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16. Abstract
Since 2001, the Missouri Department of Transportation and National Nuclear Security Administration's Kansas City Plant, operated by Honeywell Federal Manufacturing & Technologies, have collaborated on three CRADA's (Cooperative Research and Development Agreements) to develop a fully automated machine vision system to perform the analysis of the air void structure of concrete according to the ASTM linear traverse method. The first two CRADA's were focused on the development of a prototype system, designated ACES, for Automated Concrete Evaluation System. This prototype included a computer controlled two-dimensional stage and sample holder, a vision system consisting of a microscope, a digital black-and-white camera and analog frame grabber, a personal computer, and customized software to perform the image acquisition, analysis, and reporting. Initial evaluations of the accuracy of the ACE system relative to experienced human operators at MoDOT were quite positive. However, ongoing validations to baseline performance of the software against actual manually derived results provided data indicating that additional software developments were required to ensure that the results provided by the ACE System are consistent with those obtained manually. As a result, a third CRADA was initiated to improve the performance of the ACE system to consistently apply the ASTM linear traverse method and to improve the accuracy of the system relative to the results obtained by human experts.
In 2003, MODOT expanded the scope of this effort by initiating and leading a national, pooled fund effort under sponsorship by the Federal Highway Administration. This pooled fund effort included 13 state transportation departments (Arkansas, California, Colorado, Illinois, Indiana, Iowa, Minnesota, Missouri, Montana, Nebraska, Ohio, Virginia, and Wisconsin).

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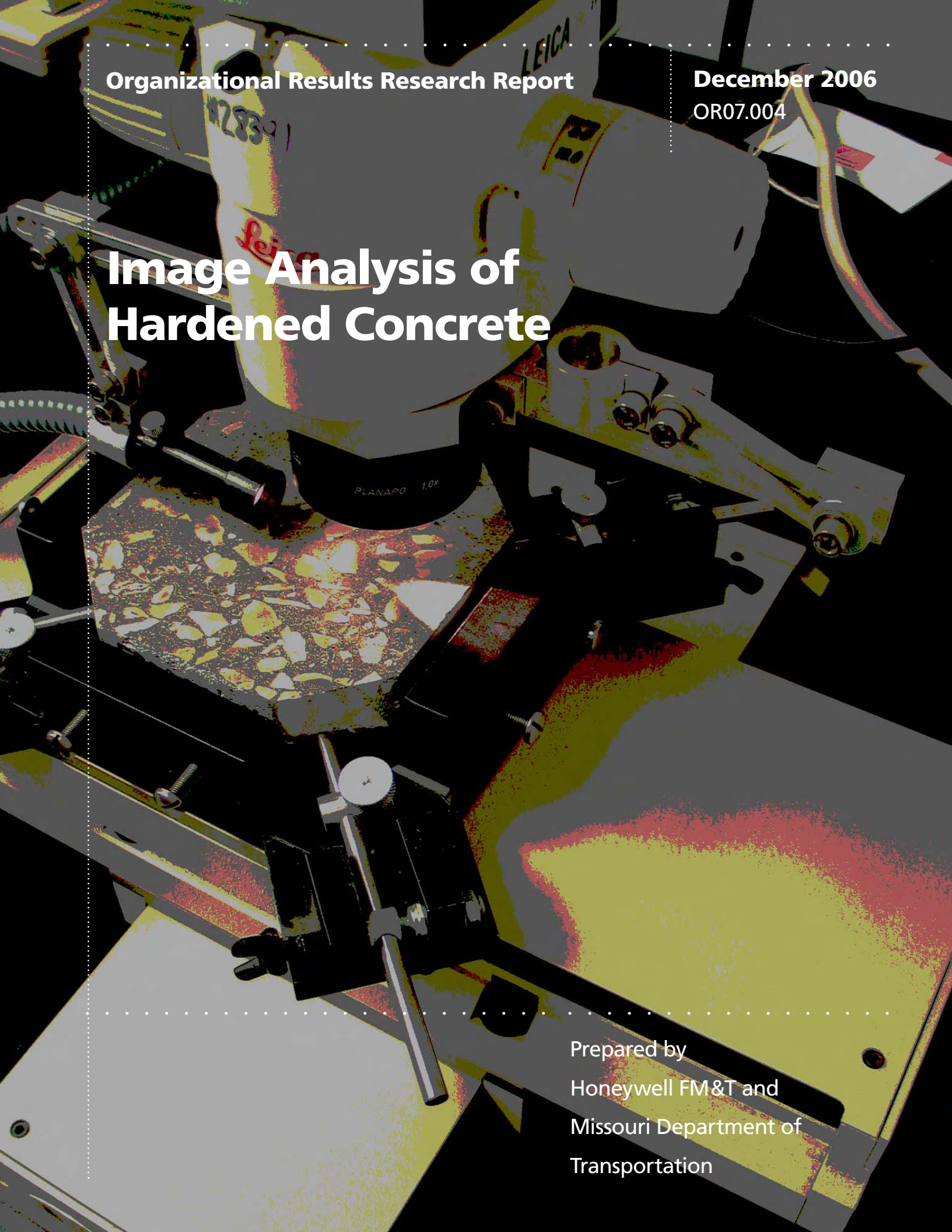

Organizational Results Research Report

December 2006

OR07.004

Image Analysis of Hardened Concrete

Prepared by

Honeywell FM&T and

Missouri Department of

Transportation

FINAL REPORT

OR 07-004

Image Analysis of Hardened Concrete

Performance Enhancement
of the Automated Concrete Evaluation System (ACES)

Prepared for the
Missouri Department of Transportation
Organizational Results

By

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December 2006

The opinions, findings, and conclusions expressed in this publication are those of the principal investigators. They are not necessarily those of the Missouri Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. This report does not constitute a standard or regulation.

Executive Summary

The vital role of air entrainment in preventing freeze-thaw damage in concrete is well known and well documented. Through the action of an air entraining agent (AEA) added to fresh concrete, an air void system comprised of various microscopic voids is established. There are several parameters of the air void system, which are considered important indicators of freeze-thaw resistance. Measuring these parameters and their adequacy provides extremely useful information on concrete freeze-thaw resistance. ASTM C 457 describes two methods for assessing the adequacy of the air void system in hardened concrete: the linear traverse and modified point count [ASTM 2004]. Both procedures in ASTM C 457 require a human operator to use a microscope, or a video monitor and camera attached to a microscope, to make the necessary observations and measurements. The process has been long recognized as tedious and time-consuming, requiring a skilled and experienced operator to ensure reliable, consistent results. In addition to operator training, ability, and bias, factors that contribute to variation in air void measurements include differences in procedures and equipment, differences in specimen preparation quality, and inherent statistical variability of the test method itself.

This report documents the results of a national pooled-fund study, led by the Missouri Department of Transportation (MoDOT), and sponsored by 13 states. The goal of the pooled-fund study was to refine and complete the development of a fully automated, computer-based linear traverse system, which could provide results equal to or better than those of a linear traverse performed by a human operator.

The overall results of this study indicate that the repeatability, accuracy, and overall assessment quality of the NG-ACE system in conducting the ASTM C457-98 linear traverse method are comparable to results obtained by manually (human-based) conducting the ASTM C457 linear traverse method. The system hardware and software presently can be deployed and customized to meet the specific needs of other users within the transportation industry.

Table of Contents

List of Figures iv
List of Tables iv
Chapter 1 Introduction 1
Chapter 2 Description 3
2.1 ACE Hardware Description 3
2.2 NG-ACE Analysis Software Approach 5
Chapter 3 Enhancements performed during the Pooled Fund Study 11
3.1 Single Image Analysis 11
3.2 Batch Processing 11
3.3 Performance Caveats 12
Chapter 4 Round Robin Testing 15
4.1 Assessment of NG-ACE Performance Relative to the Round Robin Testing Results 15
Chapter 5 Summary 22
5.1 Findings and Conclusions 22
5.2 Expected Economic Impact 22
5.3 Benefits to DOE 23
5.4 Industry Area 24
5.5 Project Status 24
Appendix.....
A Pooled Fund Study Proposal 25
B Draft Procedures 27

List of Figures

Figure 1. Hardware and data flow for automated scanning system 3
Figure 2. NG-ACE configuration 4
Figure 3. New sample scanning GUI 7
Figure 4. Color analysis method 7
Figure 5. Shape analysis method 8
Figure 6. Profile analysis method 8
Figure 7. Batch processing user interface and report format 9
Figure 8. Test and validation GUI 10
Figure 9. Comparison of NG-ACE and Round Robin testing 18
Figure 10. Chord distributions for RR2, Lab 1 19
Figure 11. Chord distributions for RR2, Lab 4 19
Figure 12. Chord distributions for RR2, Lab 8 19
Figure 13. ACE measured chord distribution - RR2 19
Figure 14. Chord distribution for RR5, Labs 1, 4, 8, 9 19
Figure 15. ACE measured chord distribution – RR5 19
Figure 16. Comparison of acceptance criteria - spacing factor 21
Figure 17. Comparison of acceptance criteria - specific surface 21

List of Tables

Table 1. NG-ACE results compared to the Round Robin testing results 17
Table 2. Repeatability of NG-ACE evaluation process as assessed for RR-2 20

Chapter 1
Introduction

The determination of the microscopical properties, hence characterization of the air-void system, in hardened concrete provides a valuable link to the durability and performance of that concrete. Because of this, knowledge of the air-void structure in hardened concrete is a valuable tool for many. Current manual methods (ASTM C 457 linear-traverse or modified point-count) used to determine the air-void structure in hardened concrete are extremely time-consuming, tedious, and require highly skilled and experienced personnel. Automating the system would save both time and effort and would improve the consistency and repeatability of the operation and its results. Previous efforts have been put forth by many to develop an automated system as such, but not to the degree of accuracy needed and required by many for total confidence. As a result, many resort to the conventional, manual methods of evaluating hardened concrete.

Since 2001, the Missouri Department of Transportation and National Nuclear Security Administration's Kansas City Plant, operated by Honeywell Federal Manufacturing & Technologies, have collaborated on three CRADA's (Cooperative Research and Development Agreements) to develop a fully automated machine vision system to perform the analysis of the air void structure of concrete according to the ASTM linear traverse method. The first two CRADA's were focused on the development of a prototype system, designated ACES, for Automated Concrete Evaluation System. This prototype included a computer controlled two-dimensional stage and sample holder, a vision system consisting of a microscope, a digital black-and-white camera and analog frame grabber, a personal computer, and customized software to perform the image acquisition, analysis, and reporting. Initial evaluations of the accuracy of the ACE system relative to experienced human operators at MoDOT were quite positive. However, ongoing validations to baseline performance of the software against actual manually derived results provided data indicating that additional software developments were required to ensure that the results provided by the ACE System are consistent with those obtained manually. As a result, a third CRADA was initiated to improve the performance of the ACE system to consistently apply the ASTM linear traverse method and to improve the accuracy of the system relative to the results obtained by human experts.

In 2003, MODOT expanded the scope of this effort by initiating and leading a national, pooled fund effort under sponsorship by the Federal Highway Administration. This pooled fund effort included 13 state transportation departments (Arkansas, California, Colorado, Illinois, Indiana, Iowa, Minnesota, Missouri, Montana, Nebraska, Ohio, Virginia, and Wisconsin). The pooled fund study effort was guided by a technical advisory committee which included members of all participating states, the FHWA, and the concrete testing industry. The goal of this pooled fund study was two-fold:

(1) develop improvements in the performance of the prototype ACE system to provide consistent and repeatable results through the automated application of the ASTM linear traverse method to concrete samples while addressing all inevitable conditions that can be encountered during hardened concrete analysis;

(2) accurately assess the variability of the ASTM linear traverse method across the concrete evaluation industry. Accomplishment of this goal then provides a meaningful metric against which the results provided by the automated system can be assessed.

The latter goal was coordinated by MODOT and completed with several participating laboratories through a series of "round robin" tests where concrete samples were evaluated by multiple laboratories (nine in all) and the results evaluated for consistency and variability. The nature of that study, and how it was performed, have been documented in a separate report.[1] However, the results from the round robin study will be used to assess the performance of the ACE system. The ultimate goal of this development effort has been to develop an automated system which will provide consistent and repeatable results and that can find implementation by users in the field of concrete materials, construction, and research.

[1] Simon, Marcia J., (2005). An Interlab Evaluation of the Variability in the ASTM C 457 Linear Traverse Method. Report. OR6-009, Missouri Department of Transportation, Jefferson City, MO, USA

Chapter 2
Project Description

This section will begin with a description of the ACE system hardware and will describe some of the improvements that have been made to the system during this current effort. The operation of the analysis software will then be described along with the enhancements that have been accomplished to improve the performance of the system. Finally, we will compare the performance of the ACE system to those obtained in the round robin testing to evaluate the overall consistency and repeatability of the system.

2.1 ACE Hardware Description

The ACE system uses a high precision, two-dimensional computer-controlled stage to move the concrete sample under a research grade microscope. The image acquisition system consists of a digital color camera, a 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. These characteristics are used to calculate the concrete microscopical properties of interest. All these system components are linked via a graphical user interface which aids the operator in the image acquisition, analysis, and review processes. Figure 1 provides a visual overview of the ACE system operation.

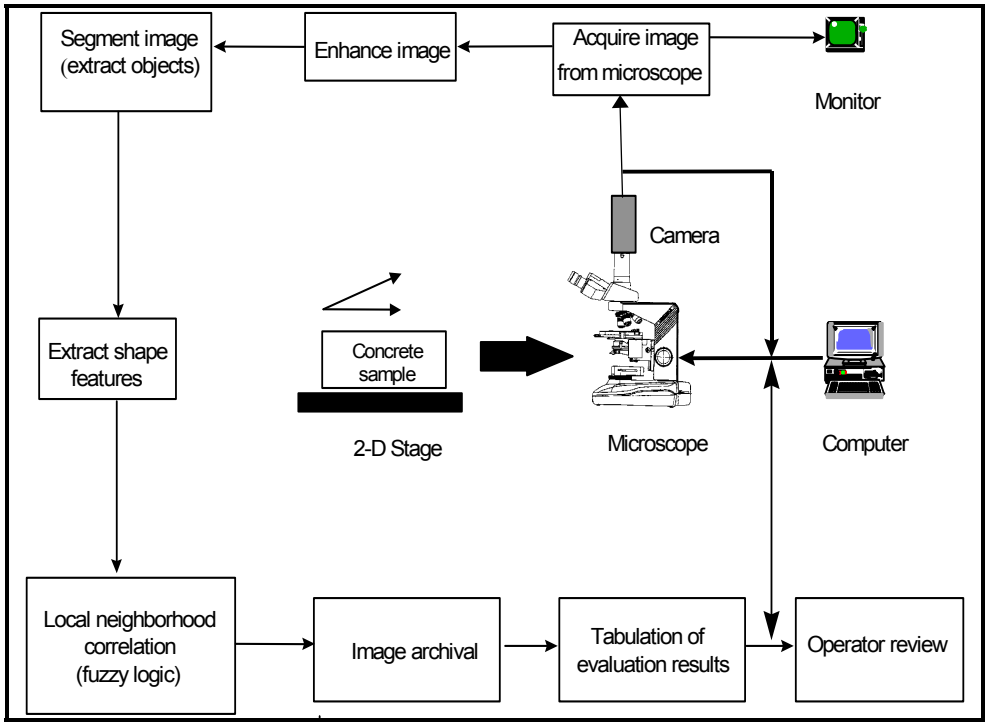

Figure 1. Hardware and data flow for automated scanning system

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.

In conjunction with the pooled fund effort, MoDOT pursued the design of an enhanced version of the ACE system. This enhanced system is designated the "Next Generation ACE" system, or NG-ACE, and incorporates several improvements to increase performance of the system. This includes the addition of a bridge mount to more securely hold the camera and reduce vibration, and the use of an inspection grade microscope, rather than a standard laboratory microscope. In addition, a fully digital camera with a high speed image transfer capability is now used to significantly increase the speed of the image acquisition and archival process over the original ACE system. Computer controlled focusing is available on the new unit, but is not used, as the depth of field of the present microscope optics is sufficient to keep the surface of the sample in focus at all times. A new base plate was also designed and fabricated out of aluminum to minimize base flexure and to prevent mount breakage, which was a problem with the previous ACE system. A picture of the current NG-ACE system is shown in Figure 2.

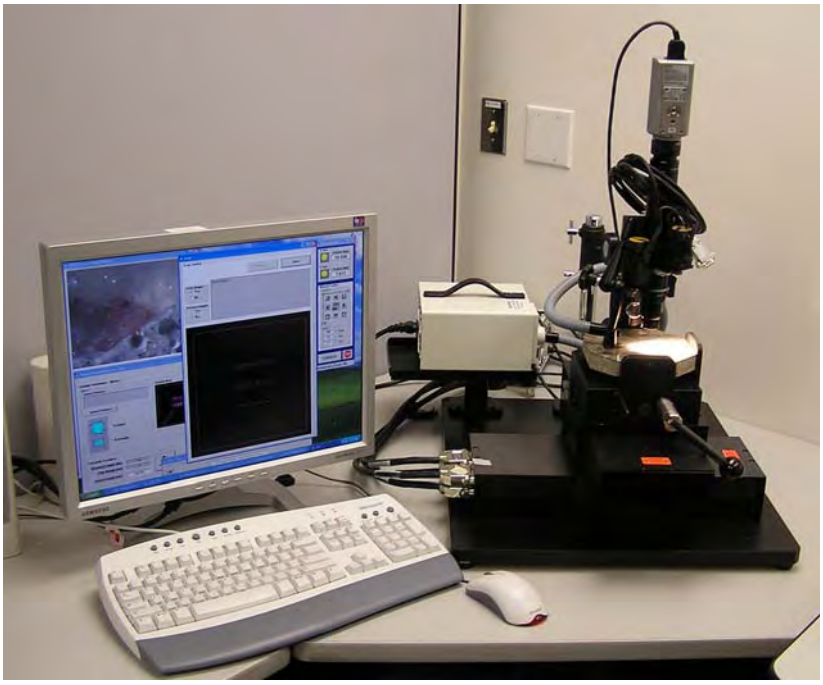

Figure 2. NG-ACE configuration showing the computer, computer-controlled stage, sample mount, digital camera, and lighting (bridge mount not shown).

The basic NG-ACE system components and estimated component costs are provided below (prices as of November 2006). A more detailed equipment specification is available upon request.

- Stage – Aerotech, 2D Linear Stage and controller $21,236
- Camera - Sony DFW-X710, or equivalent $1,900
- *(Inspection grade or Industrial inspection microscope – check on proper terminology)*
- Lens, Illumination, Stand $1,307
- Concrete Sample Mount $12,800
- Isolation table $2,500
- PC $2,500
- Sample scanning, data analysis, and reporting software $20,000
- System integration, test, and validation (at KCP) $5,000
- Shipping, system set up, and training at customer site $15,000

The total cost for the hardware for the NG-ACE system , including analysis software, system integration and setup at the customer's site, and training is approximately $70,000. Individual components may be purchased or provided by the customer for integration into the NG-ACE system, as long as those components meet the quoted NG-ACE specification.

Other services and system capabilities may also be provided, and rough cost estimates for their implementation are also provided below:

- Modify analysis software to perform modified point count - $8K
  This option will implement the modified point count analysis, as detailed in the ASTM C 457-90 standard, as an additional method for determining the air-void structure of samples.
- Incorporate manual analysis and real-time review capability - $10K
  This option will provide additional software to permit the NG-ACE operator to review analysis results and to modify those results as part of the scanning and analysis process. A separate, graphical user interface will be provided that will permit the operator to modify the automated classification results on an image-by-image basis.
- Custom modifications per customer request (TBD)
  Additional modifications to the NG-ACE system can be performed, as requested by the customer. KCP will evaluate such requests and provide a cost estimate for the requested modification.

2.2 NG-ACE Analysis Software Approach

The NG-ACE image analysis and pattern recognition software is capable of detecting features as small as 2 microns on a sample and voids as small as 5 microns. For the purposes of this study, an air void is defined as a space in cement paste, mortar, or concrete filled with air; an entrapped air void is characteristically 1 mm or more in size

and irregular in shape; an entrained air void is typically between 10 microns and 1 mm in diameter and spherical in shape (or nearly so). [2]
The analysis software is used to identify each detected feature and to classify it as void, paste, sand, or aggregate, where traditional definitions of each generally apply, such as paste being cement or cementitious material and water, sand or fine aggregate being those aggregate particles generally smaller than 5 mm (0.20 in.) and coarse aggregate as those greater than 5 mm (0.20 in.).[3] Following the analysis of all acquired imagery, a report is generated by NG-ACE which provides estimates of microscopical properties of interest, as defined in the ASTM standard. These include:

- Percent of air in concrete
- Percent of air in paste
- Voids per inch
- Spacing factor
- Specific surface
- Average air void size
- Standard deviation of air void size
- Percent paste
- Paste/void ratio
- Void/paste ratio
- Distribution of void diameters
- List of voids by size, number, and percent of total voids

A major focus of the pooled fund effort was to improve the performance of the NG-ACE analysis software. Several areas of improvement were identified in the previous CRADA and were targeted for further development in the NG-ACE system. These included:

1. Modify existing NG-ACES software to better match the manually derived void distribution
2. Perform additional validation testing of the existing NG-ACES software
3. Verify performance of the rule bases for image-to-image correlation, and for the fusion of image analysis results.

All these goals were accomplished. The approach used by the NG-ACE system analysis software is detailed below:

- Sample scanning interface
  The scanning interface of the NG-ACE system has been re-designed (Figure 3). All functionality from the earlier version of ACES has been reproduced. However, a threshold selection algorithm has been added to utilize operator input to evaluate image quality and to use this information to set segmentation thresholds. This capability will provide higher quality imagery and more consistent analysis results.

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[2] Kosmatka, S. H., Kerkhoff, B., and Panarese, W. C., "Appendix-Glosssary", *Design and Control of Concrete Mixtures*, 14th Edition, Portland Cement Association, Skokie, IL, 2002, page 335.
[3] Kosmatka, S. H., Kerkhoff, B., and Panarese, W. C., "Chapter 5 - Aggregates for Concrete," *Design and Control of Concrete Mixtures*, 14th Edition, Portland Cement Association, Skokie, IL, 2002, page 79.

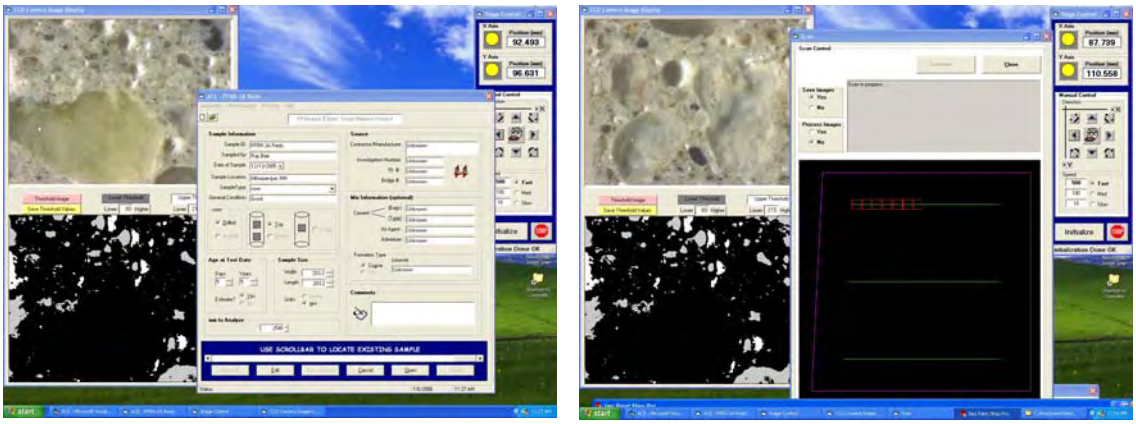


Figure 3. New sample scanning GUI.

- Analysis software
  The goal of the analysis software is to identify voids and other concrete components on an image-by-image basis. This is accomplished through the use of multiple image analysis methodologies, and through the use of data fusion methods to fuse the results provided by the multiple techniques. The NG-ACE analysis software currently uses three analysis methods to identify concrete components in the acquired imagery. The first of these is color analysis (see Figure 4). In this method, the RGB (red, green, blue) color values and band ratios at each point in the image are used as input into a neural network that has been trained to identify the specific color features of each type of component. This results in a color map of the original image which is correlated with the identified components.

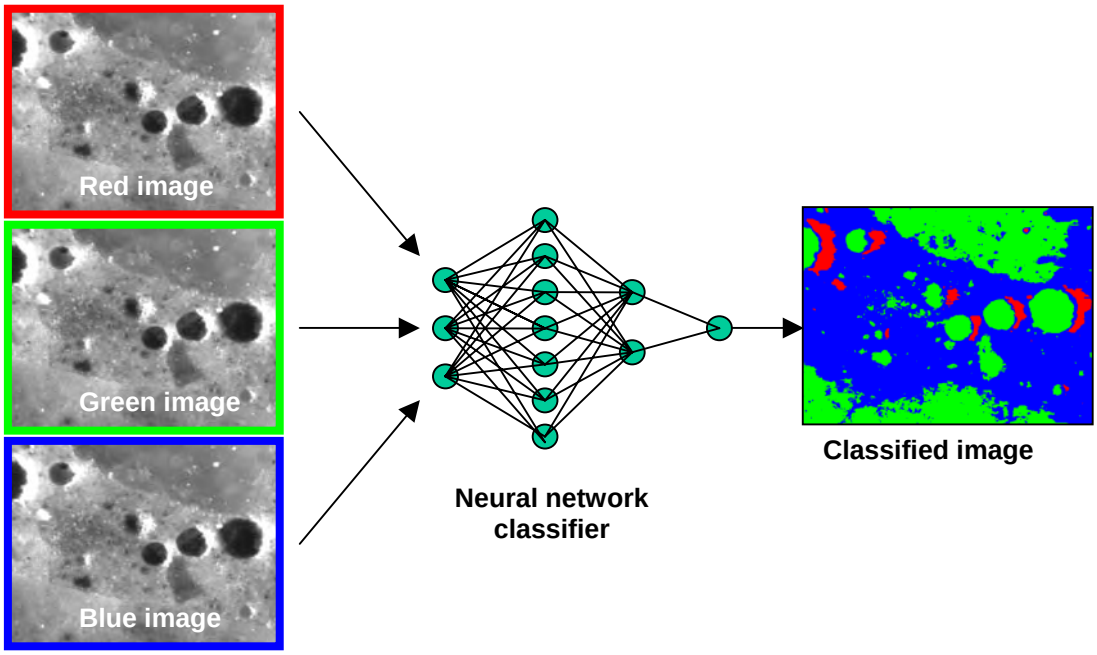


Figure 4. Color analysis method.

The second analysis approach is based on the use of morphological image analysis to identify voids in the concrete based on their shape (Figure 5). This method segments each image into individual objects, or blobs, and then analyzes each object for its unique shape and intensity characteristics. A fuzzy logic correlation algorithm is used to identify voids based on the correlation of key image components which are correlated with the voids.

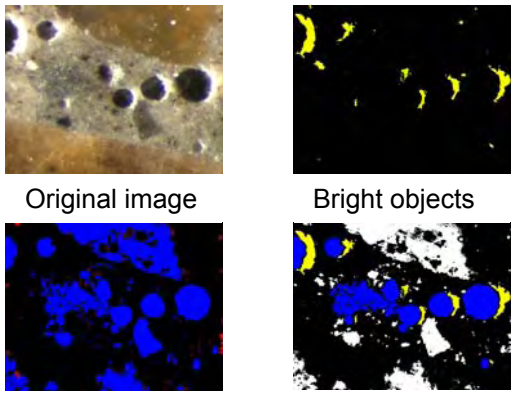


Figure 5. Shape analysis method.

The third analysis approach uses the unique intensity structure of a void to generate a model (or filter) that analyzes the intensity profile along the selected traverse line (Figure 6). The unique intensity features associated with voids are then identified using an expert system rule base, and the void is detected.

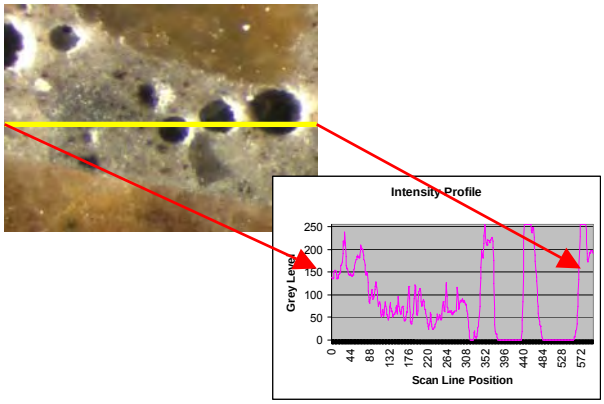


Figure 6. Profile analysis method.

Finally, the results of these three analysis methods are fused together using two different rule bases. The first rule base is applied on an image-by-image basis and correlates the classification outputs from the three individual classification methods.

By correlating the features (and combinations of features) from each of the individual analysis methods, component detection confidence is improved and the number of misclassifications is reduced.

The second rule base is applied across the entire image data set and is used to correlate single image classification results across multiple, contiguous images. Again, the correlation of classification results across multiple images helps to improve component classification and reduce misclassifications

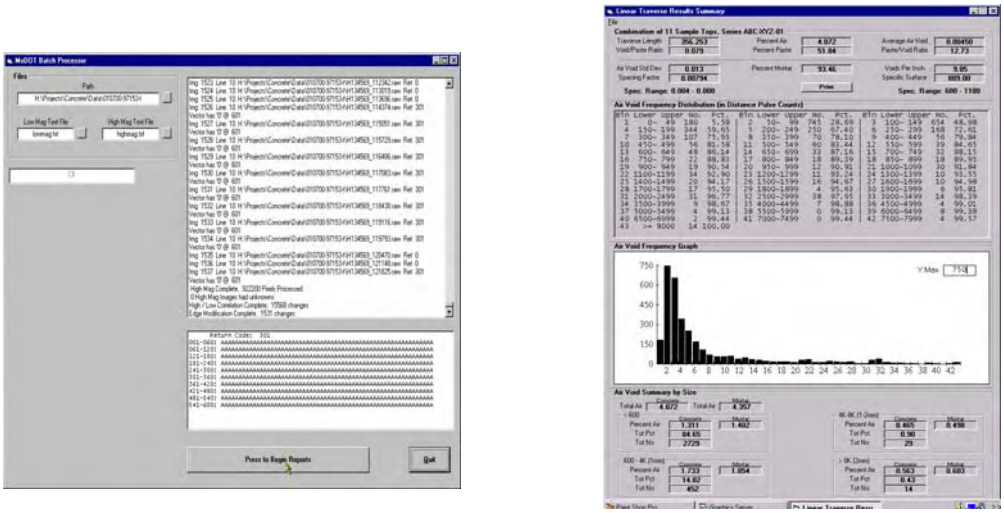


Figure 7. Batch processing user interface and report format

The NG-ACE system also includes three graphical user interfaces that are used by the operator to perform sample setup and scanning, batch processing, and test and validation. A standard term in software development, a graphical user interface or GUI facilitates program use by taking advantage of computer graphics capabilities as opposed to text and commands, enabling user-friendly interaction through graphics. The NG-ACE sample setup and scanning GUI was described above. The batch processing GUI is shown in Figure 7 and is used by the operator to process an archive of imagery acquired from a sample. The batch processor reads and analyzes each image in sequence as described above, and then combines the results of those analyses across the entire image set. The batch processing GUI also generates the final report (also shown in Figure 7) which provides the computed microscopical properties of the sample according to ASTM C457-98.

Finally, the test and validation GUI is shown in Figure 8. With this GUI, the operator is able to analyze individual images and directly assess the performance of the analysis process. It should be noted that this GUI only displays the results of the analysis on a single image basis. Classification results can change when the image-to-image correlation is performed by the batch processing GUI.

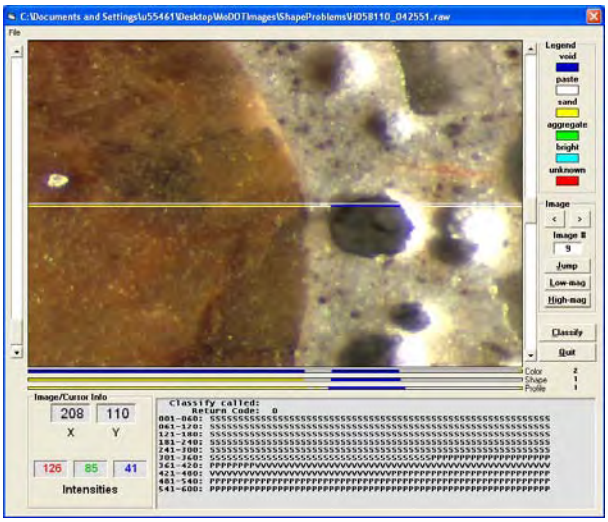


Figure 8. Test and validation GUI

Chapter 3
Enhancements performed during the Pooled Fund Study

In support of the Pooled Fund study, a significant number of modifications and enhancements were made to the NG-ACE analysis software. The most significant modifications are described in the sections below.

3.1 Single Image Analysis

- Color method - Added a neural network classifier to improve classification accuracy.
- Shape method - Improved the performance of the watershed algorithm, although this does not always yield improved results. This is because the watershed algorithm is applied after a contrast stretch of the subject image and this reduces intensity resolution within the image.
- Shape method - Added approach to identify spurious voids that may occur due to anomalous bright regions.
- Shape method - Added capability to identify separated chords belonging to the same object. This reduces false detection of multiple objects.
- Profile method - Added region analysis which analyzes the areas above and below the traverse line and correlates component identification information with that measured on the traverse line. Improves overall void detection capability and reduces false void reports.
- Single image analysis - Incorporated chord identification and evaluation into each of the three analysis methods. This simplifies the design of special rules within each analysis method to improve void detection and to reject false voids.
- Single image analysis - Added the BRIGHT category to each analysis method and the fusion algorithm. This aids in the identification of voids across multiple image boundaries, and provides confirmation of void extraction.
- Single image analysis - Incorporated texture analysis to improve the identification of single component images and to aid in the discrimination of large voids from large, dark aggregate.
- Fusion approach – Added fusion analysis at the "technique" level to improve shallow void detection and reduce false void reports. This consisted of the inclusion of a number of rules that correlate the classification output from the three evaluation techniques to improve classification accuracy on an image-by-image basis.

3.2 Batch Processing

The goal of the batch processor is to correlate single image classification results across multiple, contiguous images. The most significant change in the batch processor algorithm was the elimination of the low magnification image analysis task. Originally, the low magnification scan of the sample was required to identify the presence of large voids and large coarse aggregate. High magnification images of such large components did not provide a sufficient amount of information for analysis (i.e., high magnification images of large voids and dark aggregate are often totally dark). However, enhancements

in the single image analysis software (as described above), and in the batch processor (as described below) rendered the analysis results from the low magnification imagery as redundant. As such, this modification alone permitted the elimination of the low magnification scan from the image acquisition process, and processing of the low magnification imagery from the analysis process. Elimination of the low magnification scan resulted in the reduction of the amount of time needed to acquire imagery from a sample, as well as the length of time needed to process all acquired imagery. In addition, the need for the operator to switch the NG-ACE equipment from the low magnification setup to the high magnification setup was eliminated.

Specific capabilities that were added to the batch processor include the following:

- Added rules to identify and use the presence of BRIGHT segments to identify voids. Use of these segments improves and validates void detection.
- Incorporated a scale check using BRIGHT segments to identify large sand or aggregate chords that have been misclassified as voids. Places constraints on the relative size of the void intensity components to confirm void detections and reject false void reports.
- Incorporated new methodology to identify shallow voids. Often, shallow voids will not present an intensity structure that allows them to be consistently identified by the three analysis techniques. The new approach correlates classification data from the three analysis methods to identify a (usually) consistent intensity pattern in the chord data associated with shallow voids.

3.3 Performance Caveats

With all the improvements that have been made to the analysis software and the batch processor to improve void detection and reduce false void reports, there are still several anomalies or "pathologies" in the concrete samples that tend to reduce classification accuracy. These include:

- Missed voids
  Despite best efforts to design the NG-ACE analysis software to accurately and consistently extract voids from the acquired imagery, there still remain instances where voids are not extracted. Small variations in the lighting across the sample, unusual void structures and small, shallow voids sometimes result in a void being missed. This is to be expected as no computer algorithm can anticipate all the potential pathologies that can occur in the void intensity structure due to these effects. However, the results of the round robin testing described below, and the relatively low occurrence of missed voids suggest that any error in the measured air-void structure introduced by the missing voids will be small compared to the measured variance of the manual evaluation process.
- "Pull-outs"
  "Pull-outs" are essentially voids that are produced due to the dislodgement of a sand particle during the sample polishing process. Typically, the voids that are generated as a result of this are irregularly shaped and do not exhibit the typical circular shape of an actual void. As such, the NG-ACE analysis software often is able to discriminate these types of spurious voids from true voids. However, the software is

not always successful in identifying these types of voids and additional software would have to be developed to improve this discrimination capability.

- Quartz sand
  Quartz sand continues to be problematic within the current NG-ACE analysis process. The appearance of quartz sand mimics the intensity structure of an actual void in that a portion of the sand grain appears dark, like a void, and the complementary part appears brighter, comparable to PASTE. As such, the sand grain is never completely extracted and, typically, the lighter half of the grain is identified as paste. This elevates the reported paste percentage. One possible solution to this problem is to try to uniquely identify the quartz sand through the use of more sophisticated texture processing algorithms to try to differentiate between the smoother surface of the quartz sand and the coarser surface of the surrounding paste. Again, this approach has not yet been incorporated into the NG-ACE software.
- Voids in aggregate or sand
  Voids in aggregate and sand are not to be included as part of the entrained air percentage estimate. Several rules were designed into the analysis code and the batch processor to identify and correct these types of misclassifications, but they are by no means 100% accurate in their results. Typically, aggregate and very large sand grains will be classified as single component images and voids within these components will not be reported.
- Entrapped air voids
  Very large voids (> 1mm) are typically considered as entrapped air, rather than purposely entrained air. However, since different laboratories handle entrapped air differently, a decision was made to leave entrapped air voids in the analysis process. Individual users may choose to remove these large voids from the analysis of the air void structure by specifying the chord length to be associated with entrapped air during the batch analysis process (default is 1 mm). Specific information about the entrapped air in a sample is provided in the report as Percentage of entrapped air in sample relative to the total air in the sample, and relative to the total traverse length.
- Graphical User Interfaces (GUI's) and the reporting function
  In the course of several meetings and discussions with members of the transportation industry, a number of enhancements to the sample scanning GUI, the analysis GUI, and the final report format have been suggested. Some of these changes were incorporated into the NG-ACE system. These included:
  - Development of a lighting level calibration approach to aid the operator in selecting intensity thresholds to improve image segmentation (scanning GUI)
  - Establishment of a standard parameter file, an "ini" file, to contain selected threshold values. This file is read by the single image analysis algorithm and by the batch code.
  - Determination that an automated focus capability is not needed. The depth-of-field of the current optical system is sufficient to maintain sharp focus across the entire sample.
  - Development of an operator's manual (provided in Appendix B)
  - Measured void distribution is now provided in a separate output and is also included in the analysis report as a histogram.

- User specified entrapped air size limit (incorporated into the in the batch analysis GUI).

There were a number of additional modifications that were suggested. However, these modifications were not performed due to limited funding and due to the primary focus of the development effort which was to improve classification performance of the system. As such, these particular enhancements will be performed on an "as-needed" basis as requested by the customer:

- Run a check on field-of-view to ensure correct magnification setting
- Traverse line length, area covered feedback to operator during the traverse line setup to ensure minimum analysis area covered based on coarse aggregate size. Coarse aggregate size is input, minimum scan length and area provided as guideline to operator.

Provide operator with option to select output information in counts (1/100,000 of an inch), pixels, microns

- Update sample database information, add mix information, include on report
- Develop additional code to check for voids in aggregate
- Develop manual processing capability that allows operator to review each image, modify classification results as needed, and save modified chord data.
- Modify analysis reporting to use modified point count methodology

Chapter 4
Round Robin Testing

A key component of this pooled fund effort was the execution of a two-phase round robin study among nine laboratories (ten in phase 2) to estimate the variability of the ASTM C457 linear traverse method when applied manually. Sources of known variability associated with the linear traverse include: specimen preparation effects, operator experience and ability, equipment (magnification, method of viewing, lighting), and inherent statistical variability of the method itself. Assessing the variability, including both between-lab and within-lab variability, of the linear traverse test method would then provide a benchmark for performance of the NG-ACE system. Between-lab variability or expected accuracy of the NG-ACE system would be determined based upon results from multiple laboratories on a single specimen, while within-lab variability or expected precision would be based upon multiple test results on the same specimen.

As discussed in the final report "*An Interlab Evaluation of the Variability of the ASTM C 457 Linear Traverse Method*", the round robin testing used five concrete specimens which were obtained from different locations around the country. Air content among the five samples ranged from approximately 4.5% to 8%. In each phase, the participating labs performed a total of nine linear traverse tests – one linear traverse on four of the specimens, and five linear traverses, using five different sets of traverse lines, on the fifth specimen. This enabled the evaluation of the human operator-based ASTM test method and its between-lab and within-lab variability. All tests were to be run at 100X magnification on the participating lab's equipment. For phase 1, the concrete specimens were prepared by the lab supplying the specimen, using the lab's standard equipment and procedure. For phase 2, the five concrete specimens were collected and the surfaces were prepared again, but by one lab. Air void system parameters evaluated for variability in the study included air content, voids per inch, spacing factor, and specific surface.

Findings of the round robin study (across all nine laboratories) indicate that wide variations exist in the between-laboratory results derived from the manual application of the ASTM C457-98 standard, which strongly supports the development of an automated image analysis system for performing ASTM C457 measurements. For the purpose of comparing the round robin results with those derived from the automated NG-ACE system, a smaller subset of the manually-derived laboratory results was established based on the results from the five laboratories that demonstrated the most consistency in their measurements for phase 2.

4.1 Assessment of NG-ACE Performance Relative to the Round Robin Testing Results

The first step in assessing the performance of the NG-ACE system is to determine if the results derived by the automated system are in "agreement" with the manually derived results. First, what constitutes agreement? We know (intuitively) that the computer will never be as accurate as the most qualified, experienced human in extracting all voids and in dealing with pathologies (unusual situations which require human assessment to

resolve). Further, the results of the round robin testing identified a relatively significant amount of variance in the manually derived air void parameters. As a result, as long as the NG-ACE system provides estimates of the air void parameters which are within the observed variance of the manual results, then "agreement" is established. In the sections below, the accuracy, repeatability, and overall assessment capability of the NG-ACE system is compared to the manually derived round robin results.

Accuracy of the NG-ACE System

The accuracy, or proximity to a true value, of the NG-ACE system is determined through a between-lab comparison of the NG-ACE-derived results with those derived manually in the round robin study. Given that the true air-void parameters for each of the samples are unknown, the 95% confidence interval for each parameter, as computed from the manual round robin results, was used as a comparison metric. This interval represents the range of values, consistent with the data, that is believed to encompass the "true" value with high probability (95%). As such, the measured NG-ACE values are compared to the manually derived results by scaling the NG-ACE values relative to the lower and upper limits of the 95% confidence interval as determined by the round robin study (*An Interlab Evaluation…Method*, Table 13). In particular, the NG-ACE estimated values are scaled between 0 and 1, representing the lower and upper 95% confidence interval limits, respectively. Hence, any scaled value between 0 and 1 means that the NG-ACE estimated parameter falls within the manually derived 95% confidence interval for a particular measurement set (nine lab or five lab). Similarly, any value less than 0, or greater than 1, means the NG-ACE estimated parameter fell outside the manually derived 95% confidence interval for the particular measurement set.

The round robin results are presented in Table 1 for the five round robin samples (Phase 2). In this table, the mean and the lower and upper 95% confidence intervals for each of the five measured parameters (% air, specific surface, spacing factor, voids per inch, and average void size) are provided as derived from the nine and five laboratory datasets, along with their scaled values. Any NG-ACE estimated air-void parameter which falls outside the 95% confidence interval is highlighted in yellow. As can be seen from this table, there is excellent agreement between the NG-ACE derived results and the Round Robin results.

Table 1. NG-ACE results compared to the Round Robin testing results.

			9 Lab Sample (Phase 2)				5 Lab Sample (Phase 2)			
Sample	**Air Void Parameter**	**NG-ACES Estimate**	**Mean**	**95% Lower Limit**	**95% Upper Limit**	**Relative to 95% Confidence Interval**	**Mean**	**95% Lower Limit**	**95% Upper Limit**	**Relative to 95% Confidence Interval**
RR1	**% Air**	4.209	4.79	3.52	5.84	0.30	4.68	3.98	5.38	0.17
	Avg. Air Void	0.0057	0.0066	0.0051	0.0069	0.33	0.0060	0.0055	0.0065	0.21
	Voids per inch	7.42	7.52	5.24	10.39	0.42	7.82	6.27	9.37	0.37
	Spacing Factor	0.0072	0.0080	0.0061	0.0084	0.47	0.0073	0.0065	0.0080	0.46
	Specific Surface	705	623	574	763	0.70	668	611	725	0.82
RR2	**% Air**	6.01	6.58	4.57	8.98	0.33	6.77	5.44	8.11	0.21
	Avg. Air Void	.0034	0.0043	0.0030	0.0040	0.38	0.0035	0.0032	0.0038	0.30
	Voids per inch	18.08	16.39	14.48	23.93	0.38	19.20	16.36	22.05	0.30
	Spacing Factor	.0035	0.0040	0.0023	0.0041	0.65	0.0032	0.0027	0.0038	0.75
	Specific Surface	1206	1001	974	1310	0.69	1142	1041	1244	0.81
RR3	**% Air**	4.58	5.19	3.74	6.65	0.29	5.20	4.32	6.07	0.15
	Avg. Air Void	.0039	0.0048	0.0033	0.0050	0.34	0.0041	0.0036	0.0047	0.23
	Voids per inch	11.88	11.23	10.25	14.93	0.35	12.59	11.18	14.00	0.25
	Spacing Factor	.0050	0.0060	0.0041	0.0057	0.54	0.0049	0.0044	0.0054	0.57
	Specific Surface	1037	880	736	1224	0.62	980	833	1127	0.69
RR4	**% Air**	5.26	5.16	3.62	6.92	0.50	5.27	4.27	6.26	0.50
	Avg. Air Void	.0048	0.0053	0.0032	0.0060	0.56	0.0046	0.0038	0.0055	0.59
	Voids per inch	10.94	10.28	9.67	12.73	0.41	11.20	10.28	12.12	0.36
	Spacing Factor	.0061	0.0060	0.0046	0.0063	0.86	0.0055	0.0050	0.0060	1.09
	Specific Surface	832	797	631	1096	0.43	863	723	1003	0.39
RR5	**% Air**	6.48	7.22	5.03	10.54	0.26	7.78	6.12	9.45	0.11
	Avg. Air Void	.0047	0.0057	0.0039	0.0060	0.37	0.0049	0.0043	0.0056	0.28
	Voids per inch	13.92	13.66	11.54	20.53	0.27	16.03	13.32	18.74	0.11
	Spacing Factor	.0050	0.0050	0.0028	0.0050	0.98	0.0039	0.0032	0.0046	1.30
	Specific Surface	859	761	635	1029	0.57	832	713	951	0.61
					Average	**0.48**			**Average**	**0.47**

An additional way to view these results is to succinctly present the comparison data as a graph. This comparison, with the 5 laboratory subset, is shown in Figure 9 where the range of the NG-ACE derived parameters, and the range of the five laboratory, manually derived air-void parameters (25 for each method), are shown relative to the five lab 95% confidence interval. As can be seen from this graph, the values derived by the NG-ACE system agree quite favorably with the manually derived Round Robin results.

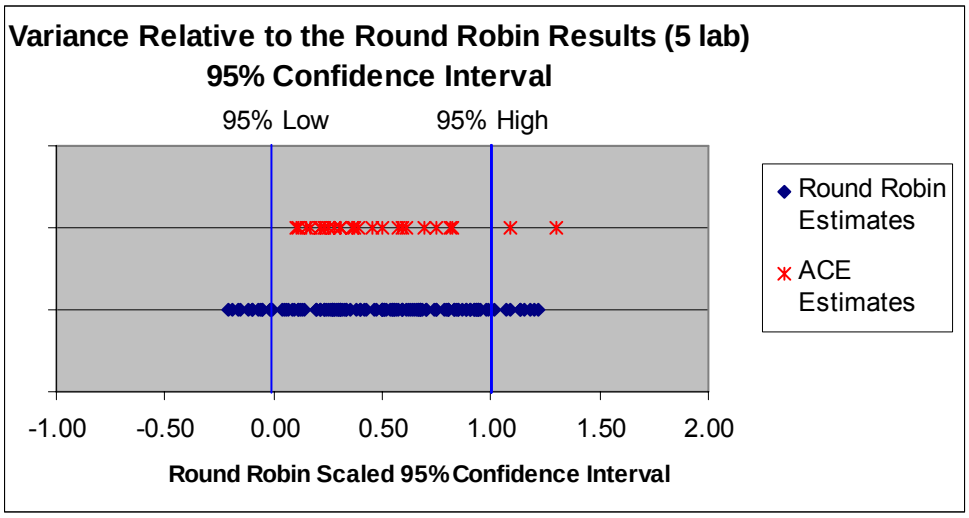


Figure 9. Comparison of NG-ACE derived parameters and those obtained from the Round Robin testing.

Figures 10 - 12 show the void chord distributions for RR-2 as measured by Labs 1,4, and 8, while figure 13 shows the void chord distribution for RR-2 as measured by the NG-ACE system. The void chord distributions shown include the chord data from the analysis of all five sides of the RR-2 sample, as described below in the section on repeatability of the NG-ACE system. The chord distribution measured by the NG-ACE system is consistent with those measured manually in the round robin testing.

Figures 14 and 15 compare the void chord distribution for yet another one of the round robin samples, RR-5. Figure 14 shows the distribution as measured by labs 1, 4, 8, and 9, while Figure 15 shows the distribution as measured by the NG-ACE system. Again, the distribution measured by the NG-ACE system is consistent with those measured manually in the round robin testing.

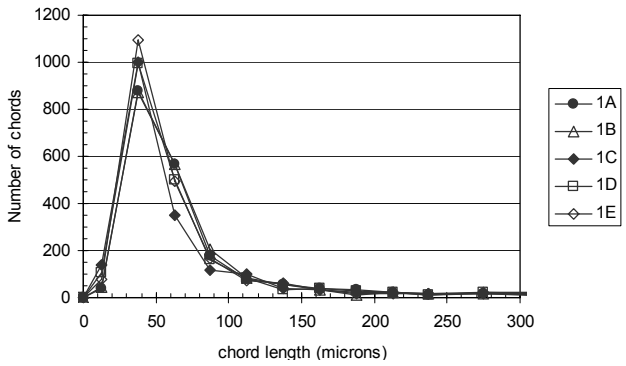


Figure10 . Chord distributions for RR2, Lab 1

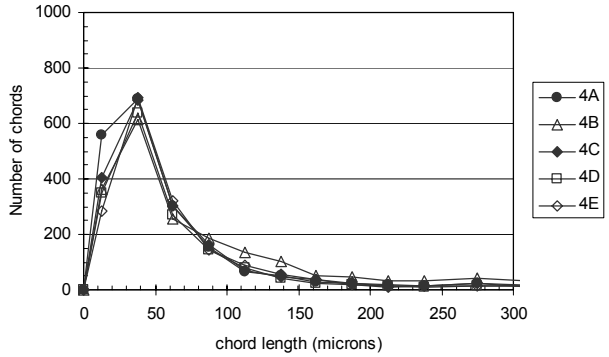


Figure 11. Chord distributions for RR2, Lab 4

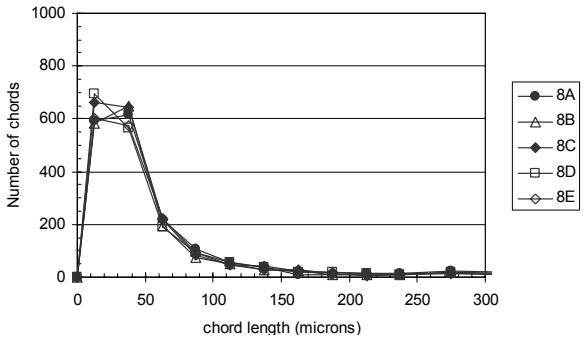


Figure 12 . Chord distributions for RR2, Lab 8

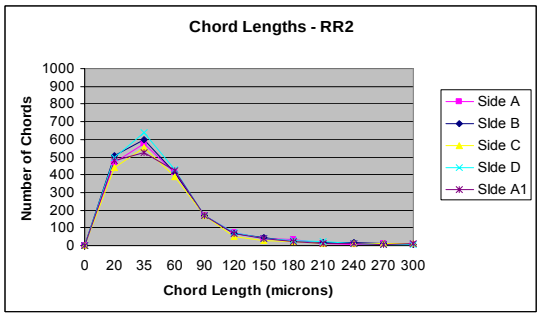


Figure 13. ACE measured chord distribution - RR2

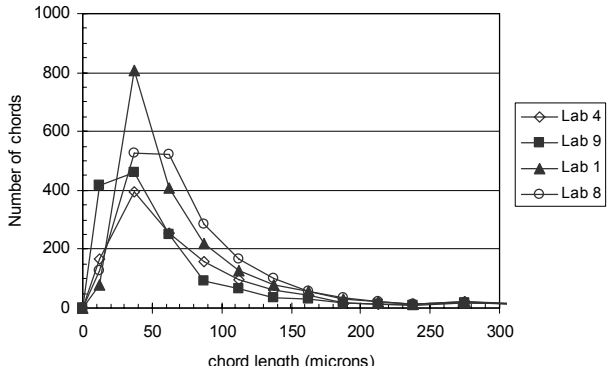


Figure 14. Chord distribution for RR5, Labs 1, 4, 8, 9

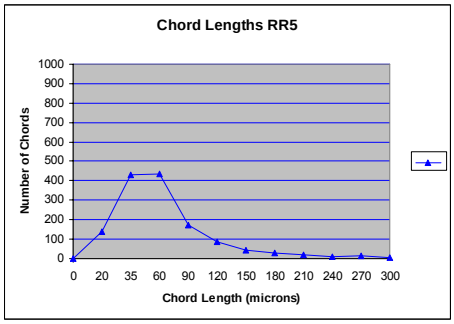


Figure 15. ACE measured chord distribution – RR5

Precision of the NG-ACE System

To evaluate the precision or the repeatability of the ACE system, round robin sample PFRR-2 was analyzed five times, with the sample rotated 90 degrees between analysis runs, generating results for each of the four rotations (Sides A, B, C, and D). For the fifth analysis run, Side A was again processed, but a different set of analysis lines was selected (Side A1). These results were then compared with the manually derived within-lab results for RR-2 of the round robin.

Repeatability results for RR2 are shown in Table 2 where either the pooled standard deviation (SD) or pooled coefficient of variation (CD), as determined for the round robin five-lab subset, is provided for the listed parameters. NG-ACE results for multiple runs of RR-2, along with values determined for standard deviation (SD) and coefficient of variation (CV) for each parameter are also included in the table.

As can be seen, the repeatability of the ACE analysis results compare favorably to those derived manually through the round robin. Another measure of the repeatability of the NG-ACE process is the consistency of the void chord measurements over the five sample runs. Figure 13 (displayed earlier) shows that the void chord distributions measured over each of the five analysis runs are very similar.

Table 2. Repeatability of NG-ACE evaluation process as assessed for RR-2.

Five Lab Round Robin Repeatability Test Results[1] --- RR-2, Phase 2				
Over All Labs	**% Air**	**Voids per inch**	**Spacing Factor**	**Specific Surface**
Pooled SD	0.35			
Pooled CV (%)		6.20	5.60	5.90
NG-ACE Repeatability Test Results --- RR-2, Phase 2				
Sample PFRR-2	**% Air**	**Voids per inch**	**Spacing Factor**	**Specific Surface**
Side A	5.7	17.85	0.0036	1260
Side B	6.035	18.82	0.00344	1247.2
Side C	6.165	16.6	0.00376	1076.5
Side D	6.41	19.32	0.0033	1207
Side A1	5.74	17.8	0.0036	1238
Mean	6.01	18.08	0.0035	1205.74
SD	0.30	1.05	0.00018	74.85
CV (%)	4.95	5.81	4.96	6.21

Overall Agreement

The ultimate goal of any manual or automated process that implements ASTM C457-98 is to assess the overall quality of the measured sample, and to determine if the sample meets standards or does not. Overall agreement between the NG-ACE system and manual operators is established if the overall "accept vs. reject" decision provided by the NG-ACE agrees with the decision provided by a manual operator. For comparison purposes, the spacing factor and specific surface parameters were used to compare the automated decisions to manual decisions. Industry accepted limits for these two parameters are that the spacing factor for a sample be less than .008 in. and the specific surface be greater than 600 in^{-1}. Figures 16 and 17 show comparisons of the NG-ACE-derived values and the manually-derived values for these two parameters.

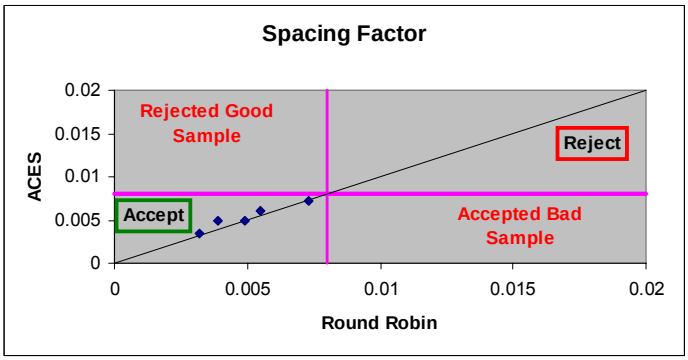


Figure 16. Comparison of acceptance criteria - spacing factor

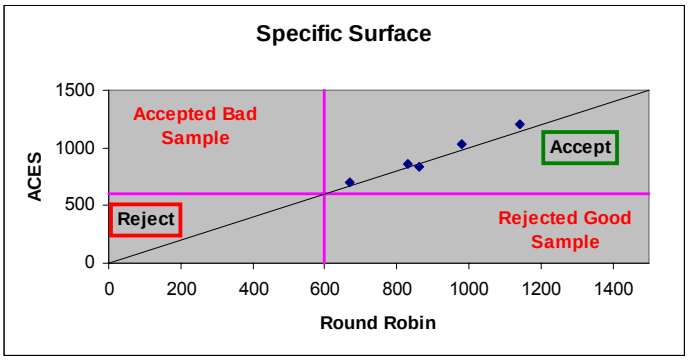


Figure 17. Comparison of acceptance criteria - specific surface

These figures show that, at least for the five round robin samples analyzed in this study, the NG-ACE system provides measurements of these two parameters which are in agreement with the manually-derived results. Further, these figures also show that NG-ACE, again for at least the five round robin samples used in this study, never rejects a sample that manual results indicate should be accepted (Type I testing error), nor does the NG-ACE accept samples that manual results indicate should be rejected (Type II testing error). As such, the automated system provides "accept vs. reject" decisions which are identical to those provided by manual analysis.

Chapter 5
Summary

5.1 Findings and Conclusions

The results of this study provide a number of findings and conclusions as listed below:

- Given the variability which is recognized to exist in manually-derived ASTM C457-98 linear traverse results, the NG-ACE derived results fall reasonably well within this range of variability and are comparable to the round robin manually-derived results. As shown in Table 1 and Figure 9, all NG-ACE values are within the 95% confidence interval of the nine laboratory results, and all but two of the values are within the 95% confidence interval of the more restrictive five laboratory results. In the small number of cases (two) where an NG-ACE estimated parameter was outside the 95% confidence interval, the deviation was never very far outside the interval limits.
- The repeatability of the automated NG-ACE system is comparable to the repeatability of the manually implemented process, as demonstrated in Table 2.
- As displayed in Figures 16 and 17, the NG-ACE system provides acceptance decisions which are in agreement with those determined by the manually implemented process.
- The NG-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 and cost is realized through the use of the NG-ACE system.
- While the NG-ACE scanning and image acquisition processes require a dedicated computer, the analysis of the archived imagery can be performed on any computer.
- Significant reduction in scanning time is possible if the image archival step is eliminated (reduces scanning time by 70%).
- Significant reduction in scanning and analysis times are possible if the pixel resolution is decreased to 2 or 3 microns per pixel, resulting in a smaller number of images to be acquired and analyzed. A slightly lower resolution is not expected to significantly alter the performance of the NG-ACE software.

The overall results of this study indicate that the repeatability, accuracy, and overall assessment quality of the NG-ACE system in conducting the ASTM C457-98 linear traverse method are comparable to results obtained by manually (human-based) conducting the ASTM C457 linear traverse method. The system hardware and software presently can be deployed and customized to meet the specific needs of other users within the transportation industry.

5.2 Expected Economic Impact

This improved process will save time and enhance the evaluation process for air-void analysis of hardened concrete. Many will realize a significant savings in the hardened concrete evaluation process. Those and other potential applications for this prototype system include:

- Scanning and evaluation services provided to state transportation departments,
- The evaluation of concrete properties for other local, state, and Federal agencies,
- The evaluation of concrete properties by research organizations including academia and private industry,
- The evaluation of concrete properties for the construction industry,
- Manufacture of multiple units of the prototype for individual use for all of the above-mentioned organizations.

The development the NG-ACE system, which would accurately determine the microscopical properties of hardened concrete, would serve as a significant benefit not only to highway agencies, but also to the general, highway construction industry. Implementation of such an automated system would save time and effort and would eliminate the need for highly skilled and trained personnel required of the current manual methods. The system would also provide accurate and repeatable results. The strong need for a system, as described, has been demonstrated by the past efforts and continued interest of those in the concrete industry to develop an accurate, automated system using image analysis techniques.

5.3 Benefits to DOE

The image processing approaches and improved image processing capabilities developed on this CRADA are currently being applied in nondestructive evaluation processes in support of weapons surety. In particular, the software analysis approach developed under this CRADA and the previous CRADA is currently being used in an Enhanced Surveillance project for the characterization of high explosive degradation.

The prototype NG-ACE system developed for MoDOT provides surface scanning and image capture capability, and can be used to identify and characterize small voids or defects in surfaces (down to 2-3 microns). The algorithms and capabilities developed in this CRADA, plus the enhanced detection resolution to micron levels, can be used to examine optical imagery and identify and characterize small surface defects and flaws in weapons components (electromechanical, microelectronic, and optical). These techniques can also be used to enhance the capabilities of similar tools being developed within the Enhanced Surveillance diagnostics program. Such projects include:

- Neutron Radiography and High Resolution X-ray Tomography. These projects are building inspection tools for the inspection of entire weapons assemblies. This requires the development of image analysis algorithms to resolve fine features (millimeter scale voids and *at least* 1-mil cracks) with the goal of early detection of potential defects resulting from corrosion, cracking, etc. This CRADA has developed such tools and, as such, represents a capability enhancement over the 1-mil requirement.
- Pit Surface Characterization and Endoscopic Imaging and Optical Coherence Tomography. These projects require the examination and characterization of the surfaces of pits to quantify and document the conditions of the pits. No specific minimum resolution is stated for these projects, but the imaging and analysis techniques that have been developed in this CRADA will provide a resolution capability down to 2-3 microns.

- Ultrasonic Characterization of Assemblies. This project is developing ultrasonic technologies to assess the strengths of bonds in weapons components. The data generated by these techniques is image data, and image analysis and pattern recognition algorithms are required to detect and characterize flaws in the bonds. This CRADA has developed similar algorithms which may be able to enhance the detection and characterization of bond flaws.

FM&T will make this technology and analysis capabilities available to other DOE researchers working on the Enhanced Surveillance Program projects mentioned above (and others). The technology that has been developed on this CRADA with MoDOT has improved DOE's ability to perform core surveillance of the weapons stockpile and has provided FM&T personnel with enhanced knowledge and experience which can be used in developing and integrating similar systems for DOE Programs. Without this CRADA, these enhanced detection and characterization techniques would not be available to the Enhanced Surveillance Program to improve the resolution and capabilities of the above-described ESP diagnostic tools.

5.4 Industry Area

A variety of industries could benefit from the technology developed under this CRADA. These would include:

- Construction industry, for the evaluation of concrete quality for buildings and roadways.
- Software industry, through the modification and application of the software techniques developed under this CRADA for other imaging, surface profiling, and pattern recognition applications.
- Medical industry, through the modification of the prototype system for use with microscope slides, or the use of the developed imaging and recognition techniques for the analysis of medical imagery.
- Federal agencies to include the FAA (for quality analysis of concrete used for runways) and the DOD (evaluation of materials for hardened facilities).

5.5 Project Status

The prototype NG-ACE system was completed in December 2005. The system hardware and software presently can be used as a baseline system to develop integrated analysis approaches for any of the other application areas or industries mentioned above.

Appendix A
Proposed Pooled Fund Study
Sponsor – Missouri Department of Transportation

PROBLEM TITLE

Advanced Research of an Image Analysis System for Hardened Concrete

PROBLEM STATEMENT

The determination of the microscopical properties, hence air-void system, in hardened concrete provides a valuable link to the durability and performance of that concrete. Because of this, knowledge of the air-void structure in hardened concrete is a valuable tool for many. Current manual methods (ASTM C 457 linear-traverse or modified point-count) used to determine the air-void structure in hardened concrete are extremely time-consuming, tedious, and require highly skilled and experienced personnel. Automating the system would save both time and effort and would improve the consistency and repeatability of the operation and its results. Previous efforts have been put forth by many to develop an automated system as such, but not to the degree of accuracy needed and required by many for total confidence. As a result, many resort to the conventional, manual methods of evaluating hardened concrete.

Over the last couple of years, a cooperative effort between the Missouri Department of Transportation and Honeywell Federal Manufacturing & Technologies has made significant progress towards the development of an image analysis system with the degree of accuracy desired. Furthering this research, specifically on a national basis, would work towards the full development of a system having the capability of accurately determining the air-void structure in hardened concrete while addressing all inevitable conditions that can be encountered during hardened concrete analysis. Complete development of this system would enable implementation by many in the field of concrete materials, construction, and research.

RESEARCH OBJECTIVE

The objective of this proposed research is to improve and expand the detection and analysis capabilities of the automated, concrete evaluation (ACE) system. MoDOT and Honeywell jointly developed this system. The focus of this proposed research will be on the following:

- Coordination of concrete imaging efforts with other states,
- Validation and testing of the NG-ACE system on a broad range of concrete samples,
- Identification and development of software and hardware enhancements.

These enhancements will meet the needs of diverse users in the field of concrete materials, construction, and research.

The proposed project will improve and broaden the applicability of the prototype NG-ACE system. This will be accomplished through extensive validation and testing of the

existing analysis software, and the development of new analysis software. Specific tasks to be completed include:

- Coordinate development efforts with other agencies
  Contacts with other organizations in the field of concrete material, construction, and research will be established early in this project to identify other efforts in concrete imaging research. Techniques that may enhance the operation and accuracy of the NG-ACE system will be identified and evaluated. Appropriate teaming relationships will be established as necessary and will ensure that the enhanced NG-ACE system will have the broadest range of applicability within the concrete industry.

- Validation of prototype NG-ACE system
  Testing of the NG-ACE system on a large number of concrete samples is necessary to assess its potential performance. The prototype version of the NG-ACE software was originally developed using scanned imagery from a relatively small number of concrete samples. This allowed the basic analysis methodology for concrete evaluation to be developed. In order to completely evaluate this methodology, a significant validation effort will be undertaken to quantify the performance of the prototype software. This will naturally lead to the identification of specific and beneficial improvements for the software. Additionally, to thoroughly test the potential applicability of the prototype to industry-wide applications, a broad range of representative concrete samples will be acquired from across the nation. Samples with different compositions will be used to validate the performance of the prototype to ensure the software is sufficiently robust to provide accurate analysis of samples, regardless of the specific composition or source. Deficiencies and limitations of the prototype software and/or hardware will be identified and reported.

- Develop additional software and hardware approaches to enhance NG-ACE system operation
  Implementation of new analysis techniques will be performed as the need is identified in the validation phase. Software techniques will be developed to address "pathologies" discovered in imagery, such as merged voids, cracks, filled voids, and debris. Potential improvements to the computing hardware will also be explored with the goal of enhancing the speed of the scanning and analysis processes. Higher speed processors, multiple processors, and high performance computing hardware options will be considered.

- Write final report
  A final report will be submitted. This report will include a summary of work others have performed in the area of concrete evaluation. Results of the prototype validation effort will be presented along with performance metrics (comparison with manually derived results). The capabilities and limitations of the prototype system will be discussed, and recommendations for application of this technology to other concrete industry tasks will be presented.

Appendix B

Draft Procedures for Operation of the Automated Concrete Evaluation (ACE) System – 2nd Generation Version 1.0. - December 10, 2004

Overview

The Automated Concrete Evaluation (ACE) system consists of three major components:

1. The scanning hardware, which includes the computer controlled stage, sample mount, CCD camera, sample illumination, a viewing monitor, and the computer.
2. The two graphical user interface (GUI)/control programs ('ACE' for sample scanning and storage, and 'Batch Process' for image analysis and reporting) written in Visual Basic.
3. An image analysis program, or DLL (written in Visual C/C++) which analyzes each image passed to it by the control program

Updates to the GUI/control programs are easily accomplished by copying the updated version to the directories c:\ace or c:\ace\vb\batchproc. Updates to the image analysis program (the DLL) are accomplished by copying the updated DLL file (MoDOT.DLL) to the directory "c:\ace\dll\release".

Sample surface preparation

ASTM C 457 requires that the surface of the concrete specimen to be examined must be ground and polished to obtain an acceptably smooth, planar surface for microscopical observation. It is important to note that a level plane or flat surface (as opposed to a crowned or rounded surface) is essential in order for the NG-ACE system to acquire the highest quality image collection from the sample's surface. However, ASTM C 457 does not specify any particular preparation method or equipment. Therefore, the preparation methods used and the definitions of what constitutes an "acceptable" surface are often unique to individual laboratories. As such, the surface preparation sequence that was used by MODOT during Phase 2 of the pooled fund study is offered below:

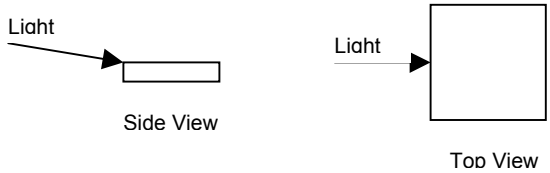
Polishing Equipment	Abrasive	Size	Time	Lubricant
Struers Abrapol	diamond-embedded disc	125 µm	2 min	water
		40 µm	3 min	
	diamond grit solution	15 µm	2 min	polishing lubricant
			4 min	
		3 µm	3 min	

In the event that a particular sample is crowned such that the acquired images do not remain in focus across the scanned area, the required number of images can be acquired over two or three smaller areas so that the imagery stays in focus. These separate sets of imagery may then be analyzed separately and the results combined during the batch analysis process.

Setup Lighting and Illumination Level

The lighting environment under which the ACE system is operated is very critical. Lighting that is not bright enough, or lighting that is too bright, will result in images of inferior quality. In some cases, this will likely result in a failure of the ACE system, requiring the current scan to be re-accomplished. The ideal lighting condition is one in which:

- The lighting illuminates the sample at a grazing angle (see accompanying figure) and ONLY from the left side of the sample (at 90 degrees).



- The sides of the voids opposite the light are brightly illuminated, but not bloomed (i.e., a thin crescent, in most cases)
- The bottoms of the voids are uniformly dark (no light of structure visible in the void bottoms)
- The paste is illuminated to a “moderate” level

Once the lighting intensity has been set, it should not be changed during a scan.

Description of the ACE scanning and image acquisition program

To prepare for an automated scan, create a new folder (directory) with XP Explorer. Once the scan is complete, the new directory will contain three text files:

NAME	DESCRIPTION
logfile.txt	Stores program variable values - primarily for diagnostic use
highmag.txt	Records high magnification image file names - for later use in batch processing
SampOprPos.txt	Records the sample ID, the operator’s name, and whether the sample is a top, bottom, or neither

and will also contain the stored image files. The image file names are generated from the X and Y coordinates where each image was acquired. The file naming scheme is shown below:

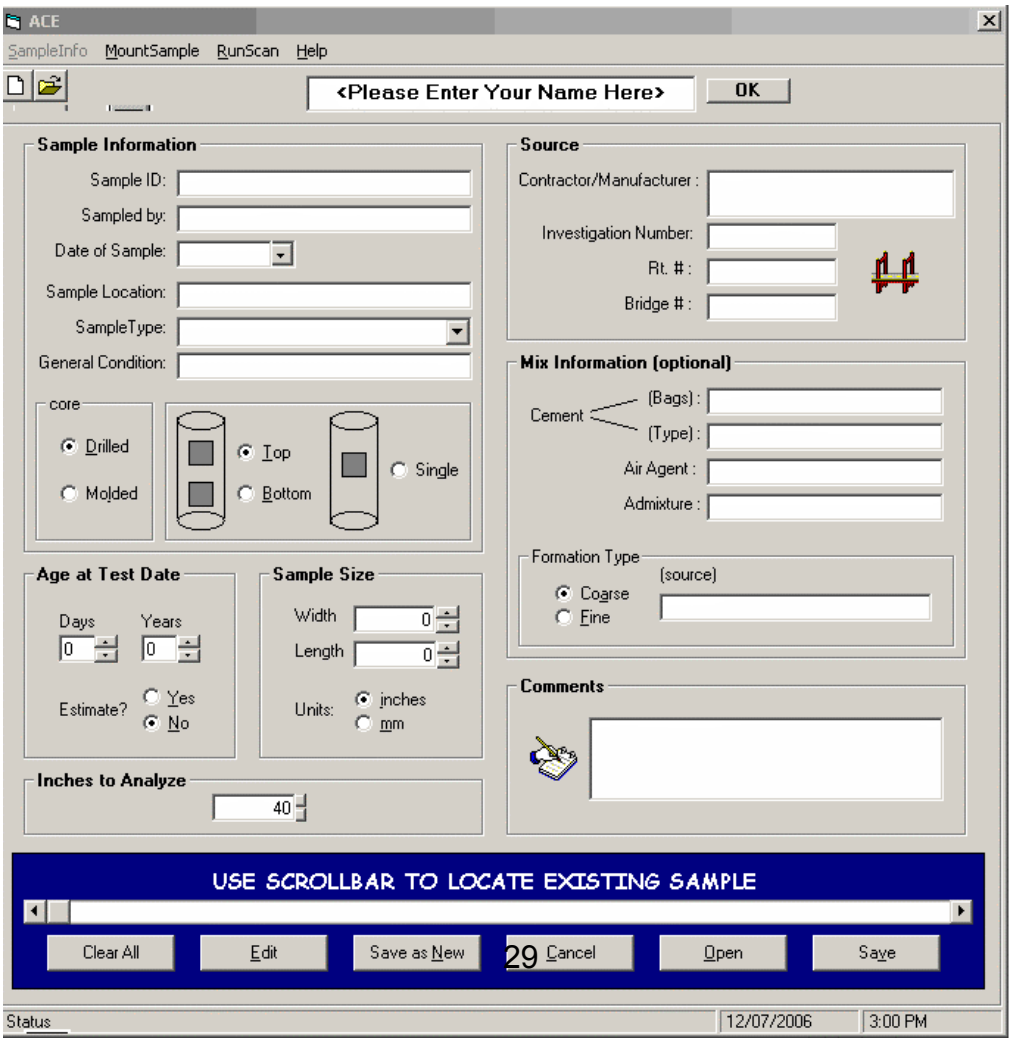
example file name: H123456_024680.raw

- the first character is H for a high magnification image (low magnification images are not used in the NG-ACE system)
- the first number (here 123456) is the Y coordinate (indicates scan line) in microns using 6 digits
- the underscore character separates the Y and X coordinates
- the second number (here 024680) is the X coordinate (distance left or right along scan line) in microns using 6 digits
- the extension for saved image files is .RAW

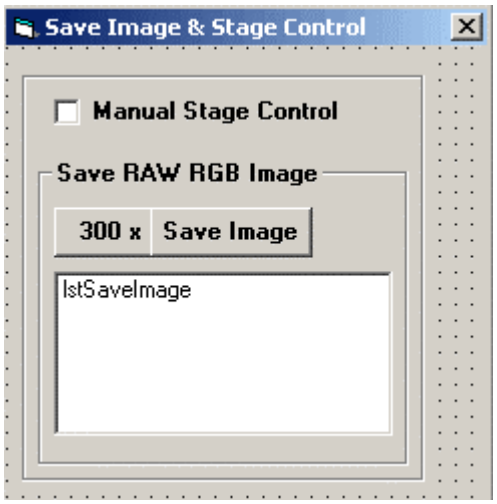
The image files are stored as 600 wide x 449 high x 3 planes x 8 bits/pixel, row major format as RRR...GGG...BBB... with resultant file size, 790KB.

Starting the Scanning Process

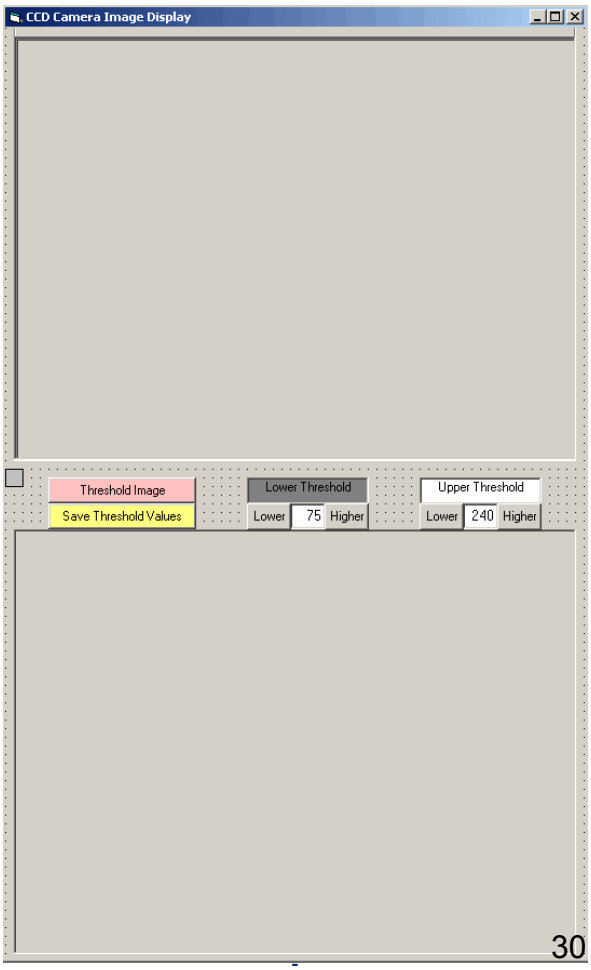
Start the ACE program. The program asks the user to enter information about the sample in the "ACE" user interface shown below:

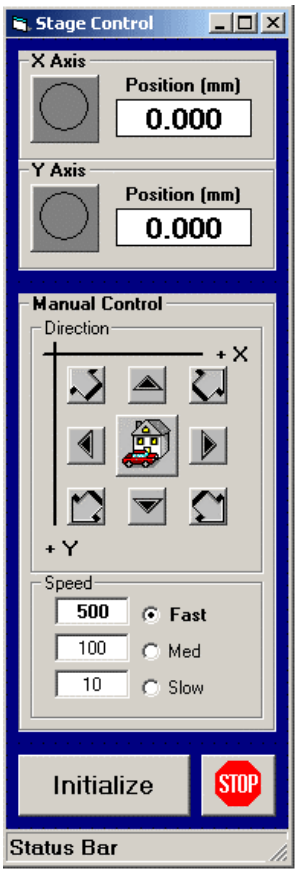


Once the information is entered and saved, check the “Manual Stage Control” box in the “Save Image and Stage Control” user interface.



The “CCD Camera Image Display” window will then open on the left with an image from the camera in the top window. The CCD camera image should be displayed with a threshold window shown below, but may not be visible due to lighting at this point. The “Stage Control” window will also open on the right.





Initialize the Stage
Enable the stage by pressing the 'initialize' button on the stage control form, and then clicking the X and Y indicators to enable the X and Y axis movements. Next, the user should press the 'home' button to send the stage to the home or reference position. After the stage reaches this position, the user should press the 'initialize' button again to zero the X and Y coordinate values at the home position.

Focus the Camera
Focusing is accomplished at the beginning of each scan procedure and once during the scan procedure. Focusing of the image should be accomplished by viewing the displayed image ON THE MONITOR. This is the image that is being captured by the camera and sent to the computer. Focus by first using the coarse adjustment on the camera mount and then the fine adjustment on the lens until a "crisp" image is seen on the monitor.

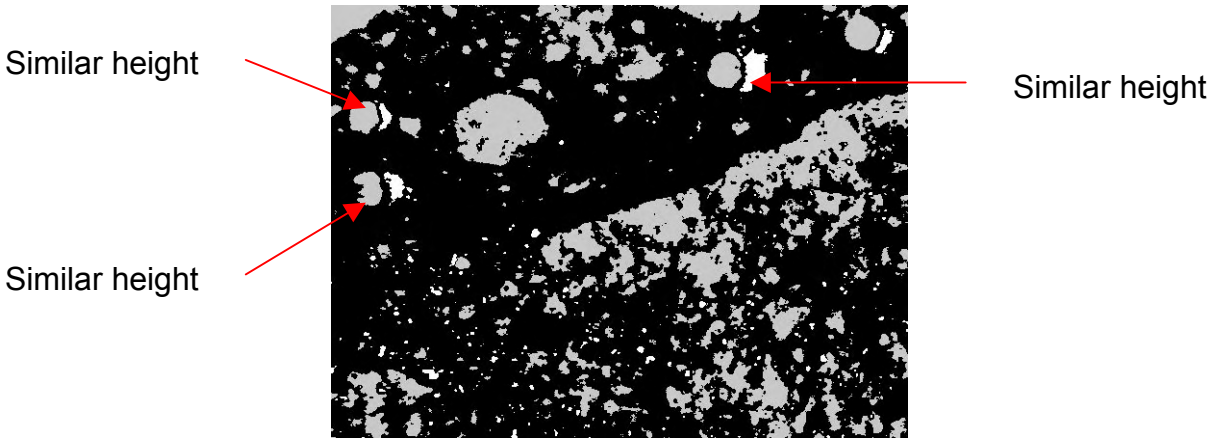
Align the Camera
The x-axis of the CCD camera must be manually aligned with the x-axis of the stage. This ensures that images collected across the concrete sample (along the x-axis of the stage) will coincide with the x-axis of the CCD camera (i.e., along a single row of pixels in the acquired images). This procedure should not have to be performed frequently, unless the camera and/or microscope are bumped out of alignment. The procedure should be performed occasionally to ensure that the camera is indeed aligned with the stage.

The procedure to align the camera is as follows:

- Mount a concrete sample, turn on light source, turn on video monitor
- Using the microscope eyepiece, obtain a good focus through the microscope
- Loosen the set screw (silver) on the silver bushing in which the camera and phototube are mounted. Slide the camera/phototube up and down until a good focus on the monitor is obtained. Tighten set screw.
- Place a straightedge on the sample and within the field of view of the microscope.
- Using the stage controls on the program, move the stage (and sample) back and forth in the x direction and note if the straightedge on the image display moves up or down in the image as the stage is moving across. If it moves, loosen the set screw on the camera and rotate the camera slightly and then retighten the set screw. Note that retightening of the set screw will in itself rotate the camera slightly so compensate for that somewhat when adjusting. Move the stage back and forth to determine if the adjustment was enough. Repeat these steps until the movement of the straightedge in the image is no more than 10% of the height of the image on the monitor while traversing the entire length.

Set the Camera Zoom
The image displayed in the camera should be 1.16mm wide. Obtain an optics scale with resolution down to at least 0.1 mm and place under the lens. Adjust the zoom on the camera until 1.16 mm fills the entire image.

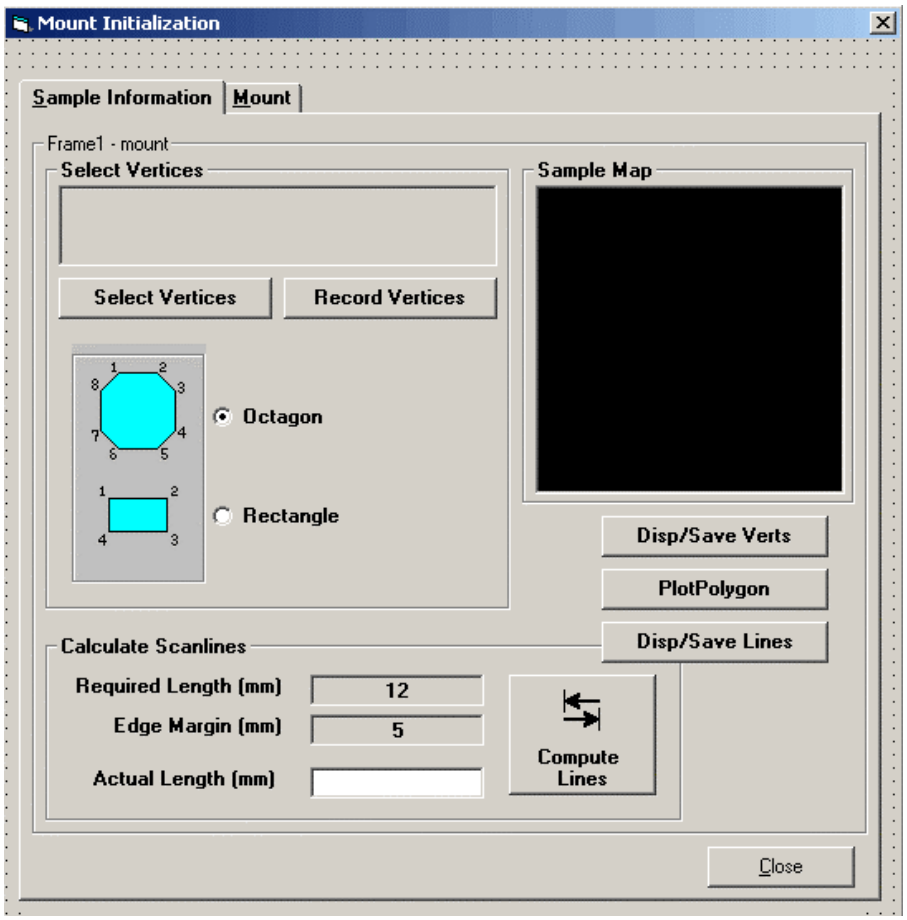
Set the Threshold Values
The purpose of the threshold is to "calibrate" the threshold limits to accommodate different shades of coloring as is found in concrete samples from different regions in the country. Using the manual control arrows, move the image until a void is displayed by the camera. Press the threshold image button and a black, white and gray image should appear that represents the thresholded image. The gray represents a dark regions usually voids and dark aggregate, the black represents the paste or mortar, and the white represents a bright regions. Adjust the threshold lower value (you will need to press the threshold image button every time you change a value) until a void is closely represented in size by a gray area. Next, adjust the upper threshold value until the white "crescent" adjacent to the void is approximately the same vertical height as shown in the image below. Very that this is true on other voids by manually moving the stage to a new area with voids and threshold that image. The voids and crescents should be approximately the same height. If not, make minor adjustments in the upper and/or lower values. The heights don't' have to be exact, but similar. Once complete, press the "Save Threshold Values" button.



After starting the ACE program, the first action the program does is to ask the user to select the directory where the scan files should be stored. The user should select the freshly created new directory discussed above

Set the Vertices for the Region to be Scanned

Select “Mount” from the ACE main menu “MountSample” pull down menu. The following window will open up.



Select a rectangular or octagonal region for the scan lines and then manually move the stage selecting the vertices for the desired region to be scanned. The vertices must go in a clockwise manner beginning in the upper left. Note the numerical sequence in the rectangle and octagon on the display. Once the vertices are set, specify the total length and the margin around the edge of the area specified. Typical values are 2540 mm (100 inches) for required length and 5 mm for edge margin...

Run the Scan

To start an image acquisition run, select “Run” from the ACE main menu “RunScan” pull down menu. The following window will be displayed.

The user must specify the path and directory where the image files will be stored. It IS POSSIBLE to use an existing scan directory. However, the text files in the existing (previously used) WILL BE OVERWRITTEN (DESTROYED) by the new scan. So, MAKE SURE that you don't want to keep the old files if you reuse an old directory. After the path and directory are specified, press the “Begin Scan” button on the “Scan” form. To acquire a complete 100 inch scan of a sample requires several hours.

Description of the BatchProc image analysis and reporting program
Once a scan had been completed and the acquired images are archived, the batch processing program is used to analyze the imagery and generate the analysis report. This program, written in Visual Basic, does the following:

- loads each previously acquired image from hard disk
- calls the DLL program to classify each mid-line pixel in the image
- accumulates the classification results across all images
- performs image edge pixel modifications to correct misclassified boundary pixel effects
- produces a chord file with the order, class, and length of each found segment
- generates the line-by-line results report (format similar to MODOT handwritten form)
- generates the overall summary report (format similar to MODOT summary report)

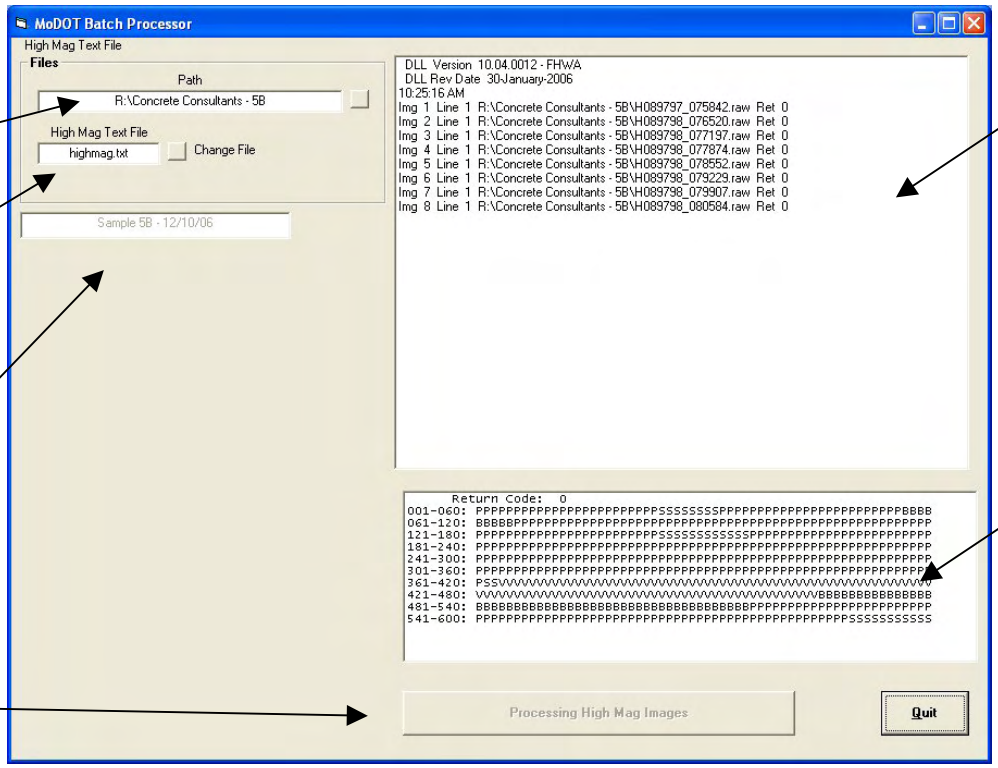
The files produced during the batch process are:

- ***batchlogfile.txt***
  A general log file containing a detailed summary of the entire batch analysis process. This file contains the detailed image-by-image, line-by-line, and overall analysis results from the batch analysis. As such, it is typically a very large file (10 – 20 Mb).
- ***lineres.txt***
  Contains a summary of the overall results on a line-by-line basis.
- ***chord.txt***
  Contains the chord information for the entire scan. This is basically a sequential listing of the chord classification and chord length for all the chords extracted from the analysis.
- ***overall.txt***
  Contains the overall report on the scan analysis in a format identical to that used by MODOT.
- ***Chorddist.txt***
  Contains the chord length distribution information summarized for the scan as a whole. This file can be used to generate a histogram of chord lengths for the sample using Microsoft Excel, or any other plotting package.
- ***RGB.dat***
  This is a small working file which provides a limited amount of information on the last image processed by the batch analysis program. Mainly used for debugging purposes.
- ***SandVoidSand.txt***
  Again, this is a working file which is mainly used for debugging purposes.

NOTE: During the course of the batch process execution, all these files are written to a directory, C:\concrete. This directory MUST exist BEFORE the batch program is executed. In addition, the C:\concrete directory MUST contain a sub-

directory titled WGT (C:\concrete\wgt). This directory will contain the neural network weight files used by the color classification technique. Typically, both of these directories, and all required files, will already exist on the computer as part of the initial installation of NG-ACE program onto the computer.

The graphical user interface for the batch analysis process is shown below:



1. Select directory where scanned imagery is located

2. Allows you to select a different highmag.txt file for processing.

3. Enter any desired information here to identify the scan or the sample.

4 - 8. User control button - changes throughout the analysis

Progress window showing progress of the batch analysis process on an image-by-image basis

Classification window showing classification results for the current image being processed.

Referencing the above figure, the following sequence of steps should be performed to execute a batch analysis:

1. To start a batch process run, the user must specify the path and directory containing the scanned imagery and supporting files.

2. Change highmag.txt file. Typically, this file is generated as part of the scanning process and is always included in the directory with the scanned imagery. As such, the operator will generally not use this option. However, this option is provided so that partial analysis runs can be performed. This is accomplished by generating a copy of the highmag.txt file in another directory (c:\concrete), and then editing that file so that a smaller number of lines are processed. This option is then used to identify the edited highmag.txt file as the one to use for the analysis.

3. Enter any desired information here. Then, hit the “Okay” button.

4. The next step in the analysis process is for the operator to press the large button, located at the lower right portion of the form. This button is the “user control button” and serves to inform the user of current analysis progress and to present the operator with guidance on each subsequent processing step. After the “OKAY” button is hit in the previous step, the user control button changes to “Press To Start Image Processing”. Hit this button to begin the image analysis sequence. The operator can view the progress of the analysis by observing the results output to the progress window and the classification window.

- Progress window - The current progress of the batch process is indicated by these status lines in the progress window. It shows the image number, scan line, path and image file name, and the DLL return code.
- Classification window - The actual classification of each mid-line pixel is shown the classification window. This window shows the DLL return code, and the class of each pixel using the letters V for void, P for paste, S for sand, A for aggregate, B for bright, and ? for unknown. Note that the classification window shows the classification results of each image as it is processed.

5. When the image analysis sequence ends, the user control button will change to “Press To Begin Edge Modification”. Hit this button to begin the image edge-to-edge correlation process.

6. When the edge modification process is complete, the user control button will change to “Press to Begin Custom Rules and Reports”. Hit this button to begin the application of the custom rules and to generate the overall report for the sample.

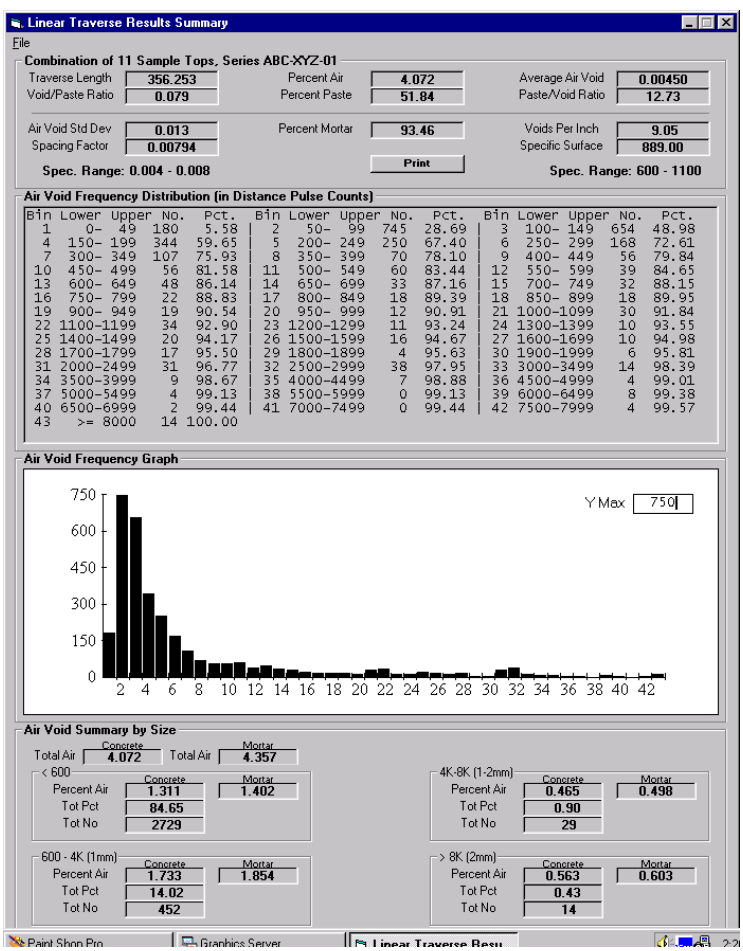
7. During the report generation process, the user will be prompted to identify whether there is a companion chord file to include in the report processing.

The batch analysis program has the ability to append an additional chord file to the current chord file so that the data from the appended file can be included in the overall report. Originally, this option was developed because the top half of a concrete sample was scanned separately from the bottom half of the sample. This option allows the chord file from a previously run sample to be appended to the chord file from the current analysis. Typically, if a sample is analyzed via a single scan, then this option will always be “No”. If there is a companion chord file, then press “Yes”. The program will then present a dialog box to the operator to allow them to specify the location of the companion chord file. The normal companion chord file would be named ‘chord.txt’ and would be located in

another, completed scan directory. Note that you would have processed the first set of imagery WITHOUT a companion file. Then, you combine the scan results from the second set of imagery with the results of the first by pressing “Yes” and identifying the location of the first chord file. The final report generated will then be for the combined scan length of the two separate scans.

8. When the reports are finished, the user control button will indicate “Reports Complete”, and then disappear. The operator can then exit out of the program by hitting the “Quit” button. The final, overall report is shown in the figure below. This report includes the 16 microscopical properties to be calculated per the ASTM standard. In addition, chord length distribution information is provided textually in a table and graphically in a histogram.

9. Final note and WARNING.
All files that are generated as part of the batch analysis process (as described above) are written to the C:\Concrete directory. Each time a batch analysis is performed, these files are OVERWRITTEN. As such, after each batch analysis, the output files should be copied to a separate, uniquely named directory (assuming these results are to be saved for subsequent review).



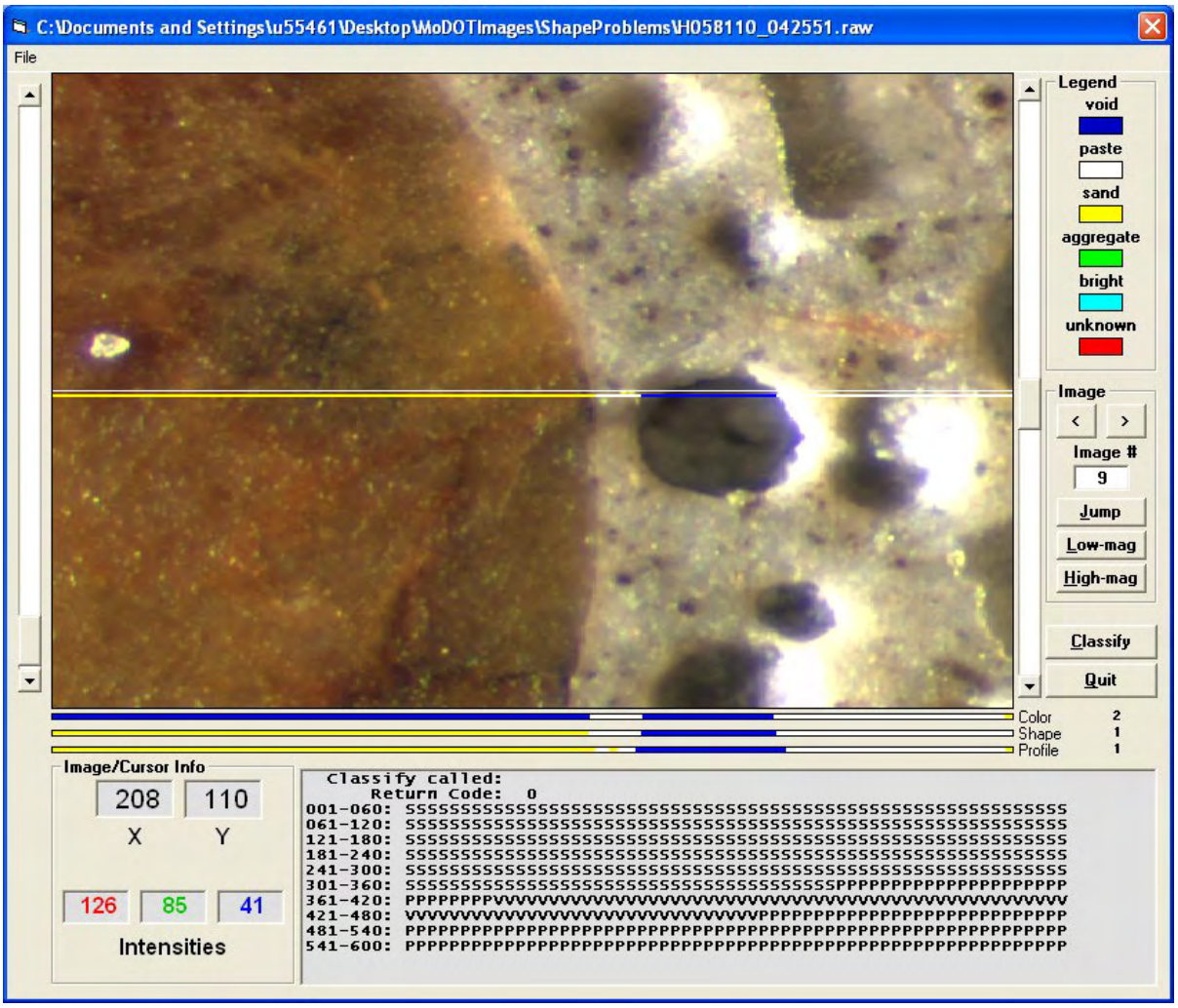
Description of the [newest] graphic DLL Test program
This program allows the operator to select a single image and to analyze the image with the same DLL that is used in the scanning program. In this way, the operator can graphically view the classification results and the results for each analysis technique (color, shape, profile). This program is named DLLTestViewAllClass.exe. The location of this executable program on the computer may vary depending upon the particular NG-ACE installation. Please refer to documentation for the particular installation of the NG-ACE package for the location of this file.

Once the program has been located, double click on its icon from within Windows Explorer.

To run the program, do the following:

- Go up to the file menu and open an image file by clicking on “Open RAW RGB Image File”. If the operator wishes to display a sequence of images collected as part of the sample scanning process, click on the first image in the directory. The program will then ask if you wish to “populate the current directory index”. If the response is “No”, the program will go on to process the single image selected. If the response is “Yes”, then all the images in the current directory will be loaded and the operator can use the forward and back arrows on the GUI to scroll through all the images in the directory.
- Wait while the image is loaded and displayed on the form
- Press the ‘Classify’ button to submit the image to the DLL for analysis and classification
- Once the DLL completes its classification, the program displays the results on the image
- The overall classification of each pixel is shown across the center of the image.
- The program also displays the results of the color, shape, and profile methods near the bottom
- The classifications are indicated by the pixel color
- The legend (which is also displayed on the form) is dark blue = void, white = paste, yellow = sand, green = aggregate, light blue = bright, and red = unknown.

An example screen capture of the tester GUI is shown below:



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