrete with a high resolution flatbed scanner [12, 13], a CCD camera [11, 15-18], or electron micrograph [19], where the section to be examined is treated to highlight air voids as white or bright areas against a black background of aggregates and paste. The flatbed scanner method developed by Michigan Technological University [12, 13] and the RapidAir 457 method developed by researchers at the Concrete Experts International [11] used in this study are some examples of such methods. In both methods lapped sections of concrete, as prepared for the ASTM C 457 test are darkened by ink or marker pen and air voids are highlighted by filling with white powder or paste (of wollastonite, barium sulfate, gypsum, alumina, titanium oxide, etc.); the binary images thus captured are used by computer-based image analysis softwares for calculating air void parameters. Details of two such methods used in this study are described by the respective developers later.

(c) A relatively new variety of automated image analysis methods on hardened concrete involve automated digital imaging of a lapped concrete section similar to that prepared for the conventional ASTM C 457 test, but without any black-and-white contrast enhancement. Examples include the automated concrete evaluation system (ACES, [14]) as developed by the Missouri Department of Transportation (MoDOT) and the National Nuclear Security Administration-Kansas City Plant (NNSA-KCP), and the HF-MAC01 device developed by the Hachiyo Consultant Co., Ltd. and Fast Corporation in Japan. Brief descriptions of these methods are included in this article by the inventors.

(d) The application of high-resolution industrial CT x-ray scans to measure air void parameters in three dimensions uses small diameter samples of fresh or hardened concrete scanned at resolutions of up to 10 micron [21]. The technique produces multiple two-dimensional x-ray images of cross sections or slices (tomographs) through the sample, stacked one on top of another to create a dataset of three dimensional representation of the sample showing the spatial distribution of aggregates, paste, and air voids. Details of this method are provided in Wiese et al. [21].

All these modern technologies for air void measurements have produced results with proven close correspondence to the conventional methods with the added benefits of time, ease of operation, less dependency on the judgment of the operator during the test, accuracy, precision, and repeatability in the results obtained. Ever since the first implementation of image analysis to analyze air void parameters in hardened concrete by Chatterji and Gudmundsson in 1977 [10], about a dozen different automated and semi-automated image analysis methods were developed to address the inherent difficulties and limitations associated with the human-operator based ASTM C 457 method [8-20]. Additionally, some methods also showed correspondence to the other new methods (such as correlations of the results obtained from the flatbed scanner and RapidAir 457 methods) on the same set of samples.

PURPOSE OF THIS ROUND ROBIN STUDY

The present round robin test is an attempt to compare results from four different automated image analysis techniques with the conventional, operator-based air measurement in ASTM C 457 on the same set of five hardened concrete cylinders carefully prepared with varying dosages of air entraining chemicals to stabilize a wide range of air contents from as low as 2 percent to as high as 10 percent. The results of automated image analysis methods are compared against the "average" results of ASTM C 457 tests from two laboratories. Instead of comparing individual results of ASTM C 457 measurements, the "average" values taken as reference are used to compare relative variability in air void parameters of the same concrete among the four different image analysis methods.

Researchers of the individual image analysis methods described here have done extensive studies on the accuracy, precision, and repeatability of their method, and correlations to the C 457 methods. Their results have already been published in numerous publications, a few of which are mentioned in the reference section.

The intention of this round robin study is NOT to evaluate the following:

(a) Whether or not one method is better than the other, or correlate well with others;
(b) Accuracy, precision, repeatability (within-laboratory precision), and reproducibility of a particular image analysis method;
(c) Intra and Inter-laboratory agreements between an individual image analysis method and the manual ASTM C 457 method;

(d) Accuracy and precision of results of ASTM C 457 method obtained by different operators/laboratories on the same cylinder, or different sections of the same cylinder by different operators;
(e) Variability in results obtained from same examined surface, by different methods or operators;
(f) Influence of sample preparation techniques (i.e., black and white contrast) for individual methods on the results (after all samples being lapped in an identical manner);
(g) Influence of any inherent heterogeneity in the sample on variability of results among different image analysis methods on the same sample. Any possible heterogeneity in air void parameters across a cylinder was attempted to be kept at a minimum by preparing all samples at the same time, with the same materials and proportions, in similar manner, by following the mixing and sample preparation procedures of ASTM C 192. The issue of sample homogeneity is further verified by ASTM C 457 tests on parallel sections of two cylinders.

The intention of this round robin study is to verify the following:
(a) The degree of consistency (or inconsistency) that exists in results obtained from different image analysis methods by circulating a same set of samples (i.e., parallel sections of same set of cylinders) to all parties and comparing their results with the "average" results of manual ASTM C 457 method (operated on the same set of samples by two laboratories) as the reference;
(b) Based on the observed agreement (or disagreement, if any) of all image analysis methods in general to the ASTM C 457 method, a suggestion to incorporate image analysis methods as suitable "alternatives" to the time-consuming manual method, at least for the overall evaluation of the air void spacing factor, apparently the most critical air void parameter for freeze-thaw durability;
(c) Whether or not results of any particular method show closer correspondence in all air void parameters than others to the corresponding average result obtained from the C 457 method;
(d) Whether or not the overall air void system and approximate air content of a concrete is consistently determined by all available methods with a reasonable degree of accuracy (which may not necessarily be in conformance to the level of accuracy desired in ASTM C 457 for the "single" manual method used by different operators/laboratories);
(e) Whether or not freeze-thaw durability of concrete (as evaluated by the air void spacing factor) can be positively diagnosed for a particular set of samples by all methods.

CONCRETE MATERIALS AND MIXTURE PROPORTIONS

Table 1 provides the mix design used for preparing five 4 × 8 in. (100 × 200 mm) concrete cylinders. All cylinders were prepared at the same time by using the same concrete ingredients but with different dosages of air entraining agents (AEA). The following paragraphs summarize the materials, proportioning, and strategies for designing the concrete mixtures:

(a) Five concrete cylinders, identified as Nos. 1 through 5 were prepared by using identical proportions of crushed limestone coarse aggregate (1009 Kg/m^3), natural siliceous sand fine aggregate (634 Kg/m^3), ASTM C 150 Type I portland cement (377 Kg/m^3), and water-cement ratios (0.47), but variable dosages of AEAs to stabilize variable plastic air contents at approximately 2, 4, 6, 8, and 10 percent levels;

(b) Four out of five mixtures contain the AEA – Samples 1, 2, 4, and 5 are the air-entrained mixtures and Sample No. 3 is the non-air-entrained mixture. Therefore, the five cylinders can be classified into three groups as follows:
   - Group I - Dosages of AEA in the mixtures of Samples 1 and 5 were so chosen to have high air contents (i.e., 8 and 10 percent, respectively) and good air void systems;
   - Group II - Dosages of AEA in the mixtures of Samples 2 and 4 were so chosen to have normal air contents commonly specified in many designs (i.e., 6 and 4 percent air in No. 2 and 4, respectively);
   - Group III - No AEA was added in the mixture of Sample 3 to have a non-air-entrained mixture.

Results of the measurements taken on the plastic concrete for unit weight, temperature, slump, yield, and air contents are given in Table 1. Air contents of plastic concrete are measured by the ASTM C 231 pressure method. Slump, unit weight/yield, and temperature were measured by following ASTM C 143 [22], C 138 [23], and C 1064 [24] methods.

SAMPLING STRATEGY AND SAMPLE PREPARATION

All cylinders were cast and prepared by following the procedures mentioned in ASTM C 192 [25], and kept in a moist-curing room for 28 days. Each cylinder was then sectioned in the CMC Laboratory by a thin, water-cooled, continuous rim diamond saw (250 mm diameter, 16 mm arbor, ~1 mm thickness) into four longitudinal slabs as shown in Figure 1. All six sectioned surfaces from each cylinder (i.e., four surfaces from the two middle slabs and two surfaces from the two end slabs) were ground to smooth, flat sections by successively grinding the saw-cut surfaces on a horizontal 450 mm diameter cast iron lapping wheel in a floor-standing lapping machine and using 240 and 400 grit metal-bonded diamond discs, followed by 600 and 1200 grit resin-bonded diamond discs and tap water as lubricant. Prior to grinding in a finer-size diamond disc, the surfaces were thoroughly cleaned with a water jet to remove the debris left over from the previous coarse grinding operations. Air voids on the final prepared surfaces are sharp and distinct with continuous margins and can clearly be distinguished in a stereo microscope at a low-angle incident illumination. Figure 2 shows the appearances of the lapped sections as prepared and sent to the participants of the round robin test.

<u>Surfaces for the Automated Image Analysis Methods</u> – The two middle slabs from each cylinder thus prepared were sent to four different parties for air void analyses by automated image analysis methods. One slab per cylinder was sent to RJ Lee and Michigan Technological University for image analyses by using the black-and-white contrast enhancement methods where both parties used their own method of contrast enhancement on the opposite lapped surfaces of the slab. The other slab was sent to Fast Corporation in Japan and NNSA-KCP where the surfaces as prepared by CMC were used directly with no additional surface preparation. Details of their image analysis methods are published elsewhere [11-14]. A brief summary of these methods and their relevant references are given in the next section.

<u>Surfaces for the C 457 Method</u> – For each cylinder, two parallel sections were used for the modified point count method of ASTM C 457 – one of these two sections was analyzed by CMC on a slab that was not circulated. The other section was the surface sent to Michigan Technological University, which they analyzed first by the C 457 modified point count method and then by the image analysis method. For Cylinder No. 4 and 5, all six sections of each cylinder were used for C 457 test in the CMC to check any possible sample heterogeneity.

DESCRIPTIONS OF THE MANUAL (ASTM C 457) AND IMAGE ANALYSIS METHODS USED IN THIS STUDY

The ASTM C 457 Method

The ASTM C 457 linear traverse and modified point count methods, developed in the late 1970s on the basis of the original works by Brown and Pierson [26], Verbeck [27], and Chayes [28] are the most common and conventional (human operator-based) method of air void measurements in hardened concrete by using an optical microscope. Details of the test methods are given in ASTM C 457 [3] and Hover [29].

All five concrete cylinders were analyzed by the modified point count method of ASTM C 457. In the CMC laboratory a research grade stereo microscope equipped with a high-resolution color CCD camera, and an LCD screen were used along with an automated stepper control motor based precision x-y stage (Unislide) developed by Velmex, Inc. Automated stage/sample movements were guided by the 'Cosmos' software developed by Velmex, Inc. Air void measurements were recorded during the stage movement, and air void parameters were calculated at the end of each traverse by a Dell Dimension PC (Intel Pentium 4, 2.0 GHz, 1 GB RAM) running on Windows XP Professional platform. An Epic, Inc. frame grabber captured the CCD camera images of the scanned surfaces where air voids were highlighted by very shallow angle illuminations. Figure 3 shows the photomicrographs of air void systems in five cylinders on the sections used for the C 457 method in the CMC Laboratory. Figure 4 shows the instrument setup for the C 457 test.

In the laboratory of Michigan Technological University, the modified point count measurements (Figure 5) were carried out in an Olympus SZH10 stereo microscope equipped with an Optronics LX-750 camera, a Scion CG-7 frame grabber, and a Prior H128 motorized stage, all connected to a Power Macintosh 9600 PC (300 MHz, 64 MB RAM, Mac 9.0 OS) and controlled by a macro written for NIH Image 1.63, a public domain image analysis program developed by the National Institutes of Health (Sutter [30]).

Image Analysis Methods

(a) The Flatbed Scanner Method (Provided by Karl W. Peterson; for details see References [12, 13])

The flatbed scanner method works on the principle of contrast enhancement where non-air portions of the surface appear black and air voids appear white (Chatterji, S., Gudmundsson, H. [4]). Prior to scanning a sample, 8 stickers (Designery Sign Co. Prismatic Mosaic Decals) are placed along the perimeter of the polished surface (Figures 6 and 8). The stickers serve multiple purposes. First, they prevent the surface from resting directly on the glass plate of the scanner to avoid scratches. Second, they provide bright end-points in the scanned image to maintain constant brightness from sample to sample. Contrast enhancement is achieved by drawing overlapping parallel lines with a wide-tipped black marker. After the ink dries, a few tablespoons of 2 micrometer white powder (NYCO Minerals Inc. NYAD 1250 $CaSiO_3$) are worked into the surface using the flat face of a glass slide. A razor blade is used to scrape away excess powder, leaving behind powder pressed into voids. Residual powder is removed by wiping with a clean lightly oiled fingertip. A fine-tipped black marker is used to darken voids in aggregates. An 8-bit grayscale, 3,175 dpi (125 dpm) image is collected with a Microtek ScanMaker s400 flatbed scanner connected to a PC (1.73 GHz, 2 GB RAM, Windows XP OS). Automatic image correction and filtering options in the Microtek ScanWizard 5 software are deactivated. When collecting an image, care is taken to include the stickers, as well as some blank space outside the perimeter of the slab. The blank space provides uniform dark end-points in the scanned image from sample to sample. Scan time is 10 min. per sample. A Visual Basic script is used to collect sample identification information, paste content can be input directly or automatically computed based on mix design. The script uses Adobe Photoshop CS to select an area on the image, to apply a threshold, and to extract traverse lines. The script uses Microsoft Excel and Word to perform air void calculations and to generate reports according to ASTM C 457. Computation time depends on the total traverse line length. For example, a 3 m traverse (a typical total analysis length) takes 5 minutes. An optimum threshold level of 140 has been determined for the Microtek ScanMaker s400. Pixels with intensities < 140 are classified as non-air, pixels with intensities > or = to 140 are classified as air. An optimum threshold level can be determined for any flatbed scanner system using a set of standards representing a variety of air void contents and size distributions. Two methods of threshold determination have been tested with similar results. For the first method, images are collected from the standards, the threshold is automatically stepped from 0-255, and air void parameters are computed at each step. A spreadsheet is used to compare the automatic parameters to manually determined parameters from the standards, and a threshold is selected to minimize the deviation from unity. For the second method, RSI ENVI 4.0 image processing software is used to align the scanned images to the coordinate system used during manual point counts. A spreadsheet is used to compare the identities of the coordinates from the manual point count (air or non-air) to the identities of the corresponding pixels in the scanned images as the threshold is stepped from 0 - 255. A threshold level is selected to maximize the Kappa statistic, a measure of the total agreement between the data sets, minus the chance agreement (Fung, T, LeDrew, E. [31]).

Figure 9 shows photomicrographs of air void systems from small areas of concrete surface as captured by using a stereomicroscope, the corresponding black-and-white contrast enhanced image from the flatbed scanner, and the binary threshold image used for air void calculations.

(b) The RapidAir 457 Method (Excerpt from the website of Concrete Experts International, with permission, for details see Reference [11])

The RapidAir 457 Automated-Air-Void-Analyzer instrument is an automated measuring system for analyzing the air content, and distribution in hardened concrete, which is of importance when evaluating the freeze-thaw resistance of concrete. The system can replace the manual tests performed as described in the ASTM designation C 457: "Standard Test Method for Microscopical Determination of Parameters of the Air Void System in Hardened Concrete, procedures A and B," or the test performed according to EN 480-11 "Determination of air void characteristics in hardened concrete" [32]. Both methods include specifications for grinding, and polishing a plane section of concrete, and for measuring the air void distribution with the use of a microscope according to the linear traverse method. A standard manual test will normally require 4 - 6 hours for a trained technician operating the microscope. The analysis time required with RapidAir 457 Automated-Air-Void-Analyzer is 15 minutes for the linear traverse analysis, 30 minutes for the modified point count and is performed automatically with no operator interference.

The RapidAir 457 Automated-Air-Void-Analyzer test equipment comprises a computerized control unit (PC) with a 19'' color monitor, a video camera, and a microscope objective mounted on a moving stage, and a user-friendly analysis software operating in MS-Windows environment designed to guide the user smoothly through the test (Figure 6).

Following the traditional grinding, and polishing steps of ASTM C 457, a contrast enhancing technique (described in EN 480-11) is used to obtain a surface of the concrete plane section where air voids are bright white, and the rest of the surface is black. Such a surface facilitates maximum precision, and identification of all air voids present in the concrete. The time needed to perform a contrast enhancement is usually not longer than 5 minutes and maximum 30 minutes. Another advantage of the RapidAir 457 Automated-Air-Void-Analyzer instrument is that it eliminates the need for "split second" human judgment during the analysis since all preparation defects are considered during the contrast enhancement procedure.

Figure 8 shows the appearances of the lapped sections of two concrete cylinders from this study after black-and-white contrast enhancement by the flatbed scanner and RapidAir 457 methods.

Following the contrast enhancement, the plane section is mounted onto the moving stage placed under the video camera. The control unit now moves the stage automatically, and the air void distribution is determined from a scan of typically 1870 areas located throughout the plane section. After scanning, the air void parameters are immediately calculated by the software, and a test report with information of air content, specific surface area, and spacing factor can be printed using the software's report generator. The raw data can also be saved in a file, and subsequently imported into spreadsheet software to perform additional user-specific analyses.

(c) The HF-MAC01 Equipment (Excerpt from the website of Fast Corporation, with permission)

HF-MAC01 is an automatic measurement device for hardened concrete, co-developed by Hachiyo Consultant Co., Ltd. and FAST Corporation.

Measurement methods for air void systems in hardened concrete are stipulated in detail in the ASTM C 457-98 "Standard Test method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." However, a visual inspection based on these measurement methods using microscopes requires a lot of time and work, and the measurement results are affected both by the level of inspectors' skill and by human error. Commercially available automatic measurement devices require special preprocessing of measured surfaces for image processing.

HF-MAC01 is a device (Figure 7) based on linear traverse methods in accordance with ASTM C 457, with high accuracy and high-speed measurements, while having solved the problems above. HF-MAC01 processes images by focusing on the differences in shadowed areas when a sample is subjected to light at various angles. This method does not require special preprocessing of measured surfaces (such as resin implants, etc) for image processing, and needs only standard abrasive processing. The basic measurement principle identifies air-voids by an addition and subtraction process using digitalized images, and converting the data into a binary image for use in the linear traverse method.

Benefits of this method include: (a) automated measurements linear traverse methods in accordance with ASTM C 475; (b) measurement is hundred times faster than conventional visual inspection. (It takes only 2 to 3 minutes); (c) highly accurate and offers consistent results; (d) capable of identifying air voids and entrapped air in aggregates; (e) no need to preprocess target surfaces for image analysis; (f) measurements using area methods are also available; (g) outputs the analysis results in real time; (h) capable of storing digital images of the sample; and (i) data outputs in CSV format.

(d) The ACE System (Provided by Chris W. Baumgart; for details see Reference [14])

Since 1998, the Missouri Department of Transportation (MoDOT) has collaborated with the National Nuclear Security Administration-Kansas City Plant (NNSA-KCP), a government contractor for the U.S. Department of Energy, to develop a fully automated system capable of reliably analyzing hardened concrete in accordance with ASTM C 457 using the linear traverse method. This effort was accomplished in early 2005 resulting in a prototype system specifically designed to analyze a sample of hardened concrete in accordance with ASTM C 457's linear traverse method. This system, called ACE for Automated Concrete Evaluation, includes both hardware components for image acquisition and customized software for image analysis and component identification.

The ACE system uses a high precision, two-dimensional computer-controlled stage to move the concrete sample under a research grade microscope (Figure 7). The image acquisition system consists of a digital color CCD camera, a fire wire digital image acquisition interface, and a 3.2 GHz tower PC. Customized image processing and pattern recognition software has been developed to identify air voids and extract void characteristics. Currently, the system is capable of identifying air voids as small as 5 microns in size. Extracted concrete component characteristics are used to calculate the concrete microscopical properties of interest in accordance with ASTM C 457. All system components are linked via a graphical user interface that aids the operator in the data acquisition, image analysis, and reporting processes.

The ACE system is designed to automatically scan and acquire imagery of a concrete sample. The acquired imagery is then stored on the analysis computer and may be written to a DVD. This latter option allows the acquired imagery to be transferred to another computer for automated analysis. In this way, a single computer workstation may be dedicated to the sample scanning and image acquisition process, while previously acquired imagery can be transferred to and processed on any other available computer.

Given the variability which is recognized to exist in manually-derived ASTM C 457 linear traverse results, the ACE-derived results fall reasonably well within this variability and are comparable to the ASTM C 457 results. The ACE image acquisition and analysis process requires 7 - 8 hours of computer time, but only 10 - 20 minutes for the operator to mount the sample and set all scan parameters. As such, a major savings in labor time is realized through the use of the ACE system. While the ACE scanning and image acquisition processes require a dedicated computer, the analysis of the archived imagery can be performed on any computer. The repeatability, accuracy, and overall assessment quality of the ACE system in conducting the ASTM C 457 linear traverse method are comparable to results obtained by manually (human-based) conducting ASTM C 457 linear traverse method.

RESULTS

Table 2 and Figures 10 through 15 provide detailed results of air void parameters of five cylinders obtained by four different automated image analysis methods and the ASTM C 457 method. In all figures, the results of ASTM C 457 test represent the "average" value of all results obtained by CMC and Michigan Technological University. In a later section, discussion will be made on the sample homogeneity and any possible variability in air void parameters among different parallel sections of the same cylinder as measured by the C 457 method.

Air Content – Based on evaluation of air content measurements in plastic concrete, in hardened concrete by four automated image analysis methods, and by the ASTM C 457 method, the following comments can be made:

(a) Air contents from all image analysis methods show good overall agreement to the results obtained in the plastic concrete and by C 457. Figures 10 and 15 show comparison of air contents obtained by various image analysis methods and C 457.

(b) The standard deviation of air content results increases with increasing total air content in the cylinder. Therefore, variability in air content results among different image analysis methods, and between image analysis methods and plastic air measurement are less for the non-air-entrained cylinder and increases with increasing air contents in the cylinders. The standard deviation is highest for the cylinder having the maximum air content.

(c) For each cylinder (i.e., air content), the two black-and-white contrast enhancement methods (B/W) gave higher air contents than the methods that did not use any additional sample preparation. The difference in air contents between the B/W contrast versus non-contrast based image analysis methods increases with increasing air content in the cylinder. For the non-air-entrained cylinder, the B/W methods (i.e., the average air contents of RJ Lee and Michigan Technological University) gave about 1 percent point higher air content than the non-B/W methods (i.e., the average of Fast Corp. and MoDOT/NNSA-KCP air contents) whereas for the Cylinder having the highest air content, the B/W-methods gave more than 5 percent points higher air content than the non-B/W methods. Therefore, the B/W contrast enhancement seems to give a higher estimation of air content than the image analysis methods that do not use such an additional surface preparation.

(d) Similar higher estimation of air content between B/W image analysis methods and ASTM C 457 method have been previously reported in many references of the followers of B/W methods. The present study shows higher estimation of average air contents of two B/W methods compared to the average air contents from C 457 on all five cylinders as well (or, lower estimation of air in all results compared to that of B/W methods). The ASTM C 457 results are somewhere in between the results obtained from B/W and non-B/W methods. The possible reasons for such variability have been discussed in various references of B/W methods where higher air contents compared to the C 457 results have been explained by reasoning such as sample heterogeneity (i.e., actual high air contents on the surfaces used for contrast enhancement), calculation of fine air bubbles in image analysis that were not measured in the C 457 test, calculation of voids in the aggregates that have not been darkened, difference in accuracy of computer and human based interpretations of air voids, etc. Based on the present round robin study, a systematic difference (and an increase in difference with increasing absolute air content of concrete) in air results exists between B/W and non-B/W image analysis, and between B/W and C 457 results where the B/W methods consistently gave higher air contents for all five cylinders than the non-B/W image analysis methods[1]. The difference, however, as reported can be minimized by careful choice of the threshold values in the B/W methods.

(e) Air contents of all five cylinders measured by C 457 show closer correspondence to the plastic air contents than the overall image analysis methods. Among the image analysis methods, the non-B/W methods show closer correspondence to the plastic air than the B/W methods [an exception to this generalization is the low air content value (6.6 percent) obtained by the ACE method in the highest air cylinder where general air contents range from 10 to 13 percent by all other methods].

<u>Void Frequency</u> – Figures 11 and 15 show comparison of air void frequency results obtained by various image analysis methods and C 457. The following statements are valid for evaluating air void frequency results obtained by all methods:

(a) Compared to the air content, results on air void frequency show tighter correspondence among various image analysis methods for cylinders having air contents from 2 to 8 percent and closer match to the corresponding C 457 methods. For all five cylinders, results from the Fast Corporation (non B/W method) are the lowest, the results from the RapidAir (B/W method) are the highest, and the results from other methods, including C 457 are somewhere in between.

(b) Since air void frequency (i.e., number of bubbles per unit length) is a better measure of concrete durability than the air content (i.e., volume), a better correspondence of image analysis results to C 457 of this parameter than the air content is encouraging for use of these methods in predicting freeze-thaw durability of concrete. All methods have

[1] Addition by Karl W. Peterson – "Even when utmost care is taken during surface preparation, there is some degree of erosion along the edges of air voids intersected by the plane surface. When observed with low-angle incident illumination, the appearance of minor edge erosion is subtle. Eroded edges at a slight incline with respect to the plane surface, when illuminated, appear similar in brightness to the plane surface, and in sharp contrast to the dark shadow cast into the air void. The human eye can easily extrapolate the location of the air void edge based on shadow. During contrast enhancement the deep cavity of an exposed air void is completely filled with white powder, along with the shallow region along the eroded edge. Since the white powder defines the edge of the air void, as opposed to the shadow, the air void appears dilated after contrast enhancement."

effectively differentiated the three concrete groups of non-air-entrained concrete, marginally air-entrained concrete, and excessively air-entrained concrete having low (< 0.15 void/mm), medium (0.15 - 0.30 void/mm), and high (> 0.30 void/mm) void frequencies, respectively.

(c) More importantly, both B/W and non-B/W image analysis methods can effectively differentiate concretes having marginal air void systems (having questionable durability) from those having a good air void system with high void frequency and good durability.

Specific Surface – Figures 12 and 15 show the results of specific surface obtained from all methods. The following statements are in line with the previous statements on void frequency:

(a) Consistent with the trend observed for the void frequency, since specific surface is directly related to the air void frequency, for all five cylinders, results from the Fast Corp (non-B/W method) are the lowest, RapidAir (B/W method) are the highest, and other methods, including C 457 are somewhere in between.
(b) The standard deviations between different image analysis methods are more or less consistent in all cylinders and independent of air content in concrete.
(c) As shown in Figure 15, for all cylinders the flatbed scanner method shows closer correspondence to the average C 457 results than the other methods.
(d) Irrespective of such reasonable inter-method variability, all image analysis methods studied can effectively differentiate concretes having a good air void system with high specific surface (i.e., Cylinder Nos. 1 and 5 having specific surfaces of > 20 mm^2/mm^3), marginal air void system with intermediate specific surfaces, and non-air-entrained concrete with low specific surfaces.

Void-Spacing Factor – Since air void spacing factor is the most important parameter for evaluating freeze-thaw durability of concrete, a close correspondence of results of this parameter among various image analysis methods and C 457 is essential for widespread acceptance of image analysis methods for fast and reliable indication of freeze-thaw durability of concrete.

(a) All methods in this study have demonstrated the capability of distinguishing concretes having poor, marginal, or good durability. Figures 13 and 14 show the lowest void spacing results (< 0.2 mm) by almost all methods for the cylinders having intended air contents of 8 and 10 percent, intermediate spacing factors (0.2 - 0.6 mm) for Cylinders 2 and 4 having 8 and 6 percent intended air, and highest spacing factor for the Cylinder 3 having non-air-entrained concrete.
(b) Among all the methods studied, the Fast Corp. method gave the highest void spacing factors for all cylinders and the RapidAir method produced the lowest results; the flatbed scanner and ACE methods produced results in close agreement to the C 457 method.
(c) As shown in Figure 15, for air-entrained concretes the flatbed scanner method showed the closet correspondence to the C 457 method. For all other methods the deviation from the 1:1 image analysis-versus-C 457 correspondence line increase with decreasing air content.
(d) Therefore, irrespective of the method used, concretes that satisfy the industry requirement of a maximum void spacing factor of 0.2 mm can be effectively determined by these automated image analysis techniques. Compared to the operated-dependent C 457 method, computer-dependent image analysis methods can more rapidly evaluate freeze-thaw durability of concrete by fast and reliable determination of the void spacing factor.

Sample Homogeneity – In order to evaluate the sample homogeneity and consistency in the results of air void measurements in each cylinder on the several parallel sections used in this study, C 457 method was used by CMC to determine air void parameters in all six parallel sections in Cylinders 4 and 5 having plastic air contents of 4.0 and 9.6 percent, respectively. Results show (Table 2) reasonably close correspondence in all parameters across the sections, indicating good reproducibility of air results and sample homogeneity. The CMC results of specific surface and void spacing factor on multiple sections of Cylinders 4 and 5 are also in good agreements with the results of Michigan Technological University on one section in each sample used for their flatbed scanner study. Their air content results of both cylinders, however, were higher than the C 457 results from all sections studied by CMC, which could indicate variability due to a combination of different operators and different instrument set ups. Nevertheless, consistent results on specific surface and void spacing factors on multiple sections of two cylinders by different laboratories justify the use of "average" values of air void parameters obtained from all C 457 tests to be used as a "reference" to compare various image analysis methods.

DISCUSSION

In a recent report on air void analysis in hardened concrete [29], Professor Kenneth Hover has provided the following statement on image analyses techniques, which is highly relevant to the present study:

> "As more image analysis systems are coming into the marketplace, it is only a matter of time until one or more of these become an accepted standard test method, interchangeable with, or perhaps as a replacement for, the human operator-based C 457 method. While any given analysis system may not be standardized, and thus might not be a valid means of determining compliance with some specifications, such systems can nevertheless provide important information for evaluating mixtures, or the effects of admixtures or construction operations on air-entrained concrete. Any method that provides fast, accurate, and reliable information can prevent serious problems in the field, and may in fact reduce the need for the more time-consuming standard C 457 analysis.
>
> One consequence of the development of automated techniques is a more thorough appreciation of the difficulties faced by the skilled C 457 operator. The current test requires that the operator make a large number of subtle distinctions and judgment calls based on color, texture, shadow, and the appearance of the feature in question compared to its background (about 1000 such judgments per analysis). The challenge of programming a computer to make the same judgments and distinctions is a measure of the power of the human eye coupled with the human brain, and an indication of the value of a skilled, experience operator. A related challenge is how to evaluate any given image analysis system. Ostensibly this is a simple matter of comparing automated results to standard C 457 results. This is complicated, however, by the variability of the C 457 test and the range of results that can be obtained over multiple runs on the same specimen by the same operator, and the broader range of results from the same specimen by different operators.
>
> Depending on the direction taken by the developing technology and the industry response, it is likely that the critical issues of sampling and surface preparation will remain. It may be that more rapid turn-around on test results or a reduced cost per test will permit a larger number of samples to be examined or each sample examined more thoroughly, with a resulting decrease in overall uncertainty and variability."

The present round robin survey, incorporating four different automated image analysis methods demonstrate excellent potential for increasing use of these methods in rapid evaluation of freeze-thaw durability of concrete. Emphases, however, should be placed more on the void frequency and air void spacing factors than on air content, which can be effectively determined by these methods in a fraction of time compared to the C 457 method. Absence of human operator-judgment, rapid cost-effective analysis, and better accuracy/precision/repeatability are the three important factors which will undoubtedly increase industry attention towards this modern technology of computer-based powerful image analysis techniques on concrete evaluation.

ACKNOWLEDGMENTS

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Table 1: Mixture proportions of five concrete cylinders and air contents

Mixtures per One Cubic Meter	**Five 100 x 200 mm Concrete Cylinders with different air contents**				
Sample ID	**1**	**2**	**3**	**4**	**5**
Desired Air Content	**8**	**6**	**2**	**4**	**10**
Portland Cement, Essroc Type I, Kg	377	377	377	377	377
Coarse Aggregate, #8 Limestone, Kg (SSD)	1009	1009	1009	1009	1009
Fine Aggregate, Sand, Kg (SSD)	634	634	634	634	634
Water, Kg	176	176	176	176	176
AEA, AE 260, oz/cwt	0.37	0.20	0.00	0.11	0.47
WRA, oz/cwt	2.00	2.00	2.00	2.00	2.00
Water-Cement Ratio	0.47	0.47	0.47	0.47	0.47
Unit Weight, Kg/m^3	2201.6	2249.6	2342.4	2304.0	2144.0
Concrete Temp., °C,	22	22	22	22	22
Slump, mm	100	82	69	75	119
Plastic Air Content, %	**7.9**	**5.8**	**2.6**	**4.0**	**9.6**
Yield, m^3	1.000	1.002	1.001	1.001	1.003

Table 2: Results of air-void parameters of five concrete cylinders measured by: (a) four different automated image analysis methods (shaded light blue) and (b) ASTM C 457 modified point count method (shaded gray)

AIR CONTENT, %

Image Analysis	Fresh Concrete	Fast Corp.	RJ Lee Group	Michigan Tech.	MoDOT/ NNSA-KCP		ASTM C 457	CMC	Michigan Tech.		
Sample		HF-MAC01	RapidAir 457	Flatbed Scanner	ACE System	Stn Dev.	Sample			Average	Stn. Dev.
1	7.90	7.40	10.51	9.05	7.57	1.45	1	8.78	9.11	8.95	0.23
2	5.80	4.00	6.00	6.02	4.67	1.01	2	5.62	4.95	5.29	0.47
3	2.60	2.30	3.60	3.57	2.24	0.76	3	2.64	3.71	3.18	0.76
4	4.00	3.30	3.82	5.35	2.99	1.05	4	3.72	4.24	3.98	0.37
5	9.60	9.50	13.42	12.71	6.66	3.12	5	10.44	13.09	11.77	1.87

VOID FREQUENCY, VOIDS/mm

Image Analysis	Fast Corp.	RJ Lee Group	Michigan Tech.	MoDOT/ NNSA-KCP		ASTM C 457	CMC	Michigan Tech.		
Sample	HF-MAC01	RapidAir 457	Flatbed Scanner	ACE System	Stn Dev.	Sample			Average	Stn. Dev.
1	0.277	0.703	0.464	0.505	0.175	1	0.461	0.565	0.513	0.074
2	0.128	0.276	0.226	0.239	0.063	2	0.239	0.247	0.243	0.006
3	0.035	0.141	0.086	0.074	0.044	3	0.054	0.054	0.054	0.000
4	0.084	0.183	0.136	0.092	0.046	4	0.129	0.116	0.123	0.009
5	0.500	0.846	0.633	0.464	0.173	5	0.611	0.768	0.690	0.111

SPECIFIC SURFACE, mm^2/mm^3

Image Analysis	Fast Corp.	RJ Lee Group	Michigan Tech.	MoDOT/ NNSA-KCP		ASTM C 457	CMC	Michigan Tech.		
Sample	HF-MAC01	RapidAir 457	Flatbed Scanner	ACE System	Stn Dev.	Sample			Average	Stn. Dev.
1	15.04	26.73	20.51	26.70	5.62	1	21.02	24.81	22.92	2.68
2	12.90	18.42	15.32	20.52	3.36	2	17.00	19.93	18.47	2.07
3	6.01	15.70	9.67	13.23	4.23	3	8.15	5.79	6.97	1.67
4	10.02	19.19	10.22	12.34	4.30	4	14.15	10.94	12.55	2.27
5	20.95	25.21	19.23	27.94	3.97	5	23.40	23.49	23.45	0.06

VOID-SPACING FACTOR, mm

Image Analysis	Fast Corp.	RJ Lee Group	Michigan Tech.	MoDOT/ NNSA-KCP		ASTM C 457	CMC	Michigan Tech.		
Sample	HF-MAC01	RapidAir 457	Flatbed Scanner	ACE System	Stn Dev.	Sample			Average	Stn. Dev.
1	0.268	0.096	0.159	0.144	0.073	1	0.165	0.121	0.143	0.031
2	0.432	0.240	0.305	0.233	0.092	2	0.287	0.253	0.270	0.024
3	1.182	0.355	0.611	0.521	0.359	3	0.853	0.991	0.922	0.098
4	0.600	0.283	0.474	0.437	0.131	4	0.429	0.498	0.464	0.049
5	0.148	0.080	0.113	0.156	0.035	5	0.117	0.091	0.104	0.018

Table 3: Results of ASTM C 457 modified point count analysis of Cylinder Nos. 4 and 5 on all six parallel lapped sections of each sample, analyzed by CMC for evaluation of homogeneity of these cylinders between separate parallel surfaces in terms of air void parameters

Cylinder No. 4	Entrained Air Content %	Total Air Content (%)	Void Frequency # / mm	Aggregate Content %	Paste Content %	Specific Surface mm^2/mm^3	Paste-Air Ratio	Spacing Factor L (mm)
CMC -1	2.11	2.71	0.120	63.79	33.51	17.74	12.38	0.393
CMC - 4	3.24	4.13	0.131	63.91	31.96	12.67	7.74	0.446
2A, Fast Corp	2.36	3.93	0.125	66.19	29.87	12.72	7.60	0.440
2B, MoDOT/NNSA-KCP	2.50	3.66	0.160	65.29	31.05	17.50	8.48	0.336
3A, RJ Lee	3.09	3.86	0.130	63.13	33.01	13.44	8.55	0.440
3B, Michigan Tech	2.99	4.01	0.108	65.41	30.58	10.80	7.62	0.519
Average	**2.72**	**3.72**	**0.129**	**64.62**	**31.66**	**14.15**	**8.73**	**0.429**
St Dev	0.45	0.52	0.017	1.18	1.42	2.83	1.84	0.061
Michigan Tech	**-**	**4.24**	**0.116**	**-**	**-**	**10.94**	**-**	**0.498**

Cylinder No. 5	Entrained Air Content %	Total Air Content (%)	Void Frequency # / mm	Aggregate Content %	Paste Content %	Specific Surface mm^2/mm^3	Paste-Air Ratio	Spacing Factor L (mm)
CMC -1	9.65	10.65	0.605	62.98	26.37	22.72	2.48	0.109
CMC - 4	8.08	9.43	0.538	61.88	28.69	22.83	3.04	0.133
2A, Fast Corp	9.13	10.74	0.646	61.60	27.66	24.07	2.58	0.107
2B, MoDOT/NNSA-KCP	8.74	10.67	0.702	60.67	28.67	26.32	2.69	0.102
3A, RJ Lee	9.17	10.86	0.559	59.21	29.93	20.61	2.76	0.134
3B, Michigan Tech	8.77	10.32	0.615	61.29	28.40	23.82	2.75	0.116
Average	**8.92**	**10.44**	**0.611**	**61.27**	**28.28**	**23.40**	**2.71**	**0.117**
St Dev	0.53	0.53	0.059	1.27	1.19	1.89	0.19	0.014
Michigan Tech	**-**	**13.09**	**0.768**	**-**	**-**	**23.49**	**-**	**0.091**

Note: All surfaces were analyzed by CMC. Surfaces marked as "2A," "2B," "3A," "3B" represent opposite sides of rectangular slabs "2" and "3" analyzed by Fast Corporation, NNSA-KCP, RJ Lee, and Michigan Technological University, respectively (see Figure 1 for sampling strategy). ASTM C 457 runs on these surfaces were done by CMC after all parties finished their image analyses procedures. Also shown at the end of each Table are C 457 modified point count analysis by Michigan Technological University on their assigned surface prior to their image analysis; the results are given to compare inter-laboratory variation of air void parameters on the same surface analyzed by CMC and Michigan Technological University. In all runs by CMC, the minimum points counted were 1500 and the minimum traverse lengths were 2540 mm.

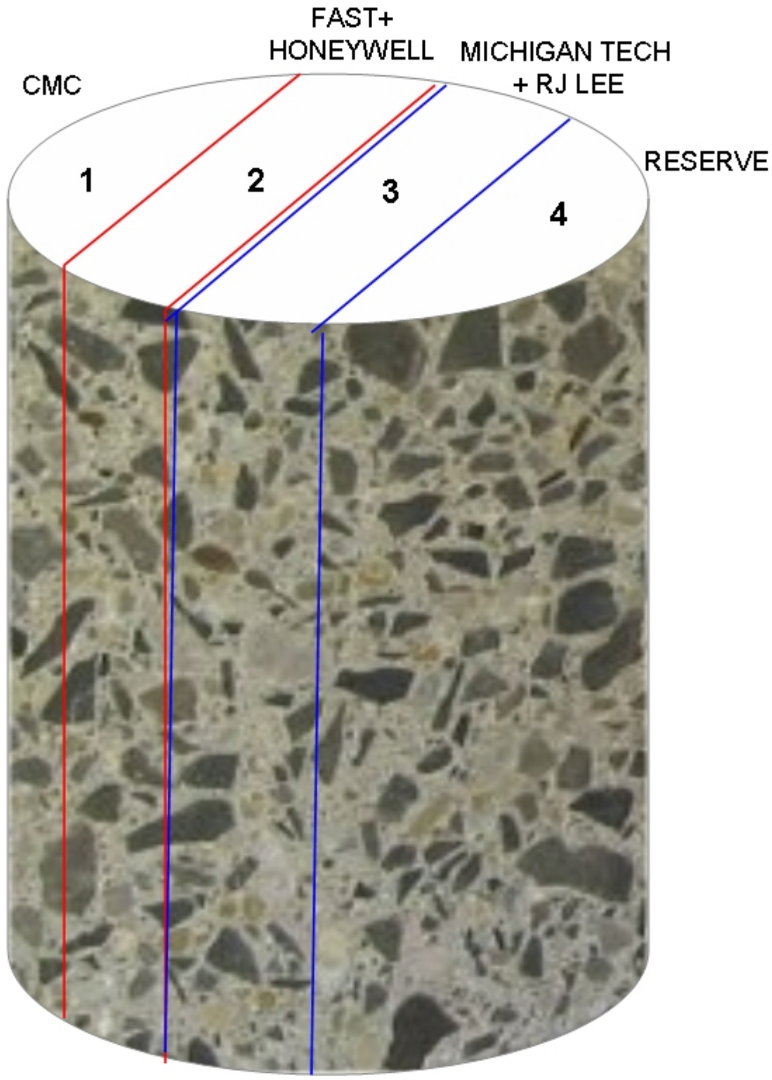


Figure 1: Schematic diagram of sampling strategy for the round robin test. A set of five 4 × 8 in. (100x 200 mm) size hardened concrete cylinders were prepared from five different concrete mixtures (shown in Table 1) having identical mixture proportions and fresh concrete properties but five different dosages of air entraining chemicals to stabilize five levels of air contents at approximately 2, 4, 6, 8, and 10 percent. Each cylinder was cured for 28 days in a moist cure room and then sectioned into four pieces along their length, as shown in this figure. Slab No. 1 was used for air void analysis by the modified point count method of ASTM C 457 by CMC. Slab No. 2 was sent for hardened air measurements by automated image analysis methods involving no further sample treatment (by Fast Corp.'s HF-MAC01 and MoDOT/NNSA-KCP's ACE System). Slab No. 3 was used for methods involving black-and-white contrast enhancement (by RapidAir 457 by RJ Lee Group and flatbed scanner by Michigan Technological University). Slab No. 4 is kept in reserve for any additional party interested in this round robin test. For Cylinder Nos. 4 and 5 all six sections (one section each from Slabs 1 and 4 and two opposite sections from Slabs 2 and 3) were used for C 457 tests by CMC.

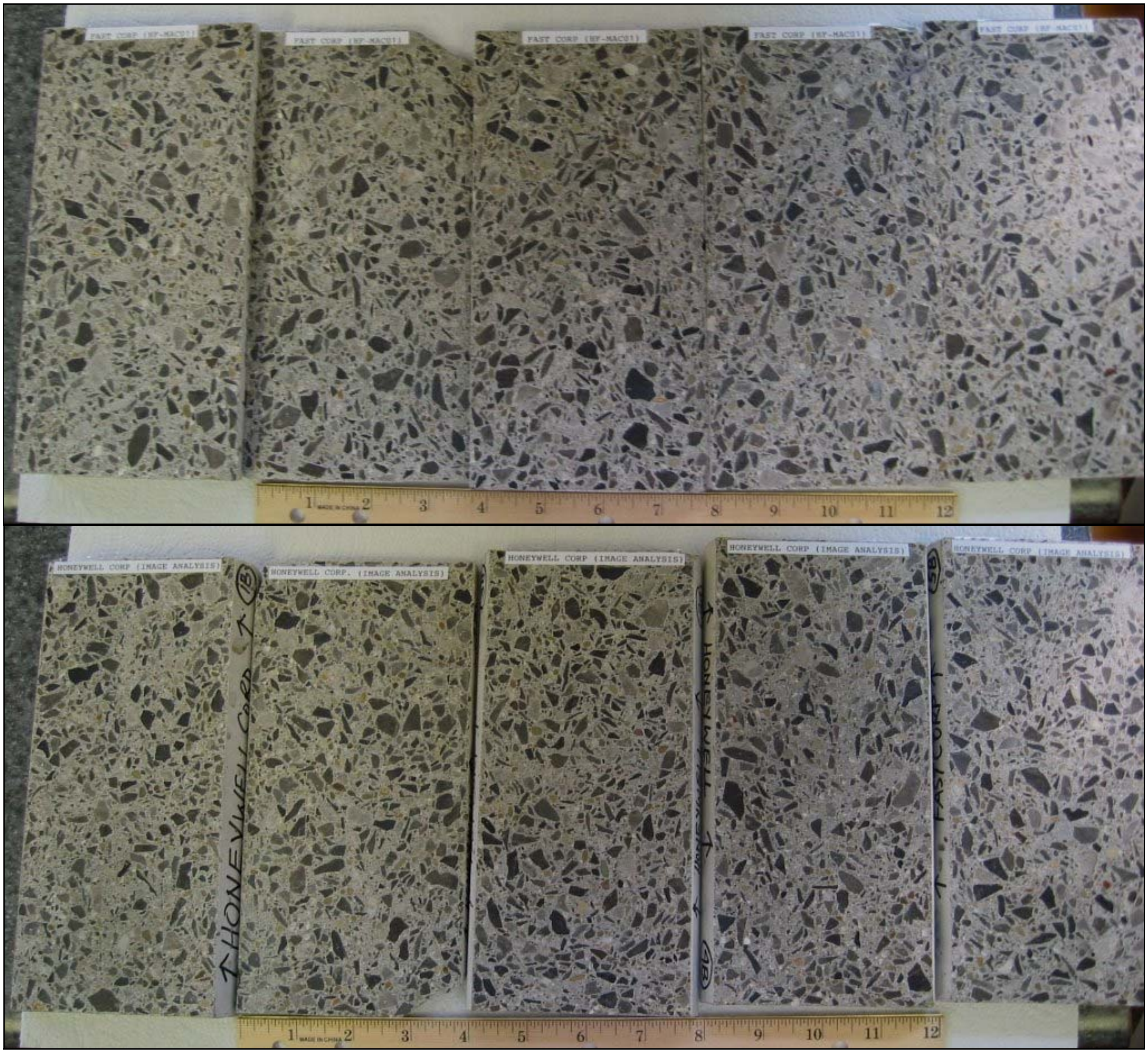


Figure 2: Photographs of lapped cross sections of five slabs from five concrete cylinders having different air contents sent to Fast Corporation, Japan and NNSA-KCP. In each slab, both sides where lapped in the CMC Laboratory for automated image analysis method of HF-MAC01 (Fast Corp.) and automated concrete evaluation (ACE) system (MoDOT/NNSA-KCP). The top photos show the sides for the Fast Corporation, prepared by CMC. The bottom photo shows the opposite sides of the same slabs that were used by the NNSA-KCP for their ACE system. Neither side required any further sample preparation (e.g., black and white contrast enhancement) for their image analysis methods.

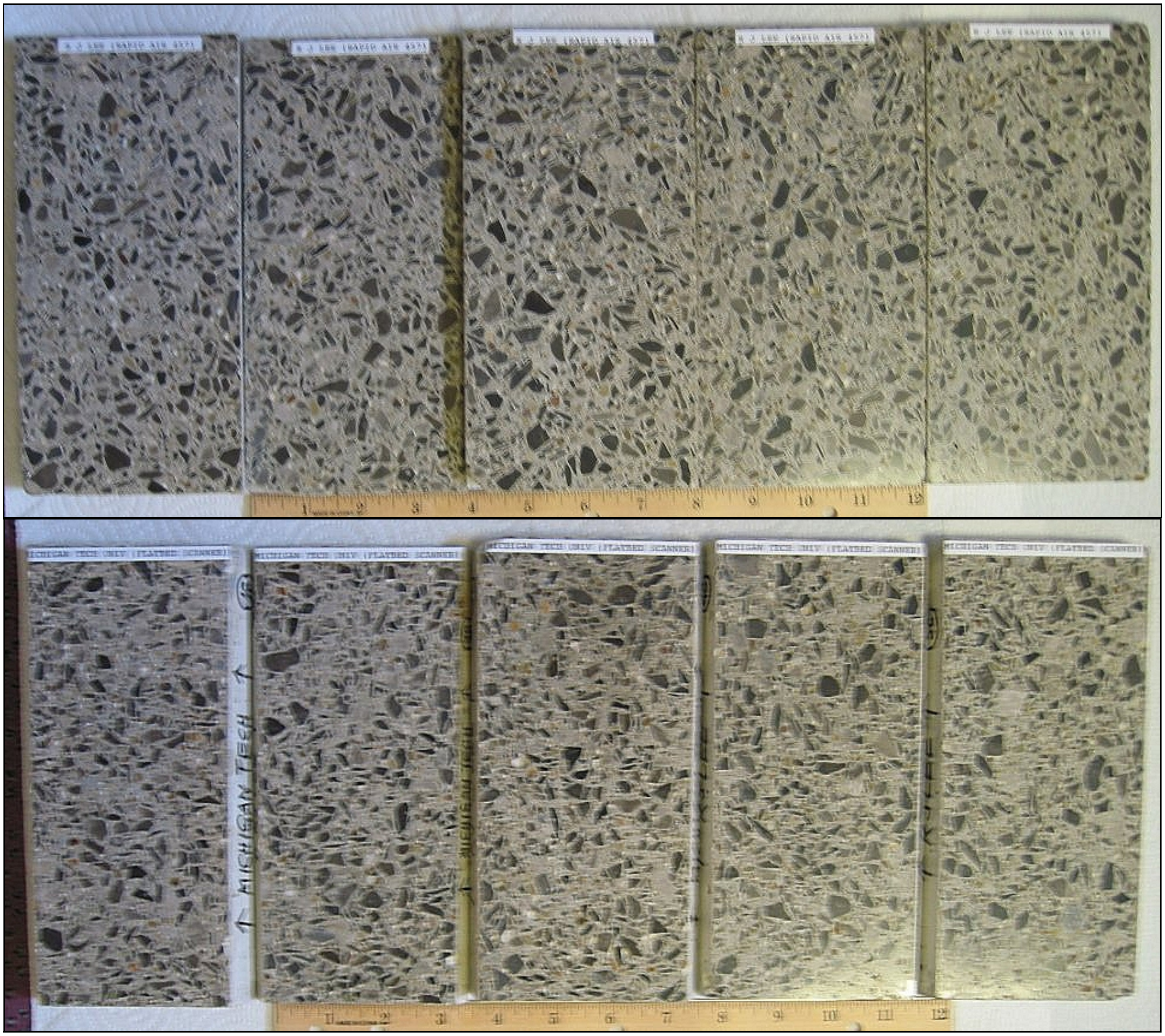
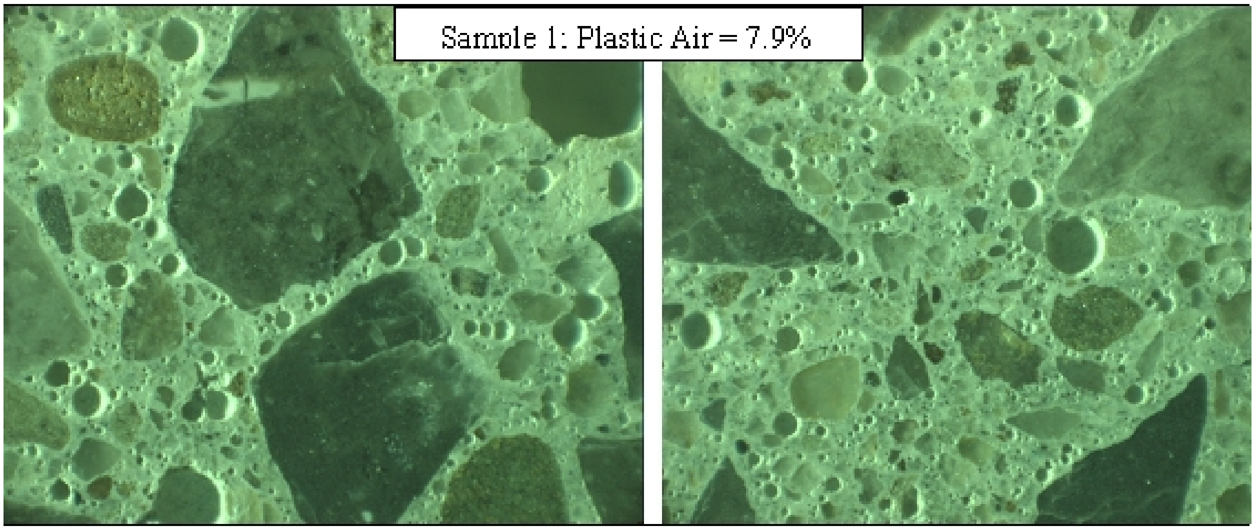
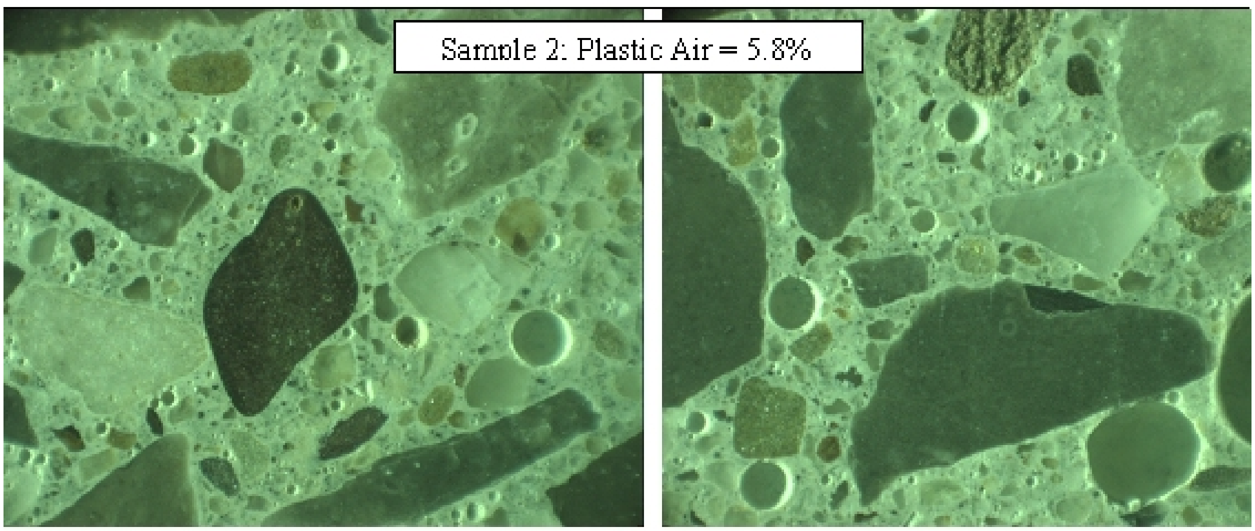
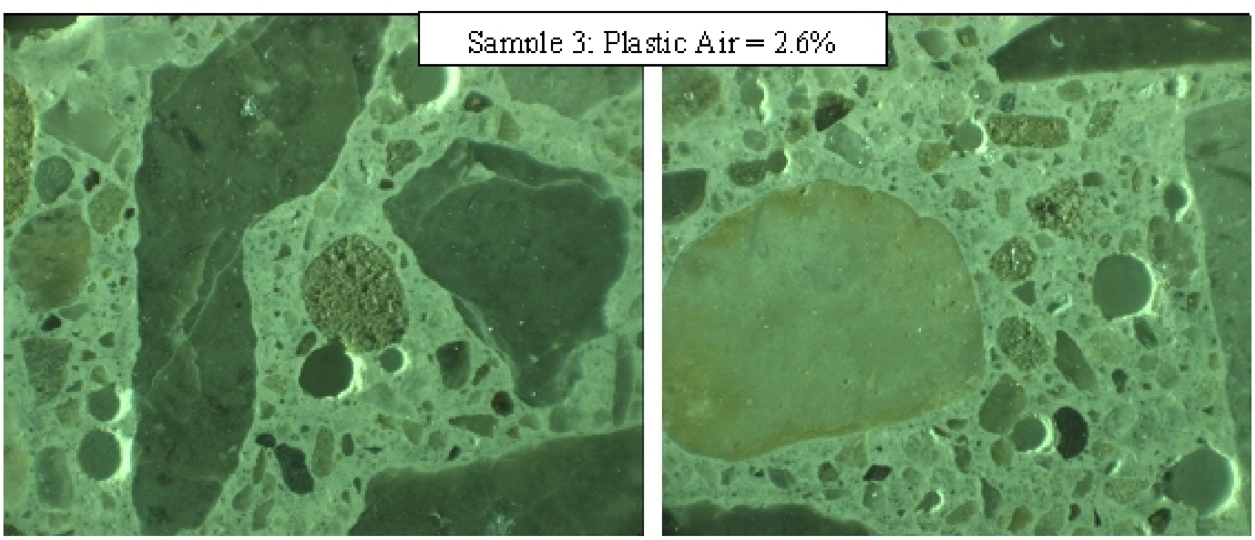
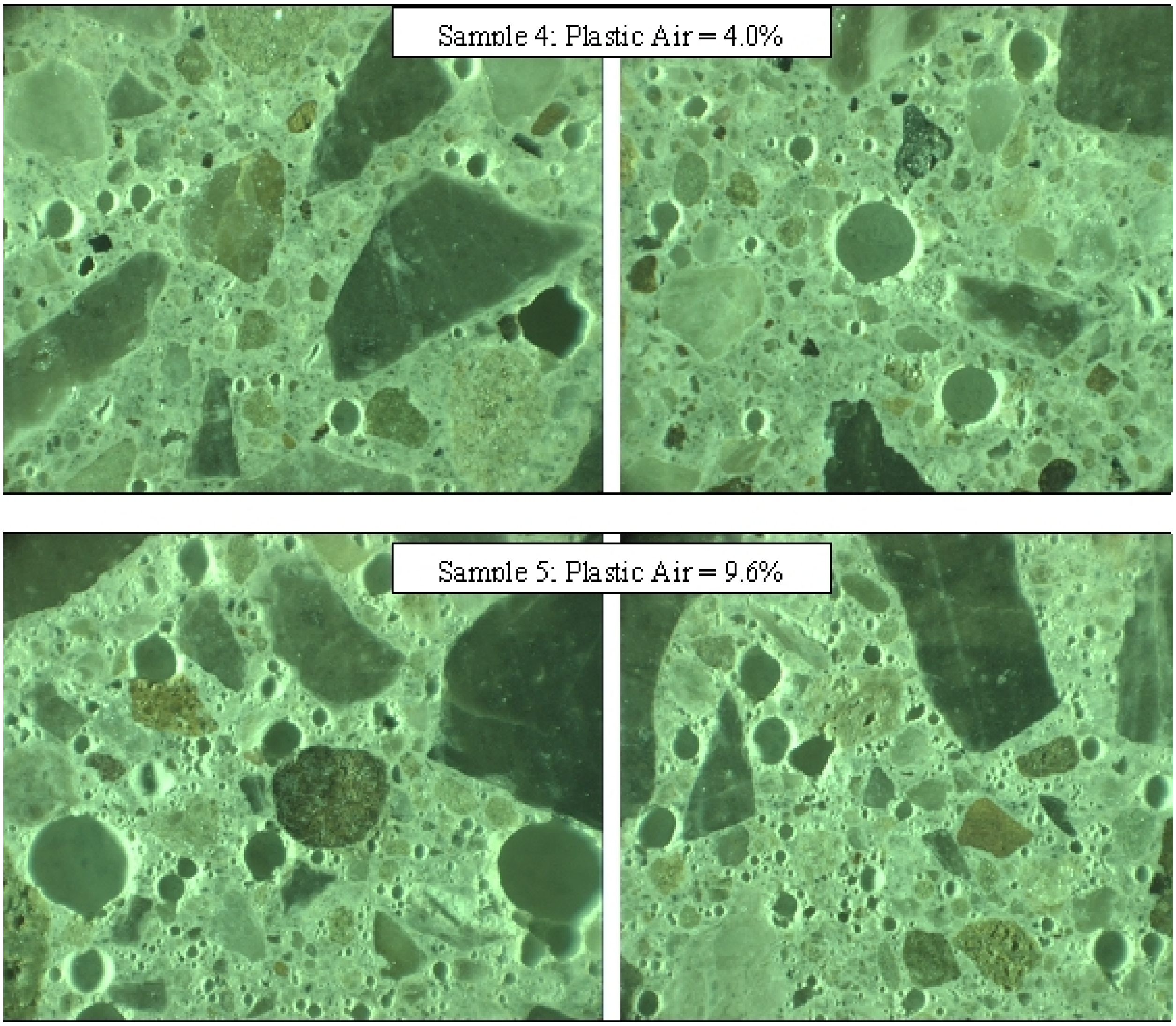


Figure 2(Cont'd): Photographs of lapped cross sections of five slabs from five concrete cylinders having different air contents sent to R J Lee Group and Michigan Technological University. In each slab, both sides where lapped in the CMC Laboratory for automated image analysis methods of RapidAir 457 (RJ Lee Group) and flatbed scanner (Michigan Technological University). The top photo shows the sides for the R.J. Lee Group prepared by CMC; RJ Lee Group did the black-and-white contrast enhancement for the RapidAir 457 method. The bottom photo shows the opposite sides of the same slabs that were used by Michigan Technological University for the black and white contrast enhancement for the flatbed scanner method.


Sample 1: Plastic Air = 7.9%


Sample 2: Plastic Air = 5.8%


Sample 3: Plastic Air = 2.6%



<u>Figure 3</u>: Photomicrographs of lapped sections of five concrete cylinders after sectioning and lapping at the CMC Laboratory. “Plastic air” represents air contents measured in the fresh concrete mixtures after mixing, and prior to preparing the cylinders. Field width of each photo is 10 mm.

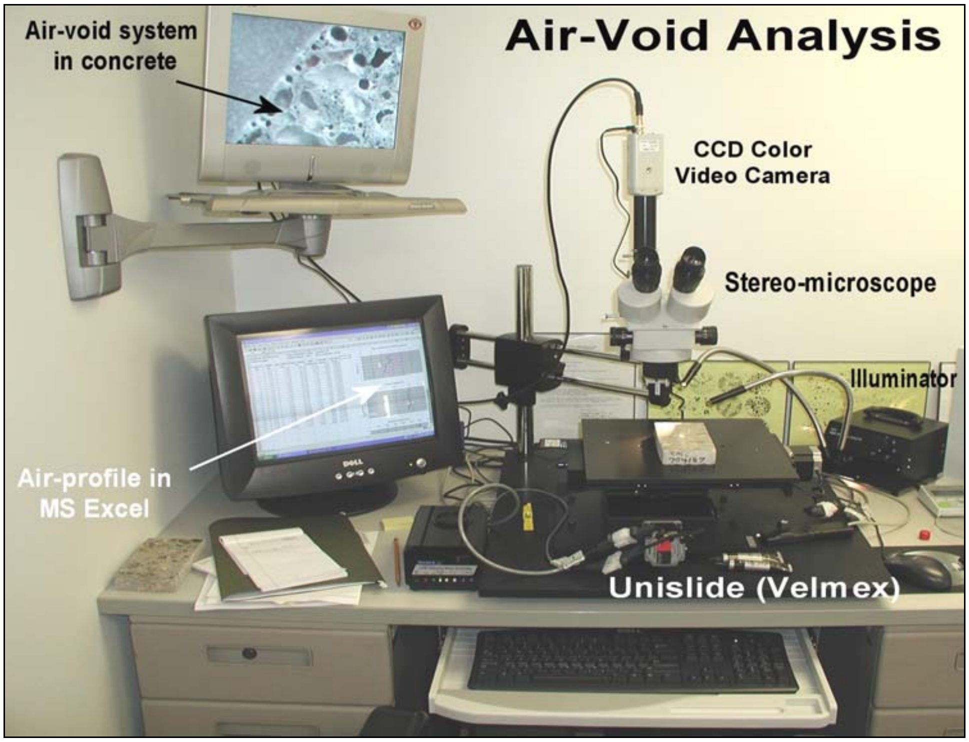


Figure 4: Instrument setup for the modified point count (manual) method of ASTM C 457 used in the laboratory of Construction Materials Consultants, Inc.

Figure 5: Instrument setup for the modified point count (manual) method of ASTM C 457 used in Michigan Technological University.

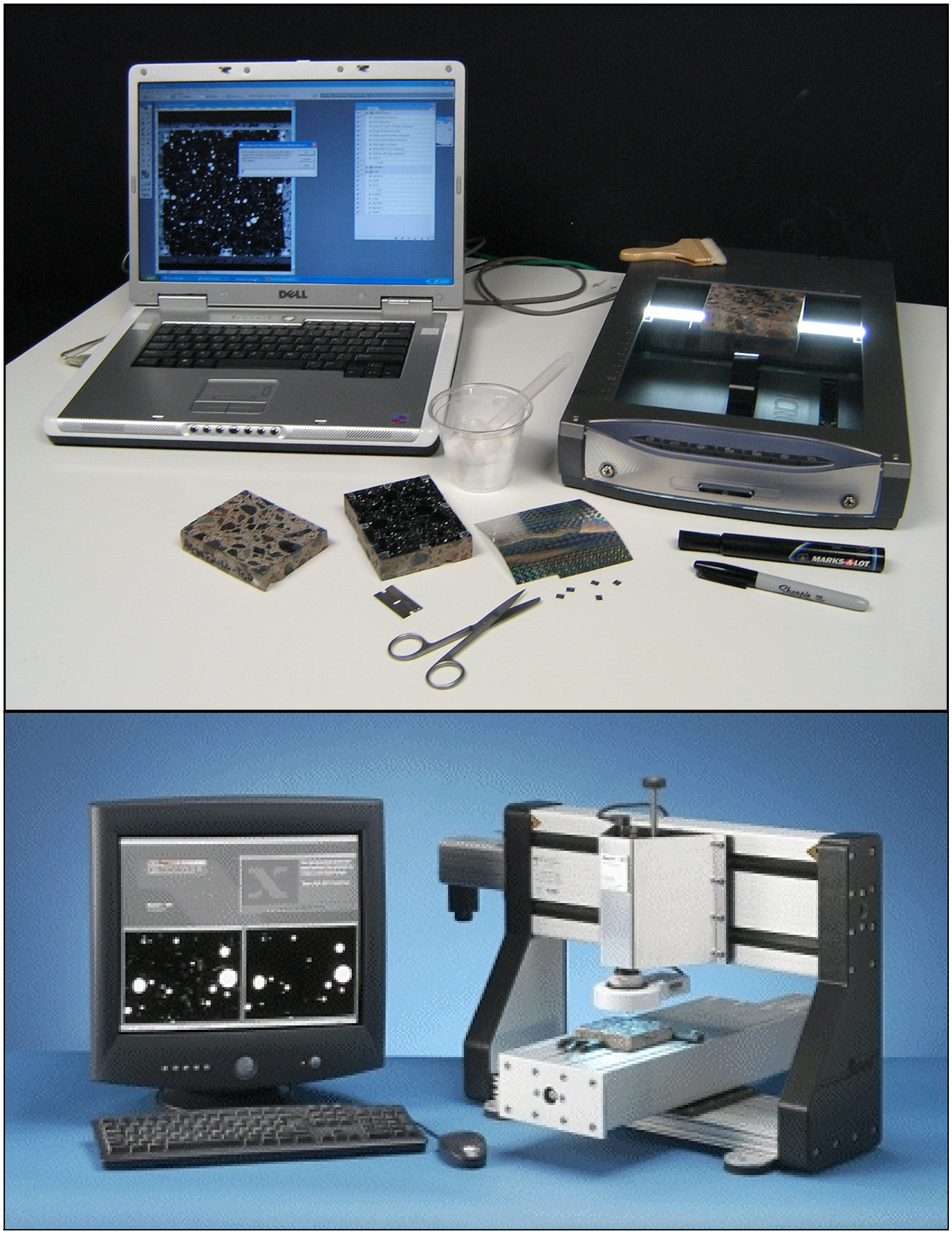


Figure 6: Instrument setup for the flatbed scanner method (top photo) and the RapidAir 457 method (bottom photo) both of which require a black and white contrast enhancement of the lapped section being scanned. Photos curtsey of Michigan Technological University and Concrete Experts International.

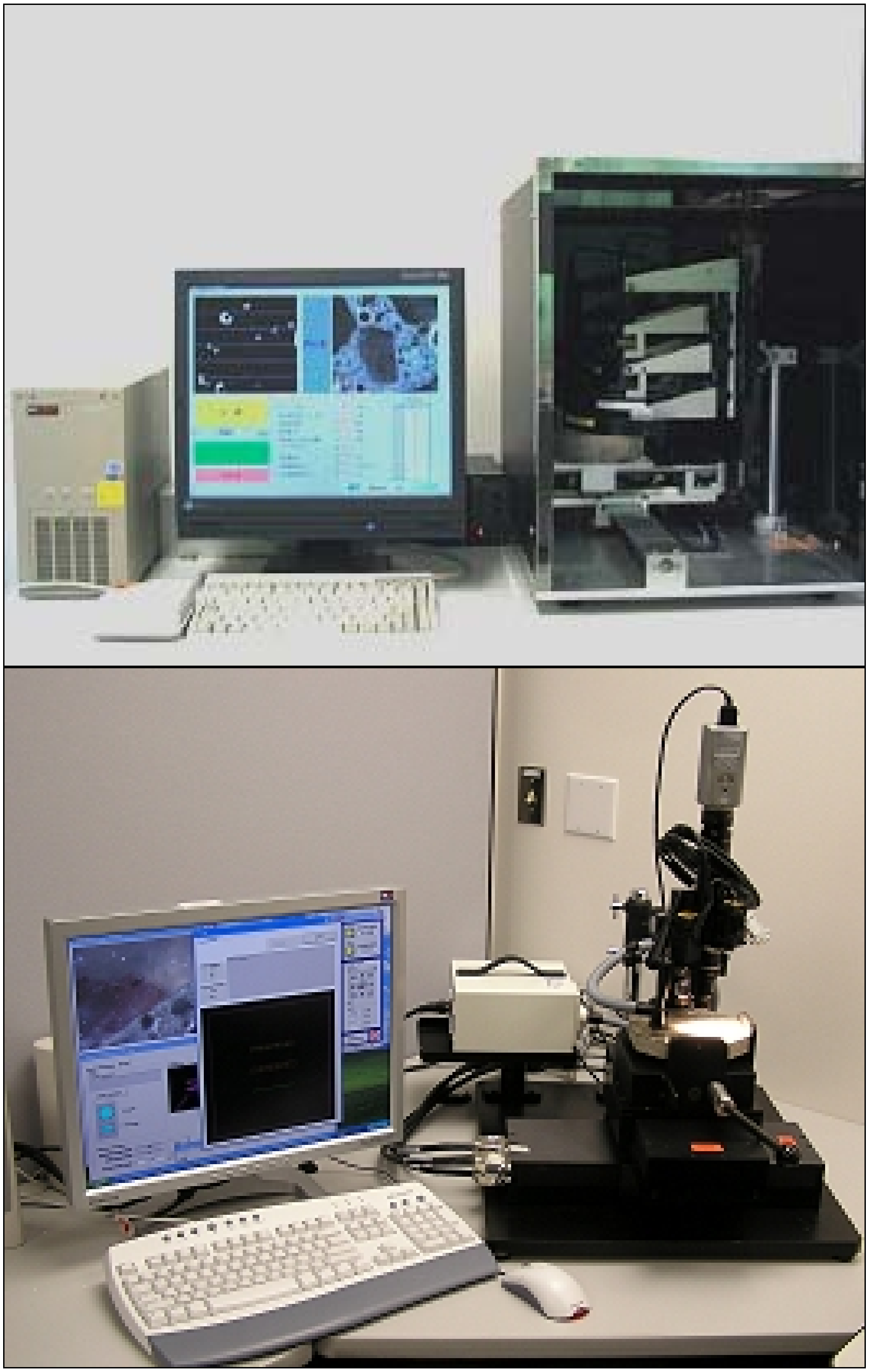


Figure 7: Instrument set up for HF-MAC01 method (top photo) and ACE system (bottom photo) neither of which require black-and-white contrast enhancement of the lapped section. Photos curtsey of Fast Corporation and NNSA-KCP.

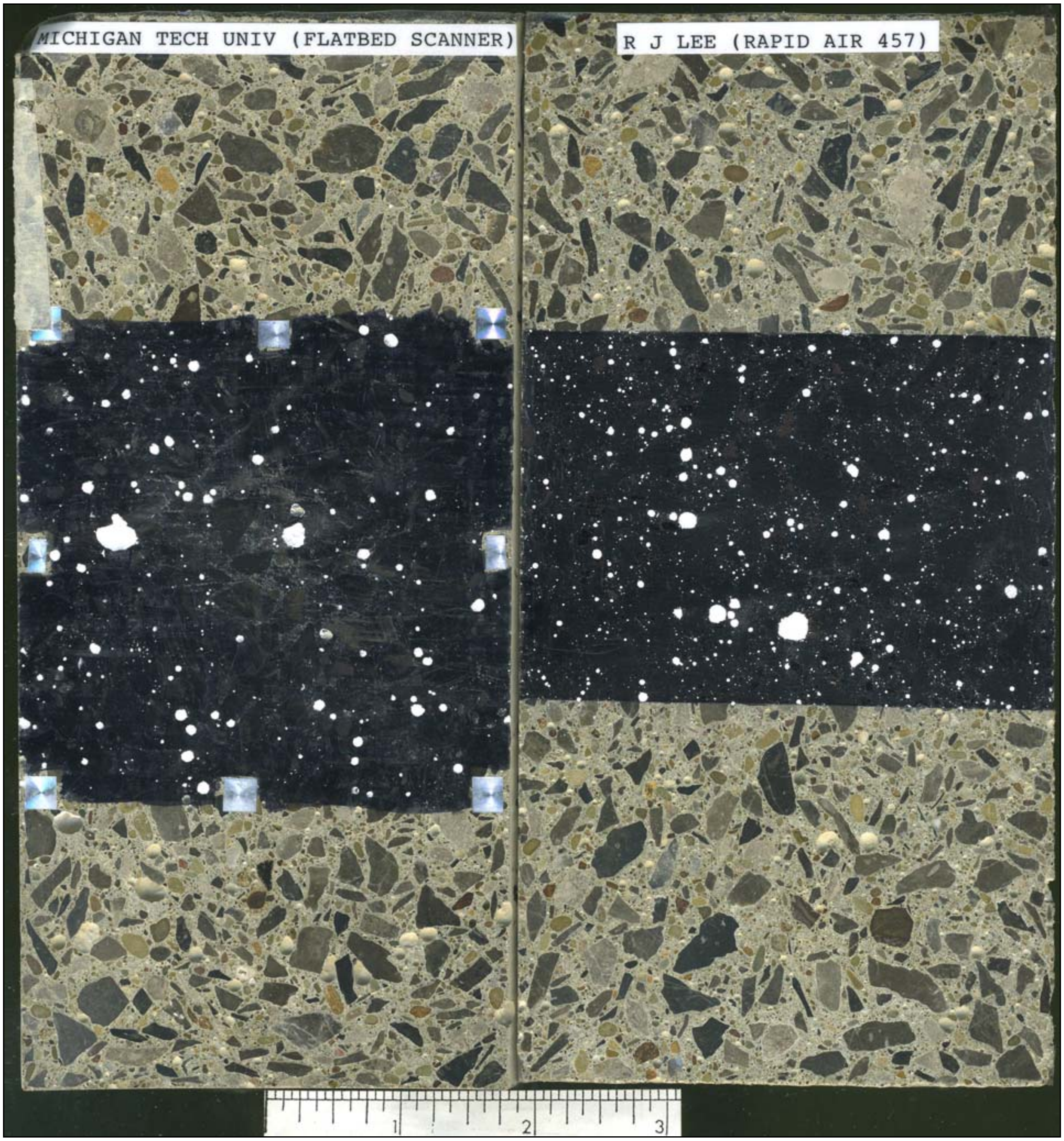


Figure 8: Black and white contrast enhancements on the lapped sections for the flatbed scanner method (left photo, Cylinder 3) and RapidAir 457 method (right photo, Cylinder 4).

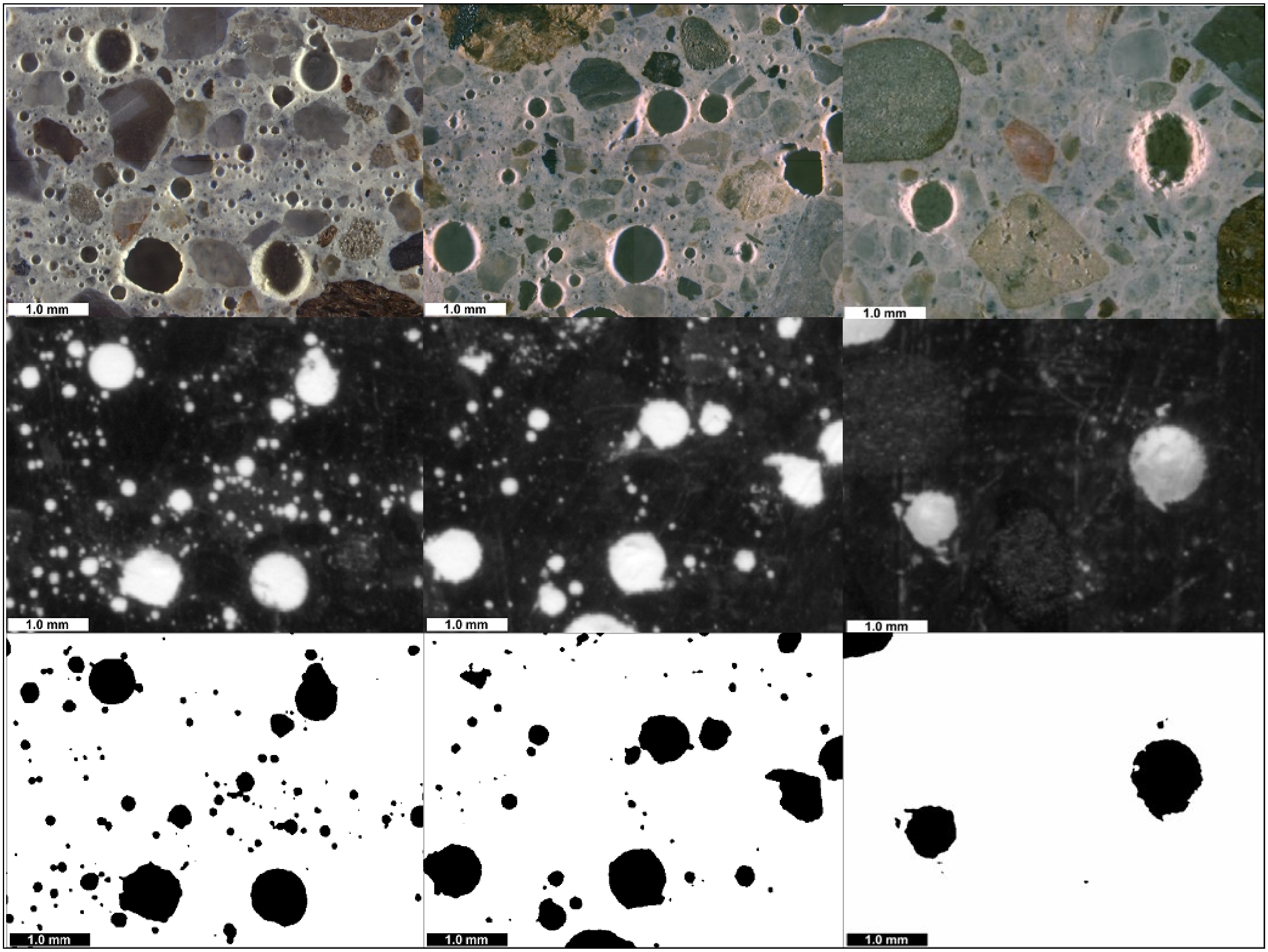


Figure 9: Samples 1(left photo), 2 (middle photo) and 3 (right photo) used for the flatbed scanner method; their determined air contents from the method are 9, 6, and 3.5 percent, respectively. In each photo, from top to bottom: A 2 x 2 mosaic of stereomicroscope image (as received), corresponding area from flatbed scanner image, and threshold image (Photos courtesy of Karl W. Peterson).

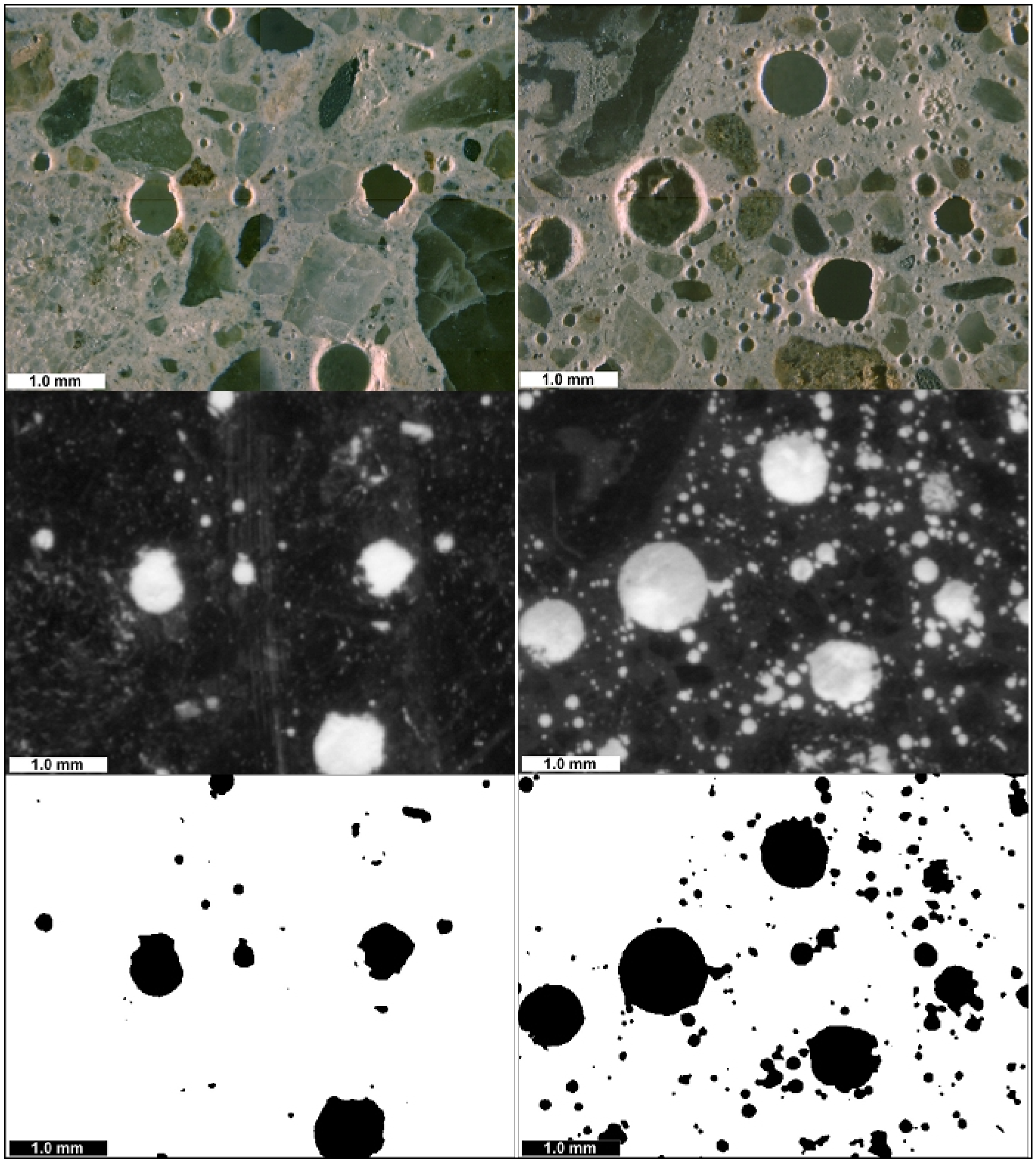
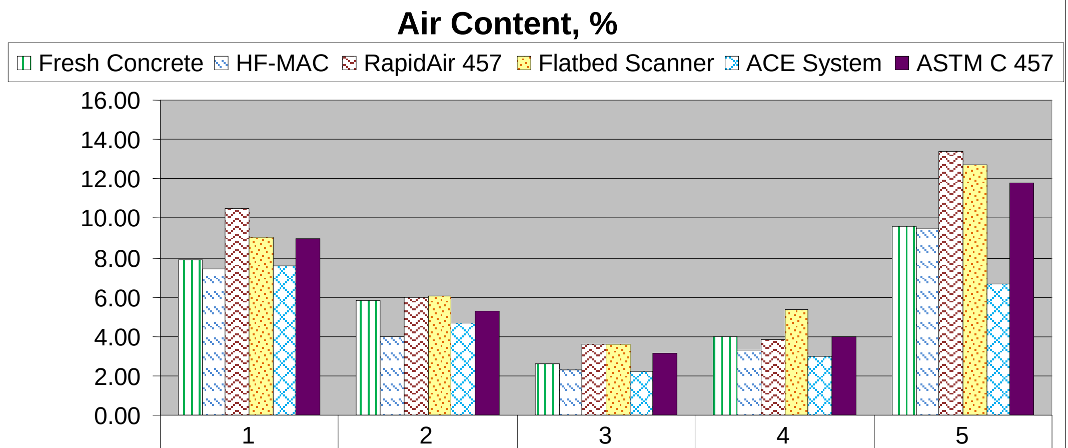
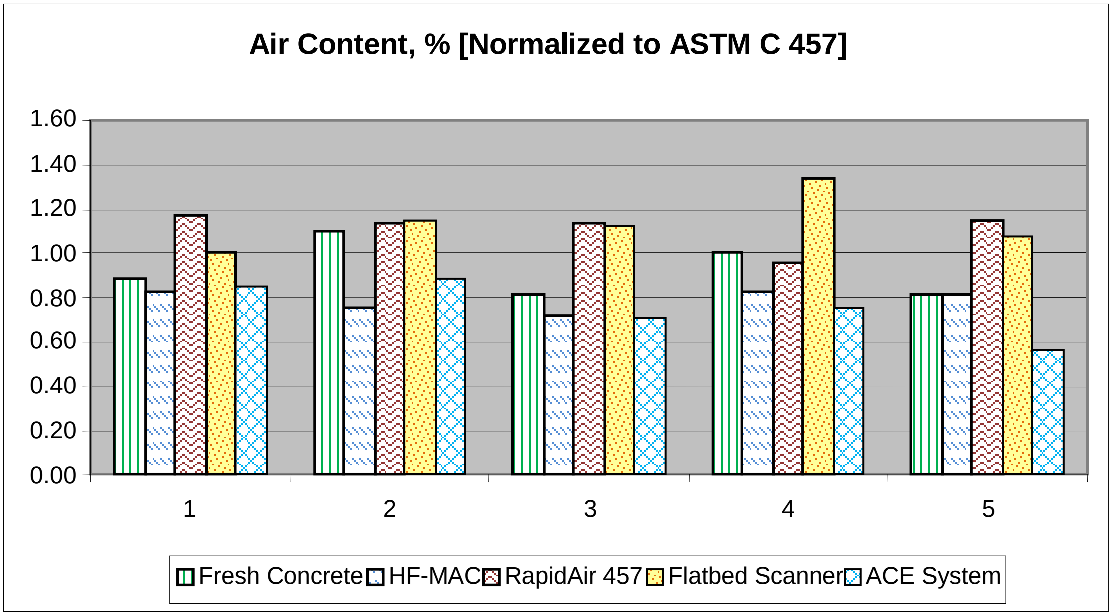


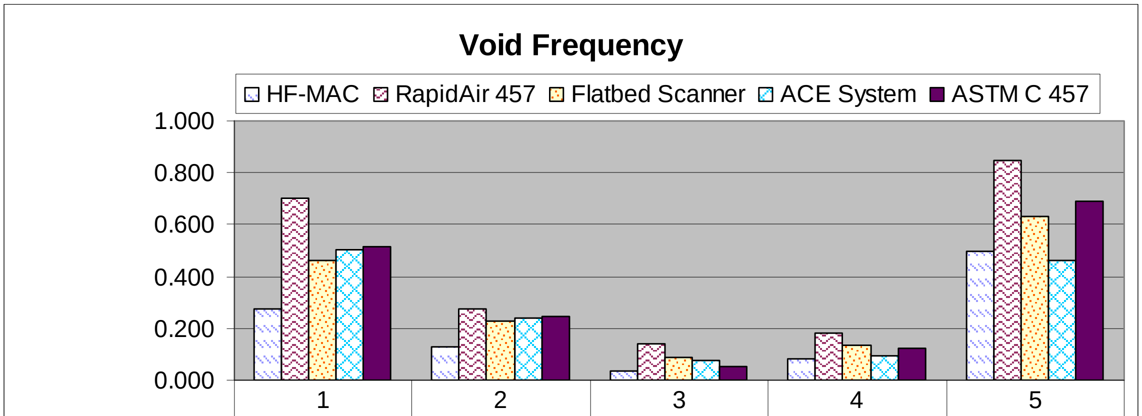
Figure 9 (Cont'd): Samples 4 (left photo) and 5 (right photo) used for flatbed scanner method; their determined air contents from the method are 5.3 and 12.7 percent. In each photo, from top to bottom: A 2 x 2 mosaic of stereomicroscope image (as received), corresponding area from flatbed scanner image, and threshold image (Photo courtesy of Karl W. Peterson).



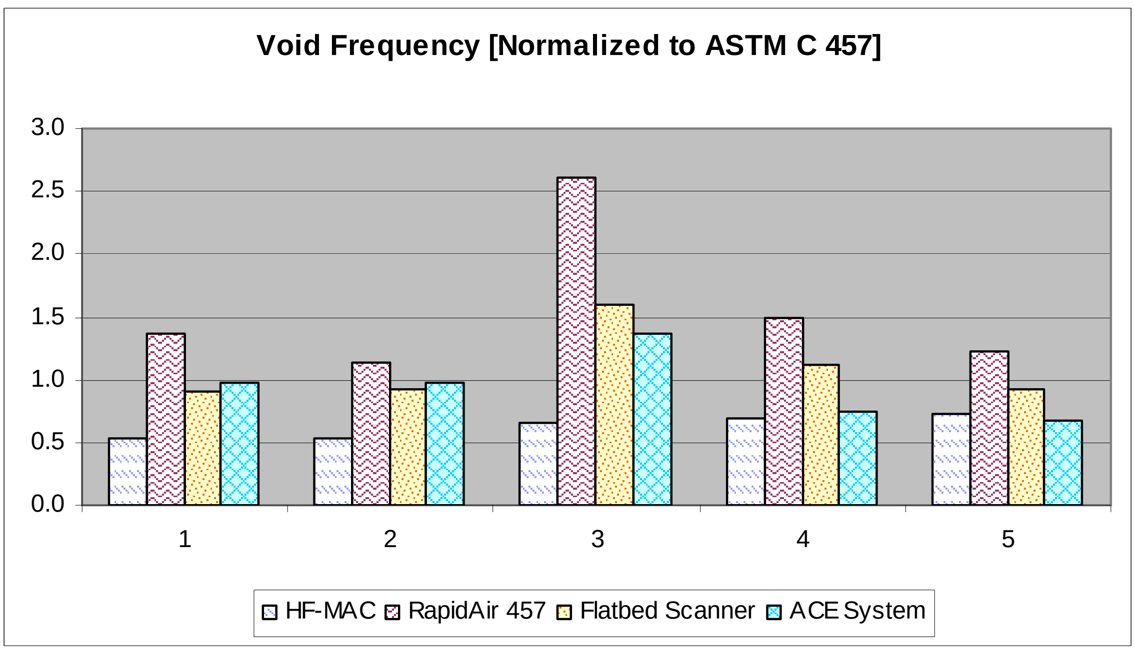
	1	2	3	4	5
Fresh Concrete	7.90	5.80	2.60	4.00	9.60
HF-MAC	7.40	4.00	2.30	3.30	9.50
RapidAir 457	10.51	6.00	3.60	3.82	13.42
Flatbed Scanner	9.05	6.02	3.57	5.35	12.71
ACE System	7.57	4.67	2.24	2.99	6.66
ASTM C 457	8.95	5.29	3.18	3.98	11.77



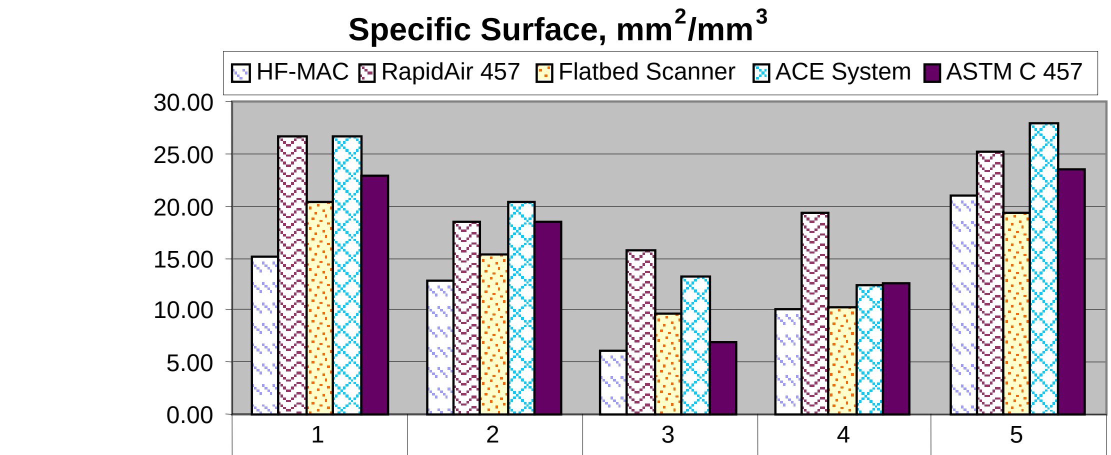
<u>Figure 10</u>: Results of air contents in five concrete cylinders measured in plastic concrete, by four different methods of automated image analysis, and by the modified point count method of ASTM C 457. The bottom diagram shows relative variations in air contents among four different image analyses methods after normalizing their results by the ASTM C 457 result.



	1	2	3	4	5
HF-MAC	0.277	0.128	0.035	0.084	0.500
RapidAir 457	0.703	0.276	0.141	0.183	0.846
Flatbed Scanner	0.464	0.226	0.086	0.136	0.633
ACE System	0.505	0.239	0.074	0.092	0.464
ASTM C 457	0.513	0.243	0.054	0.123	0.690



<u>Figure 11</u>: Results of void frequency of air void systems in five concrete cylinders measured by four different methods of automated image analysis, and by the modified point count method of ASTM C 457. The bottom diagram shows relative variations in void frequencies among four different image analysis methods after normalizing their results by the ASTM C 457 result.



	1	2	3	4	5
HF-MAC	15.04	12.90	6.01	10.02	20.95
RapidAir 457	26.73	18.42	15.70	19.19	25.21
Flatbed Scanner	20.51	15.32	9.67	10.22	19.23
ACE System	26.70	20.52	13.23	12.34	27.94
ASTM C 457	22.92	18.47	6.97	12.55	23.45

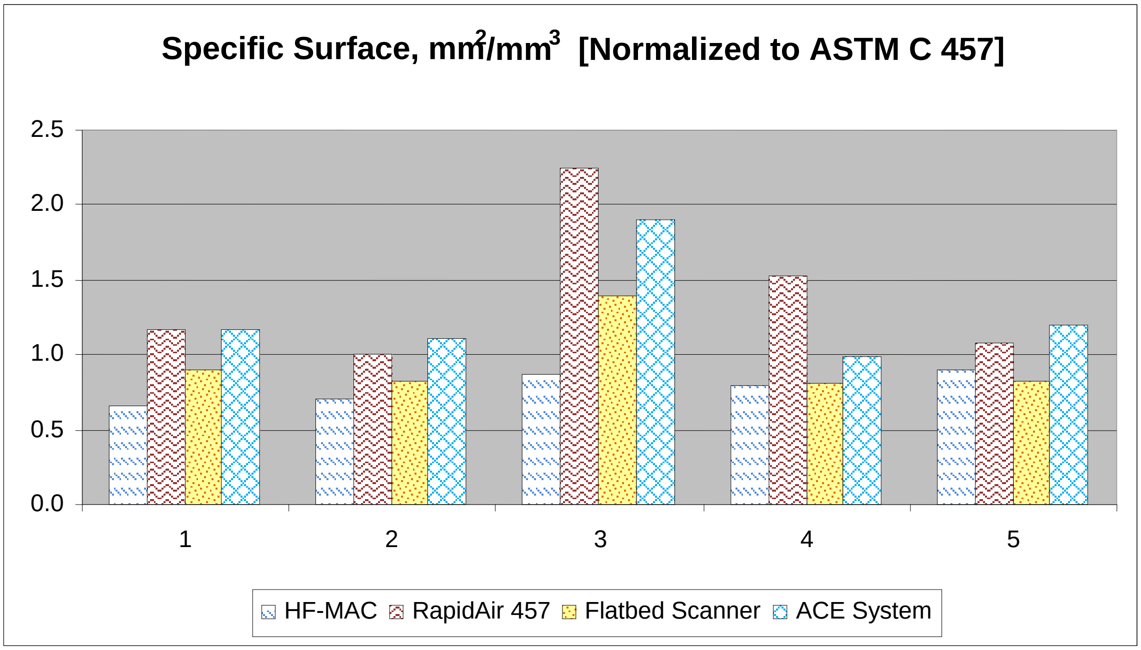
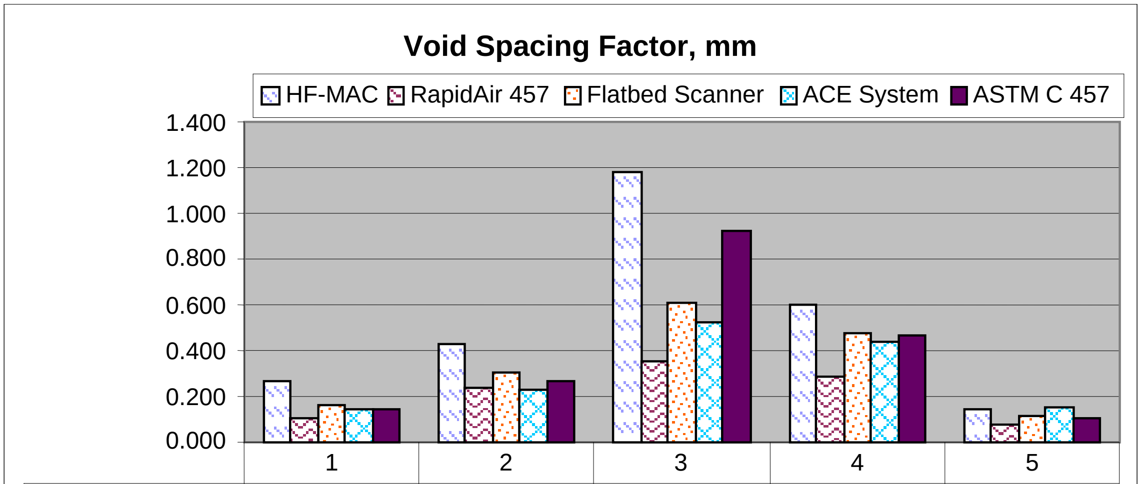


Figure 12: Results of specific surfaces of air void systems in five concrete cylinders measured by four different methods of automated image analysis, and by the modified point count method of ASTM C 457. The bottom diagram shows relative variations in a specific surface among four different image analysis methods after normalizing their results by the ASTM C 457 result.



	1	2	3	4	5
HF-MAC	0.268	0.432	1.182	0.600	0.148
RapidAir 457	0.096	0.240	0.355	0.283	0.080
Flatbed Scanner	0.159	0.305	0.611	0.474	0.113
ACE System	0.144	0.233	0.521	0.437	0.156
ASTM C 457	0.143	0.270	0.922	0.464	0.104

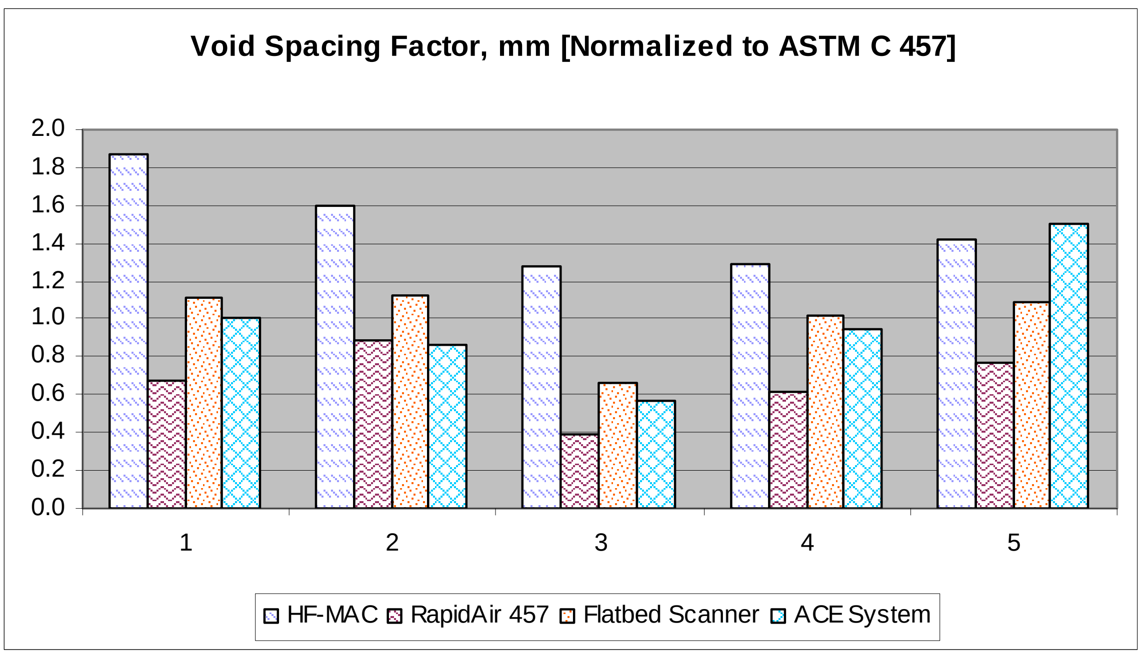
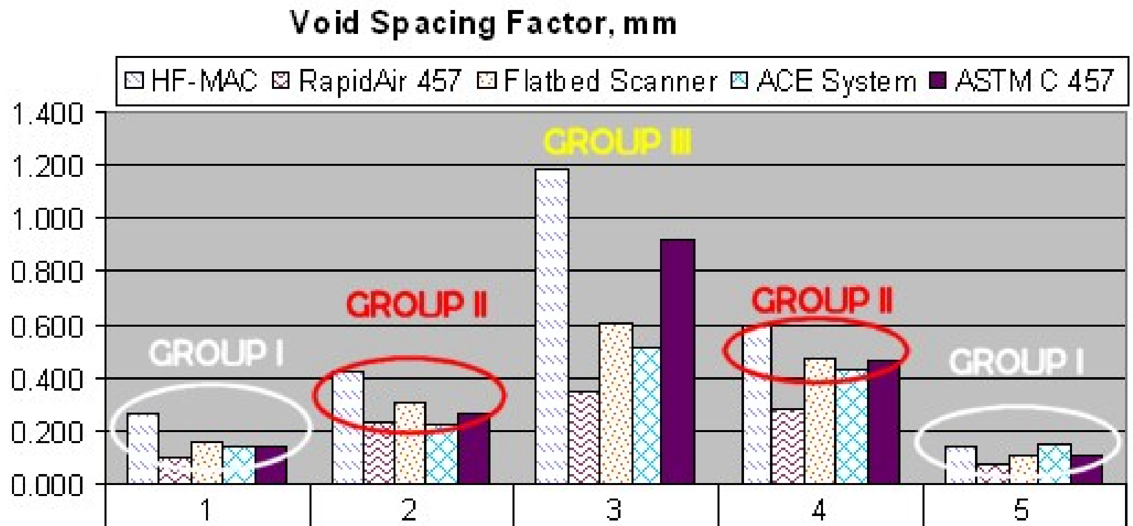
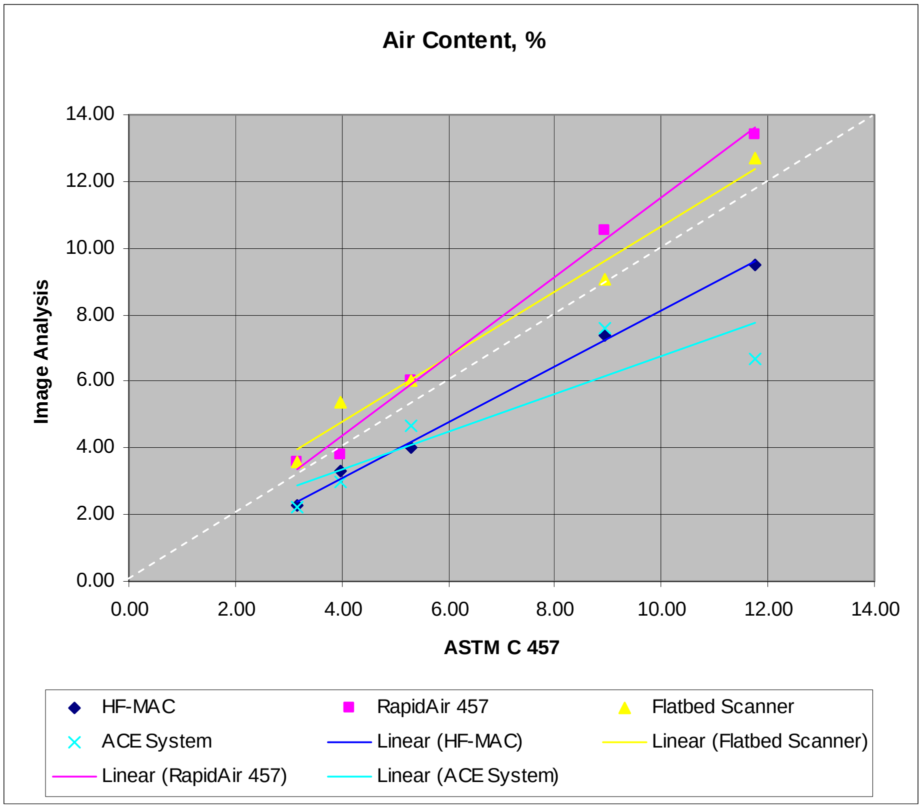


Figure 13: Results of void spacing factors of air void systems in five concrete cylinders measured by four different methods of automated image analysis, and by the modified point count method of ASTM C 457. The bottom diagram shows relative variations in void spacing factor among four different image analysis methods after normalizing their results by the ASTM C 457 result.



	1	2	3	4	5
HF-MAC	0.268	0.432	1.182	0.600	0.148
RapidAir 457	0.096	0.240	0.355	0.283	0.080
Flatbed Scanner	0.159	0.305	0.611	0.474	0.113
ACE System	0.144	0.233	0.521	0.437	0.156
ASTM C 457	0.143	0.270	0.922	0.464	0.104

Figure 14: Despite the differences in absolute void spacing factors among various image analysis methods – all showed more or less consistent results in distinguishing the following three different air void systems in five samples – Group I including air-entrained samples having a good air void system and lowest void spacing factor, Group II including air-entrained samples having a marginal air void system and higher than industry-recommended maximum void spacing factor of 0.2 mm, and Group III non-air-entrained sample having a poor air void system and the highest void spacing factor. Irrespective of the method used, all image analysis methods can distinguish concretes having good air void systems from the ones having marginal or poor air void systems.



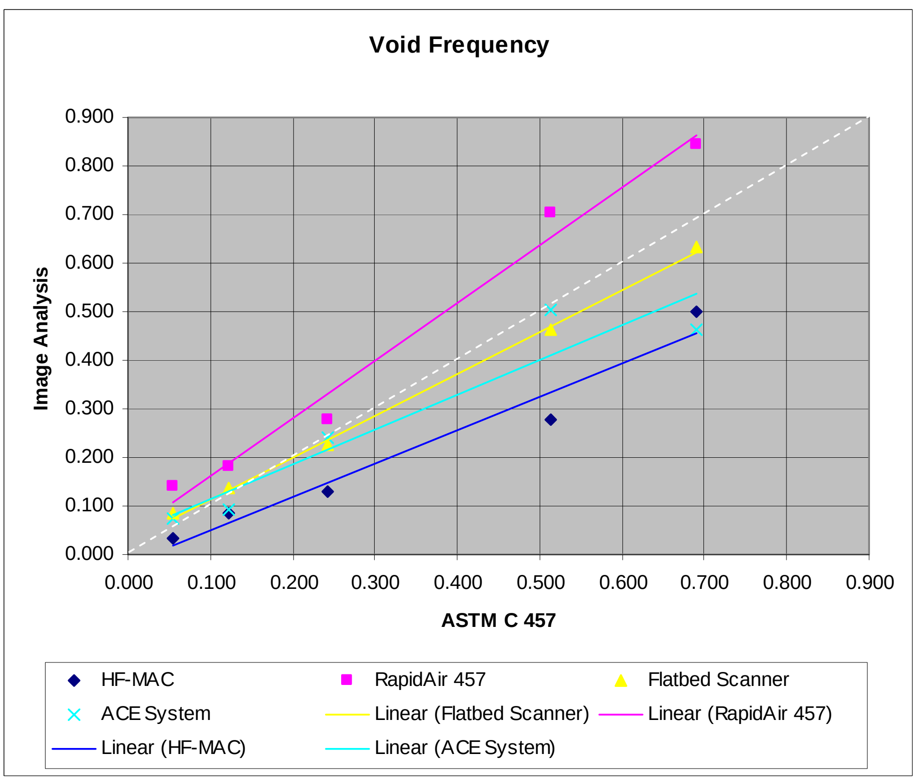
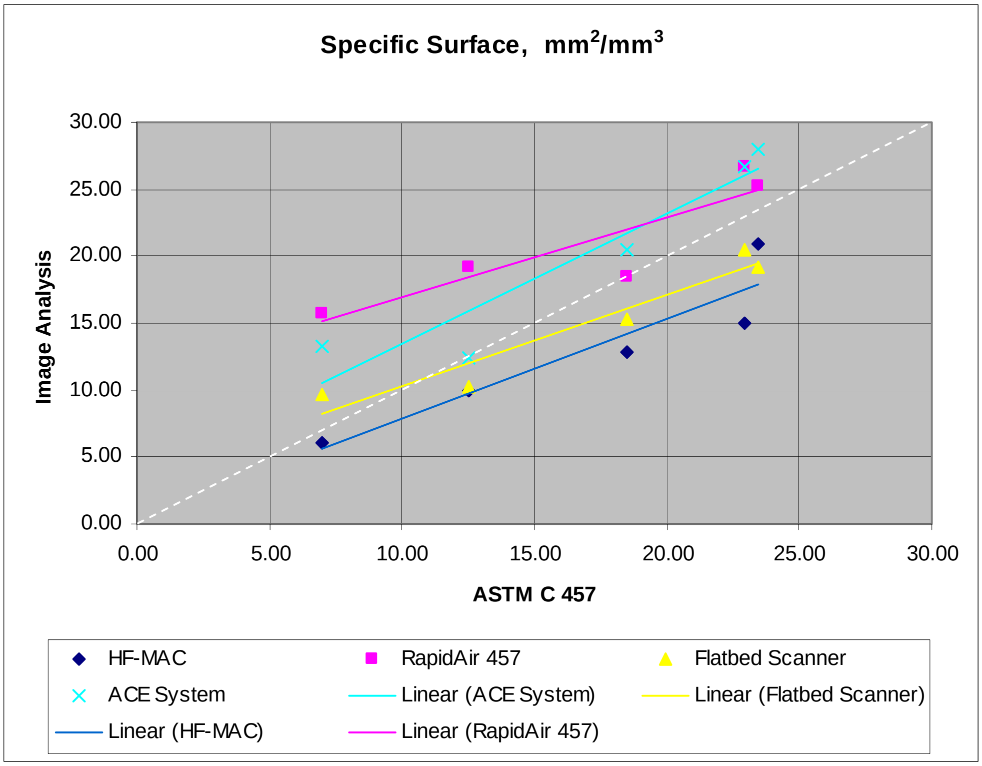


Figure 15: Results of air contents and void frequency of five samples determined from four different image analysis methods plotted against the corresponding average values determined from the manual modified point methods of ASTM C 457 by two laboratories.



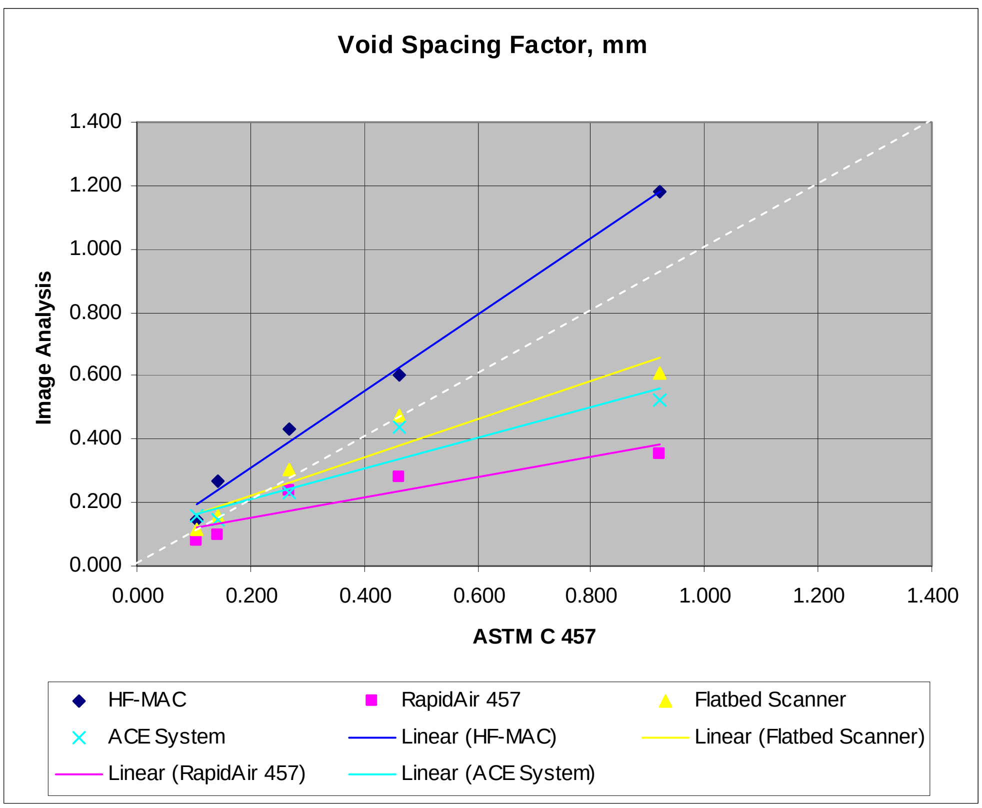


Figure 15 (Cont'd): Results of specific surface and void spacing factor of five samples determined from four different image analysis methods plotted against the corresponding average values determined from the manual modified point methods of ASTM C 457 by two laboratories.