A-9

SCHOOL OF
CIVIL ENGINEERING
INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-88/3 - 2

Executive Summary

AN AUTOMATIC, QUANTITATIVE IMAGE
ANALYSIS SYSTEM FOR CONSTRUCTION
MATERIALS

Dexiang Shi

PURDUE UNIVERSITY

F: 74.01028
L: 8-19-88

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-88/3 - 2

Executive Summary

AN AUTOMATIC, QUANTITATIVE IMAGE
ANALYSIS SYSTEM FOR CONSTRUCTION
MATERIALS

Dexiang Shi

Executive Summary

AN AUTOMATIC, QUANTITATIVE IMAGE ANALYSIS SYSTEM
FOR CONSTRUCTION MATERIALS

Final Report

TO: H. L. Michael, Director
Joint Highway Research Project

January 26, 1988

FROM: D. N. Winslow, Research Engineer
Joint Highway Research Project

Project: C-36-58C

File: 5-12-3

Attached is the Final Report on the HPR Part II study titled "Image Analysis of Highway Materials." This report discusses the development of an automatic quantitative image analysis (AQIA) software system specially designed for materials' analysis. It is implemented on a UNIX operating system with a Tektronix graphics terminal, as was specified in the study proposal.

The report is forwarded to IDOH and FHWA in fulfillment of the objectives of the study.

Sincerely yours,

D. N. Winslow

D. N. Winslow
Research Engineer

DNW/mlc

cc: A.G. Altschaeffl	D.E. Hancher	P.L. Owens
J.M. Bell	R.A. Howden	B.K. Partridge
M.E. Cantrall	M.K. Hunter	G.T. Satterly
W.F. Chen	J.P. Isenbarger	C.F. Scholer
W.L. Dolch	J.F. McLaughlin	K.C. Sinha
R.L. Eskew	K.M. Mellinger	C.A. Venable
J.D. Fricker	R.D. Miles	T.D. White
		L.E. Wood

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

Executive Summary

AN AUTOMATIC, QUANTITATIVE IMAGE ANALYSIS SYSTEM
FOR CONSTRUCTION MATERIALS

by

Dexiang Shi
Graduate Research Assistant

Joint Highway Research Project

Project No.: C-36-58C

File No.: 5-12-3

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Highways

and the

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Purdue University
West Lafayette, Indiana

January 26, 1988

1. Report No. FHWA/IN/JHRP-88/3	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle An Automatic, Quantitative Image Analysis System for Construction Materials		5. Report Date 26 January 1988	
		6. Performing Organization Code	
7. Author(s) Shi, Dexiang		8. Performing Organization Report No. JHRP-88/3	
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West LaFayette, Indiana - 47907		10. Work Unit No.	
		11. Contract or Grant No. HPR Part II	
12. Sponsoring Agency Name and Address Indiana Department of Highways State Office Building 100 North Senate Avenue Indianapolis, Indiana - 46204		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.			
16. Abstract An image analysis software system has been developed for a UNIX operating system and a Tektronix terminal. It is designed for the particles and/or pores in construction materials. This system provides a means to measure many discrete fields of view, in order to obtain statistically meaningful results. The system can process images from either an electron or light microscope, or from an ordinary camera. Either negatives or positives can be used. A new method based on fuzzy probability has been developed to segment digital images into binary images. It is more consistent than existing techniques. The accuracy of the system has been verified with images having known geometric properties. Measurements have an error of less than 1% with an image of appropriate resolution. The system makes different measurements on separate particles and cut planes through massive samples. In the former case, the measurements are: the perimeters, areas, and maximum chords of particles in orthogonal directions, the maximum, minimum and mean values of these parameters, and their distributions. Also, the area of the image, the area fraction of particles and the number of particles are measured. In the case of the cut planes, the estimated parameters are: volume fraction of particles, surface area per unit bulk volume, and surface area per unit particle volume. The size distribution, total number of particles and mean diameter can also be estimated.			
17. Key Words Image Analysis, Construction Materials, Fuzzy Sets, Fuzzy Probability Thresholding		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 129	22. Price

INTRODUCTION

The goal of quantitative microscopy is to measure the geometric properties of particles or microstructures. These measurements are performed on two dimensional images. Stereology is used to estimate the three dimensional properties from the direct measurements made on the two dimensional images. Manual microscopic examinations are time consuming and tedious. In order to obtain statistically meaningful results, it is usually required that many measurements be made. This requirement has been ignored frequently because of the effort that would be required. Recently, computer image analysis has been applied to quantitative microscopy. Because the major advantage of a computer is its capability for processing data, computer image analysis makes practical the measurement of many objects in many images. Therefore, statistical requirements can be satisfied with little human effort.

The process of quantitative image analysis is as follows. The original, analog image is first transformed into a digital image by a digitizer. A digital image is a two dimensional array of numbers, each number representing the light intensity, or gray level, of the corresponding point in the original image. The points are usually called pixels. In order to display the image on a typical computer monitor, the digital image must next be segmented into a binary image. A binary image consists of two types of pixels: object pixels and background pixels. Next, it is sometimes possible to improve the binary image by removing

imperfections and separateing touching objects. This improvement is based upon the user's knowledge of what the real image looks like. Finally, the desired geometric properties of the objects of interest are measured by the computer on the segmented, and improved, image.

Some images are of discrete particles. In this case, one can view the full profile of each particle. When this is the case, the following measurements can be made on the image.

1. Total number of particles
2. Number of particles per unit image area
3. Projected perimeters of particles
4. Projected areas of particles
5. Projected maximum chords of particles
6. Distribution of projected perimeters
7. Distribution of projected areas
8. Distribution of projected maximum chords
9. Maximal, minimal and mean values of projected perimeters
10. Maximal, minimal and mean values of projected areas
11. Maximal, minimal and mean values of projected maximum chords

Other images are of a plane cut through a solid mass of material. Such a plane will generally intersect imbedded objects that are of interest. The following parameters can be determined from measurements of these intersected objects.

1. Volume fraction of objects

2. Surface area of objects per unit bulk volume
3. Surface area of objects per unit object volume
4. Size distribution of objects
5. Number of objects per unit bulk volume
6. Mean size of objects
7. Mean value of the maximum dimensions of objects

Many image analyzers are not specially designed for the study of materials. There are several common computer methods for segmenting an image that are not specially designed for quantitative image analysis because this requires more accurate segmentation than non-quantitative image analysis. Also, object labeling and counting are important in quantitative microscopy. This is very difficult for some automatic image analysis systems because it involves the process of individual object labeling. Sometimes geometric properties such as the areas and perimeters of individual objects are desired. These individual measurements require object labeling and some image analyzers cannot do this.

The current research work has developed an automatic quantitative image analysis (AQIA) software system specially designed for materials' analysis. It is implemented on an UNIX operating system with a Tektronix graphics terminal as a monitor. Compared with many image analyzers, it is almost hardware independent. With a few changes, it can be run on any UNIX operating system with any high resolution monochromatic monitor. With some additional changes it can also be transported to a microcomputer with an appropriate graphic terminal. Therefore, it is much less

expensive than the existing hardware-type automatic image analyzers. It is specially developed for quantitative microscopy of construction materials.

This system tries to combine the advantages of manual examination and automatic image analysis. It has some unique features. It simulates the process of human segmentation to make this process more realistic. It labels objects to make individual measurements easy. With labeled objects, AQIA can process an image more accurately and with more flexibility than can a non-labeling analysis system. Because the reliability of image measurement depends on the accuracy of image segmentation and processing, AQIA is expected to provide more reliable measurements.

AQIA can have a variety of specific applications to cement and concrete research. Image analysis may be the only reliable technique for some measurements such as the distribution of big pores in concrete and flyash particle sizes. AQIA can provide solutions to these kinds of difficult measurements. However, the aim in the development of the AQIA system has been to produce a package of programs that are generally applicable to the broad spectrum of construction materials research. Thus, specialized programs that produce only one result have been avoided. It is hoped that this has produced a package that will be broadly applicable to researchers.

BRIEF GUIDE TO THE AQIA PROGRAMS

The AQIA system is a package of 13 major programs and 6 auxiliary programs. The following is a brief description of the use of these in a typical image processing application. The program names are written in capital letters, and are listed in the order in which they would be used usually.

First, DSCRB initiates the package. It creates a file to hold the processed image. In the file, the initiation time will be recorded automatically. DSCRB also allows the user to briefly describe the sample from which the image has been taken, and to enter the length of one pixel. The segmented image and other relevant information will be appended to this file as processing continues.

REDUCE extracts the image gray level data from the raw image file produced by the digitizer. It also allows the user to reduce the image size and/or the number of gray levels. REDUCE produces a reduced image. After REDUCE, the user must select the method of segmentation.

AQIA has two ways to segment a digital image: straight gray level histogramming and edge-detection histogram thresholding. If straight histogramming is desired, HISTO will be called next. It compiles a histogram of the occurrence of various gray levels. If edge-detection is desired, EGEHIS will be called instead. It singles out the boundaries of objects, and compiles a histogram of the occurrence of gray level gradients.

Then, the user must decide if he/she wants automatic selection of thresholds for either histogram. If the user chooses the automatic method, FUZZTHR must be called next. FUZZTHR will suggest thresholding bounds based on fuzzy set theory.

With or without automatic thresholding, BITSHOW must be called next. BITSHOW asks the user to enter the lower and upper bounds for thresholding. It then displays the binary image on the screen with pixels between the bounds being illuminated. It allows the user to change the bounds until he/she is satisfied with the binary image. If there are some spots in the objects that need to be filled, 'bitshow' allows the user to choose either the overall or individual filling mode, or the individual followed by the overall mode. It outputs the spot-free binary image to the file created by DSCRB.

Next, the user must decide if he/she needs to trim the borders of the binary image. If the user needs this, TRIM will be called next. If there is more than one image of the same sample, the user may call EQUAL to cut all the images to the same size in order to make statistical calculations meaningful.

After this, the user must decide if he/she needs erosion of the binary image to separate objects before measurement. If erosion is desired, EROD.CALC will be called next. It allows the user to choose either the overall or individual mode of erosion, or the overall followed by the individual mode. After erosion, the appropriate dilation will be performed. Then, the desired

measurements will be performed on the processed binary image. EROD.CALC can perform measurements on projections of separate particles or sections cut through a solid sample. EROD.CALC will output the final results of the measurements, and the eroded/dilated image.

If no erosion is needed, the binary image can be directly measured by the following three programs. SEP.CALC measures the projections of separated particles. CUT.CALC estimates 3-dimensional properties of microstructures from 2-dimensional measurements on cut planes. ALL.CALC does both. Finally, NEWPSD can be used to estimate the size distribution of particles that are imbedded in a massive sample when the image is of a plane cut through it.

For the user's convenience, AQIA also provides 6 auxiliary programs. These are:

1. DESIGN	3. INF	5. RESULTS
2. SHOW	4. HARDCP	6. PLOTPREP

DESIGN allows the user to find the number of required images for volume fraction estimation, given the image size, the estimated mean value of the area fraction, the desired estimation accuracy (half-width) and the desired confidence level.

SHOW simply displays a binary image on the screen, but does not allow processing. INF gives the relevant information on an image such as the size of the binary image, the size reduction

factor, the number of gray levels, the percentages of 1 and 0 pixels, the thresholding bounds, etc.. HARDCP gives the user a hard copy of the binary image if the user is working on a Tektronix 4014 terminal equipped with a hardcopy unit.

RESULTS either displays the numeric results of the measuring programs on the screen or prints them on a specified printer. PLOTPREP collects the results of measurements from EROD.CALC, or SEP.CALC, or CUT.CALC, or ALL.CALC, to provide input for plotting by the UNIX Qplot program.

This flow chart summarizes the use of most of these programs.

DEMONSTRATION OF SOME OF AQIA's FEATURES

Typical Results for Separated Particles

The entire AQIA package has more features than can be demonstrated in this summary. However, some of the more important functions will be described here. Figures 1 and 2 show two digitized images of some particles of quartz sand. These images have already been prepared for measurement by separating and labeling the particles that touch (followed by dilation of the objects). These images will be used to demonstrate the typical results of using AQIA to measure separate particles.

Figure 1

Figure 2

Images of Quartz Sand Particles

These two images are called Sample 1 and Sample 2. Since these two images are from the same material, the mean values of the measurements from separate images are also calculated. In the following tables, the notation " $x \text{ e}^n$ " means that the value " x " is multiplied by 10^n ; the notation, " $x \text{ e}^4$ " means that the value x is multiplied by the factor, 10^4 .

Table 1 shows the basic individual measurements that include perimeters, areas, and maximum chords in orthogonal directions. ("Extent" means maximum chord). Note that label 1 has been assigned to the background so that there is no object labeled 1 listed in the table. Table 1 also gives the size (area) of the whole image, the area fraction of objects (intersections), the total number of objects, the number of objects per unit image area, and the maximum, minimum and mean values of the individual measurements. Sample 1 was processed first. Therefore, the mean values given in parentheses are the same as the Sample 1 values. When Sample 2 was processed next, the values in the parentheses were updated to reflect the means of both samples.

Table 2 shows the distribution of the perimeters. The number frequency, the relative frequency and the cumulative frequency are included. The interval between classes is 300 microns. Taking the data for the 4th interval as an example, the results show that, in Sample 1, there are 2 particles, or 25% of the total particles that have perimeters between 90 and 120 microns, and that 50% of the total particles have perimeters less than 120 microns. The data for the 4th interval for Sample 2 show that the average number of particles in the two images with perimeters between 90 and 120 microns is 1.5, the average percentage of particles with perimeters between 90 and 120 microns is 17.05%, and the average percentage of particles with perimeters less than 120 microns is 43.18%. Note that the number of classes in Sample 2 is greater than that in Sample 1 because the biggest

perimeter in Sample 2 is greater than that in Sample 1.

Tables 3 to 5 show the distributions of maximum chords and areas. Again, the number frequency, the relative frequency and the cumulative frequency are included. The structure of these tables is similar to Table 2. In the distribution of west-east maximum chords, the interval between classes is 50 microns. In the distribution of north-south maximum chords, the interval is 100 microns. In the distribution of areas, the interval is 4×10^4 square microns.

Table 1

Sample 1

The length unit is microns

In the () is the mean value for all the samples above.

Image size (x e8):	0.0355
Area fraction of intersections:	0.3057
	(0.3057)
Total Number of intersections:	8
# of intersection/unit area (x e-8):	225.51
	(225.51)
Max. perimeter of intersections (x e4):	0.1860
Min. perimeter of intersections:	0.0670
Mean perimeter of intersections:	0.1220
	(0.1220)
Maximun area of intersections (x e8):	0.0026
Minimum area of intersections:	0.0003
Mean area of intersections:	0.0014
	(0.0014)
Max.w-e extent of intersections (x e4):	0.0590
Min.w-e extent of intersections:	0.0110
Mean w-e extent of intersections:	0.0371
	(0.0371)
Max.n-s extent of intersections (x e4):	0.0770
Min.n-s extent of intersections:	0.0180
Mean n-s extent of intersections:	0.0426
	(0.0426)

Labels	Perimeter (x e4)	Area (x e8)	W-E Extent (x e4)	N-S Extent (x e4)
0	0.0750	0.0003	0.0110	0.0330
2	0.0670	0.0004	0.0250	0.0180
3	0.1160	0.0010	0.0380	0.0320
4	0.1240	0.0016	0.0450	0.0480
5	0.1860	0.0026	0.0420	0.0770
6	0.1600	0.0026	0.0590	0.0570
7	0.1360	0.0014	0.0410	0.0420
8	0.1120	0.0010	0.0360	0.0340

Table 1 (continued)

Sample 2

The length unit is microns

In the () is the mean value for all the samples above.

Image size (x e8): 0.0355
 Area fraction of intersections: 0.4798
 (0.3927)
 Total Number of intersections: 11
 # of intersection/unit area (x e-8): 309.56
 (267.54)
 Max. perimeter of intersections (x e4): 0.2580
 Min. perimeter of intersections: 0.0680
 Mean perimeter of intersections: 0.1328
 (0.1274)
 Maximun area of intersections (x e8): 0.0041
 Minimum area of intersections: 0.0002
 Mean area of intersections: 0.0015
 (0.0015)
 Max.w-e extent of intersections (x e4): 0.0600
 Min.w-e extent of intersections: 0.0120
 Mean w-e extent of intersections: 0.0425
 (0.0398)
 Max.n-s extent of intersections (x e4): 0.1020
 Min.n-s extent of intersections: 0.0130
 Mean n-s extent of intersections: 0.0448
 (0.0437)

Labels	Perimeter (x e4)	Area (x e8)	W-E Extent (x e4)	N-S Extent (x e4)
0	0.0730	0.0004	0.0180	0.0280
2	0.1240	0.0008	0.0600	0.0160
3	0.1300	0.0011	0.0510	0.0270
4	0.1140	0.0012	0.0360	0.0380
5	0.1200	0.0014	0.0470	0.0390
6	0.2580	0.0041	0.0510	0.1020
7	0.1910	0.0034	0.0580	0.0740
8	0.1410	0.0017	0.0410	0.0570
9	0.1610	0.0023	0.0540	0.0660
10	0.0680	0.0002	0.0120	0.0330
11	0.0810	0.0004	0.0400	0.0130

Table 2

Distribution of Perimeters of Quartz

The length unit is microns.

In the () are the mean values for all the samples above.

Sample #	Start-with (x e4)	Frequency	Rel.Freq.	Cum.Freq.
1	0.000	0	0.0000	0.0000
		(0)	(0.0000)	(0.0000)
1	0.030	0	0.0000	0.0000
		(0)	(0.0000)	(0.0000)
1	0.060	2	0.2500	0.2500
		(2)	(0.2500)	(0.2500)
1	0.090	2	0.2500	0.5000
		(2)	(0.2500)	(0.5000)
1	0.120	2	0.2500	0.7500
		(2)	(0.2500)	(0.7500)
1	0.150	1	0.1250	0.8750
		(1)	(0.1250)	(0.8750)
1	0.180	1	0.1250	1.0000
		(1)	(0.1250)	(1.0000)
2	0.000	0	0.0000	0.0000
		(0.0000)	(0.0000)	(0.0000)
2	0.030	0	0.0000	0.0000
		(0.0000)	(0.0000)	(0.0000)
2	0.060	3	0.2727	0.2727
		(2.5000)	(0.2614)	(0.2614)
2	0.090	1	0.0909	0.3636
		(1.5000)	(0.1705)	(0.4318)
2	0.120	4	0.3636	0.7273
		(3.0000)	(0.3068)	(0.7386)
2	0.150	1	0.0909	0.8182
		(1.0000)	(0.1080)	(0.8466)
2	0.180	1	0.0909	0.9091
		(1.0000)	(0.1080)	(0.9545)
2	0.210	0	0.0000	0.9091
		(0.0000)	(0.0000)	(0.9545)
2	0.240	1	0.0909	1.0000
		(0.5000)	(0.0455)	(1.0000)

Table 3

Distribution of Max. W-E Chords of Quartz

The length unit is microns.

In the () are the mean values for all the samples above.

Sample #	Start-with (x e4)	Frequency	Rel.Freq.	Cum.Freq.
1	0.000	0	0.0000	0.0000
		(0)	(0.0000)	(0.0000)
1	0.005	0	0.0000	0.0000
		(0)	(0.0000)	(0.0000)
1	0.010	1	0.1250	0.1250
		(1)	(0.1250)	(0.1250)
1	0.015	0	0.0000	0.1250
		(0)	(0.0000)	(0.1250)
1	0.020	0	0.0000	0.1250
		(0)	(0.0000)	(0.1250)
1	0.025	1	0.1250	0.2500
		(1)	(0.1250)	(0.2500)
1	0.030	0	0.0000	0.2500
		(0)	(0.0000)	(0.2500)
1	0.035	2	0.2500	0.5000
		(2)	(0.2500)	(0.5000)
1	0.040	2	0.2500	0.7500
		(2)	(0.2500)	(0.7500)
1	0.045	1	0.1250	0.8750
		(1)	(0.1250)	(0.8750)
1	0.050	0	0.0000	0.8750
		(0)	(0.0000)	(0.8750)
1	0.055	1	0.1250	1.0000
		(1)	(0.1250)	(1.0000)

Table 3 (continued)

Distribution of Max. W-E Chords of Quartz

Sample #	Start-with (x e4)	Frequency	Rel.Freq.	Cum.Freq.
2	0.000	0	0.0000	0.0000
		(0.0000)	(0.0000)	(0.0000)
2	0.005	0	0.0000	0.0000
		(0.0000)	(0.0000)	(0.0000)
2	0.010	1	0.0909	0.0909
		(1.0000)	(0.1080)	(0.1080)
2	0.015	1	0.0909	0.1818
		(0.5000)	(0.0455)	(0.1534)
2	0.020	0	0.0000	0.1818
		(0.0000)	(0.0000)	(0.1534)
2	0.025	0	0.0000	0.1818
		(0.5000)	(0.0625)	(0.2159)
2	0.030	0	0.0000	0.1818
		(0.0000)	(0.0000)	(0.2159)
2	0.035	1	0.0909	0.2727
		(1.5000)	(0.1705)	(0.3864)
2	0.040	2	0.1818	0.4545
		(2.0000)	(0.2159)	(0.6023)
2	0.045	1	0.0909	0.5455
		(1.0000)	(0.1080)	(0.7102)
2	0.050	3	0.2727	0.8182
		(1.5000)	(0.1364)	(0.8466)
2	0.055	1	0.0909	0.9091
		(1.0000)	(0.1080)	(0.9545)
2	0.060	1	0.0909	1.0000
		(0.5000)	(0.0455)	(1.0000)

Table 4

Distribution of Max. N-S Chords of Quartz

The length unit is microns.

In the () are the mean values for all the samples above.

Sample #	Start-with (x e4)	Frequency	Rel.Freq.	Cum.Freq.
1	0.000	0	0.0000	0.0000
		(0)	(0.0000)	(0.0000)
1	0.010	1	0.1250	0.1250
		(1)	(0.1250)	(0.1250)
1	0.020	0	0.0000	0.1250
		(0)	(0.0000)	(0.1250)
1	0.030	3	0.3750	0.5000
		(3)	(0.3750)	(0.5000)
1	0.040	2	0.2500	0.7500
		(2)	(0.2500)	(0.7500)
1	0.050	1	0.1250	0.8750
		(1)	(0.1250)	(0.8750)
1	0.060	0	0.0000	0.8750
		(0)	(0.0000)	(0.8750)
1	0.070	1	0.1250	1.0000
		(1)	(0.1250)	(1.0000)
2	0.000	0	0.0000	0.0000
		(0.0000)	(0.0000)	(0.0000)
2	0.010	2	0.1818	0.1818
		(1.5000)	(0.1534)	(0.1534)
2	0.020	2	0.1818	0.3636
		(1.0000)	(0.0909)	(0.2443)
2	0.030	3	0.2727	0.6364
		(3.0000)	(0.3239)	(0.5682)
2	0.040	0	0.0000	0.6364
		(1.0000)	(0.1250)	(0.6932)
2	0.050	1	0.0909	0.7273
		(1.0000)	(0.1080)	(0.8011)
2	0.060	1	0.0909	0.8182
		(0.5000)	(0.0455)	(0.8466)
2	0.070	1	0.0909	0.9091
		(1.0000)	(0.1080)	(0.9545)
2	0.080	0	0.0000	0.9091
		(0.0000)	(0.0000)	(0.9545)
2	0.090	0	0.0000	0.9091
		(0.0000)	(0.0000)	(0.9545)
2	0.100	1	0.0909	1.0000
		(0.5000)	(0.0455)	(1.0000)

Table 5

Distribution of Areas of Quartz

The length unit is microns.

In the () are the mean values for all the samples above.

Sample #	Start-with (x e6)	Frequency	Rel.Freq.	Cum.Freq.
1	0.000	2	0.2500	0.2500
		(2)	(0.2500)	(0.2500)
1	0.040	0	0.0000	0.2500
		(0)	(0.0000)	(0.2500)
1	0.080	2	0.2500	0.5000
		(2)	(0.2500)	(0.5000)
1	0.120	2	0.2500	0.7500
		(2)	(0.2500)	(0.7500)
1	0.160	0	0.0000	0.7500
		(0)	(0.0000)	(0.7500)
1	0.200	0	0.0000	0.7500
		(0)	(0.0000)	(0.7500)
1	0.240	2	0.2500	1.0000
		(2)	(0.2500)	(1.0000)
2	0.000	3	0.2727	0.2727
		(2.5000)	(0.2614)	(0.2614)
2	0.040	1	0.0909	0.3636
		(0.5000)	(0.0455)	(0.3068)
2	0.080	2	0.1818	0.5455
		(2.0000)	(0.2159)	(0.5227)
2	0.120	1	0.0909	0.6364
		(1.5000)	(0.1705)	(0.6932)
2	0.160	1	0.0909	0.7273
		(0.5000)	(0.0455)	(0.7386)
2	0.200	1	0.0909	0.8182
		(0.5000)	(0.0455)	(0.7841)
2	0.240	0	0.0000	0.8182
		(1.0000)	(0.1250)	(0.9091)
2	0.280	0	0.0000	0.8182
		(0.0000)	(0.0000)	(0.9091)
2	0.320	1	0.0909	0.9091
		(0.5000)	(0.0455)	(0.9545)
2	0.360	0	0.0000	0.9091
		(0.0000)	(0.0000)	(0.9545)
2	0.400	1	0.0909	1.0000
		(0.5000)	(0.0455)	(1.0000)

Typical Results of Estimation of 3-Dimensional Properties

If Figures 1 and 2 were cut planes through a solid sample, the results in Tables 1 to 5 could be used to obtain estimates of the properties of the solid. In what follows, it will be assumed that Figures 1 and 2 are such planes. (This ruse is used to circumvent the need for preparing a special sample merely to demonstrate the AQIA package.) The 3-dimensional properties that can be estimated by AQIA are shown in Tables 6 and 7. These two tables also show the length unit used in the estimations and the mean values from the two separate images.

Table 6 shows the volume fraction, the surface area of objects per unit bulk volume, and the surface area of objects per unit object volume (based on the former two values). The total number of objects per unit bulk volume is given and is calculated from the particle size distribution. Table 6 also shows the mean diameter of the objects, assuming that the objects are spheres.

Table 7 shows the particle size distribution. The number frequency, the relative frequency and the cumulative frequency are included. The interval between classes is 100 microns. The mean lengths of the intercepted chords in each class are used as the mean diameters of objects in that class. Table 7 also includes the number frequency of intersected chords' lengths. For example, the data for the 4th interval for Sample 1 show that there are 109 intercepted chords with mean length 350 microns, or 8.6025×10^{-10} particles with a mean diameter of 350 microns per

Table 6

Volume Fraction and Surface Areas

VFA is volume fraction.

SV is surface area per unit bulk volume.

SSA is specific surface area per unit object volume.

TN is the total number of particles per unit bulk volume.

MD is the mean diameter of particles

The length unit is microns

In the () are the mean values for all the samples above.

Sample #	VFA	SV(x e-4)	SSA(x e-4)	TN(x e-10)	MD(x e4)
1	0.3057	29.9366	97.9280	44.8639	0.0367
	(0.3057)	(29.9366)	(97.9280)	(44.8639)	(0.0367)
2	0.4798	46.2093	96.3094	116.1319	0.0278
	(0.3927)	(38.0729)	(97.1187)	(80.4979)	(0.0322)

cubic micron of bulk volume, the percentage of particles with a mean diameter of 350 microns is 19.17%, and the percentage of particles with diameter less than 400 microns is 56.89%.

Table 7

Particles Size Distribution

The length unit is microns. Chd stands for intersected chords.
 In the () are the mean values for all the samples above.
 Frequency is the number of particles per unit bulk volume.

Sample #	Ave.Dia. (x e4)	Freq.(x e-10)	Rel.freq.	Cum.Freq.	Chd.Freq.
1	0.0050	0.0000 (0.0000)	0.0000 (0.0000)	0.0000 (0.0000)	25 (25)
1	0.0150	14.7153 (14.7153)	0.3280 (0.3280)	0.3280 (0.3280)	75 (75)
1	0.0250	2.2047 (2.2047)	0.0491 (0.0491)	0.3771 (0.3771)	84 (84)
1	0.0350	8.6025 (8.6025)	0.1917 (0.1917)	0.5689 (0.5689)	109 (109)
1	0.0450	6.6163 (6.6163)	0.1475 (0.1475)	0.7164 (0.7164)	97 (97)
1	0.0550	8.8598 (8.8598)	0.1975 (0.1975)	0.9138 (0.9138)	78 (78)
1	0.0650	0.9939 (0.9939)	0.0222 (0.0222)	0.9360 (0.9360)	28 (28)
1	0.0750	2.4490 (2.4490)	0.0546 (0.0546)	0.9906 (0.9906)	24 (24)
1	0.0850	0.4222 (0.4222)	0.0094 (0.0094)	1.0000 (1.0000)	4 (4)
2	0.0050	48.9697 (24.4849)	0.4217 (0.2108)	0.4217 (0.2108)	55 (40.00)
2	0.0150	1.1944 (7.9548)	0.0103 (0.1691)	0.4320 (0.3800)	83 (79.00)
2	0.0250	0.0000 (1.1023)	0.0000 (0.0246)	0.4320 (0.4045)	135 (109.50)
2	0.0350	41.5190 (25.0608)	0.3575 (0.2746)	0.7895 (0.6792)	247 (178.00)
2	0.0450	0.3619 (3.4891)	0.0031 (0.0753)	0.7926 (0.7545)	109 (103.00)
2	0.0550	19.2688 (14.0643)	0.1659 (0.1817)	0.9585 (0.9362)	131 (104.50)
2	0.0650	0.0000 (0.4970)	0.0000 (0.0111)	0.9585 (0.9473)	15 (21.50)
2	0.0750	2.3536 (2.4013)	0.0203 (0.0374)	0.9788 (0.9847)	25 (24.50)
2	0.0850	0.1609 (0.2915)	0.0014 (0.0054)	0.9802 (0.9901)	6 (5.00)
2	0.0950	0.0000 (0.0000)	0.0000 (0.0000)	0.9802 (0.9901)	5 (2.50)
2	0.1050	2.3035 (1.1517)	0.0198 (0.0099)	1.0000 (1.0000)	27 (13.50)

CONCLUSIONS

1. An automatic, quantitative image analysis (AQIA) system has been developed for construction materials.
2. A special technique of image segmentation, based on the concepts of fuzzy probability, has been developed. It models the cognition process of humans, and produces consistent binary images.
3. The system uses object labeling to process the binary images more accurately than non-labeling image analysis systems.
4. In the case of discrete particles, the system can measure the perimeters, areas, maximum chords of the particles, the maximum, minimum and mean values of these parameters, the distributions of these parameters, the area fraction of the particles and the total number of particles.
5. In the case of a cut surface through a massive sample, the system can estimate the volume fraction of objects, the surface area of objects per unit bulk volume, and the surface area of objects per unit object volume. Assuming that the objects are spheres, the particle size distribution of objects in a massive sample, the total number of objects per unit bulk volume and the mean diameter can also be estimated.

COVER DESIGN BY ALDO GIORGINI