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INFRAME

A COMPARISON OF OPTICAL GRADATION ANALYSIS DEVICES TO CURRENT TEST METHODS – PHASE 1

Final Report

Arudi Rajagopal, Ph. D.

Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department Transportation, Federal Highway Administration

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16. Abstract:

Optical devices for gradation analysis are being developed to deliver accurate gradation results with, less labor, less consistency error, and greater reliability. The goal of this study was to conduct a review and develop comprehensive understanding of the existing technology for gradation analysis, and generate basic data to determine when and where such devices are appropriate from the standpoint of both economies and performance. Following a review of available optical devices, an optical device called Computerized Particle Analyzer (CPA) was selected for laboratory evaluation to determine its suitability for gradation analysis. This device has been designed to examine particles as they freely fall in front of a light source, while a sophisticated camera capable of making 10,000 scans per second captures images. Aggregate samples were collected from 46 different sources in Ohio. These sources included various sizes of limestone and gravel with varying amounts of crushed faces. Gradation tests were first performed according to the standard AASHTO procedure. The samples were then tested in CPA. Preliminary test results revealed that the CPA device has the potential to produce gradation results comparable to the traditional ASTM and AASHTO procedures. The device is capable of producing consistent and repeatable test data. It is computer-controlled and user-friendly. Two primary benefits noted during the evaluation are: (i) time savings, and (ii) generation of additional information. One gradation test can be completed in less than five minutes, compared to 30 to 60 minutes for the conventional procedure. More importantly, the same data can also be used to obtain additional information about elongation index and angularity. While the results so far show promise, a definitive determination of the suitability of the device for use in Ohio will require further research.

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DISCLAIMER

A COMPARISON OF OPTICAL GRADATION ANALYSIS DEVICES TO CURRENT TEST METHODS – PHASE 1

1. ABOUT THIS REPORT

This report provides preliminary details of an ongoing investigation designed to evaluate optical gradation devices for the determination of particle size distribution of aggregate samples. The report includes information about the project activities conducted from September 1, 2005 to August 30, 2006 along with a description of data, test results, and additional tasks proposed to achieve the project objectives.

2. BACKGROUND AND SIGNIFICANCE OF WORK

The sieve analysis, commonly known as the "gradation analysis" is an essential test for all aggregate technicians. The sieve analysis determines the gradation (the distribution of aggregate particles, by size, within a given sample) in order to determine compliance with design, production control requirements, and verification specifications. To name just a few uses, the gradation data can discern relationships between various aggregate or aggregate blends, to check compliance with such blends, and to predict trends during production by plotting gradation curves graphically. Used in conjunction with other tests, the sieve analysis is a powerful quality control and quality acceptance tool [1].

Sieve analysis consists of two parts:

- Determination of the amount and proportion of *coarse* material, and
- Determination of the amount and proportion of *fine* material.

The coarse aggregate is a graded aggregate made up of particles that are retained on No.4 sieve. Fine aggregate is a graded aggregate and consists of particles that almost entirely pass a No. 4 sieve. Traditionally, sieve analysis is done using either a *dry* or *wet* process. Standard procedures for a dry sieve analysis are given in ASTM C136/AASHTO T27 while the procedures for a wet (washed) sieve analysis are given in ASTM C117/AASHTO T11. When an aggregate sample consists of an appreciable amount of materials finer than No. 200 sieve, wet sieving is performed.

2.1 Extent of Gradation Tests Conducted in Ohio

The Aggregate Section [2] of the Office of Materials Management (OMM) at the Ohio Department of Transportation (ODOT) has established specifications in developing tests required for the design of Portland cement concrete, Hot Mix Asphalt (HMA), and special aggregate bases in Ohio. Sieve analysis of aggregates is a basic test on aggregates specified by ODOT in its Quality Control and Quality Assurance Program. Quality control tests are those tests necessary to control the quality of a product and are conducted by the contractors. Quality assurance tests are acceptance tests, performed by the owner. In a hot mix asphalt production facility, for QC/QA tests, aggregate samples are typically taken from the stockpile, cold feeder belt, hot bins and asphalt mixture. ODOT has established a testing frequency which defines the number of gradation tests to be conducted at each location. As an example, the total number of gradation tests conducted by a hot mix asphalt production facility in Ohio which produces approximately 250,000 tons of asphalt concrete mix in a year is as follows:

- Mix design: 500 gradation tests
- Stockpile gradation: 250 tests
- Hot bin gradation: 100 tests

- Cold feed gradation: 100 tests
- TOTAL: 950 tests per year

Given that approximately 16 million tons of hot mix asphalt was produced in Ohio in 2005, it is possible that a total of (16,000,000 x 950/250,000) = 60,800 tests are conducted in Ohio in a typical year. It should be recognized that this number does not include the gradation tests conducted by ODOT for quality assurance and tests for Portland cement concrete and base course applications.

2.2 Present Study

In the recent years, a number of agencies are exploring the applicability of advanced technologies to measure the particle size distribution of aggregate used to construct highway pavements. The primary intent of such an effort is to obtain faster results while, at the same time, improving the accuracy of results. Most notable among the new technologies are optical test methods that use computer controlled video enhancement pictures. Some studies suggest that the optical devices have shown promise to produce comparable results and also reduce the time required to perform a grading test thereby reducing the technician time required.

In its continuing efforts to improve its material testing practices in Ohio, the OMM initiated this study to conduct a comparative evaluation of the optical devices and conventional test procedures to determine particle size distribution of aggregate samples. The study included various types of materials for multiple tests to arrive at sound conclusions as to the device reliability, repeatability, precision and durability compared to conventional methods. The basic focus of this study was two issues:

- What types of optical devices are in use or under investigation by other agencies?
- Do these new devices have potential applicability to Ohio's conditions?

This report outlines the details of a study to review the available optical devices and an experimental plan to conduct lab studies on a range of aggregate samples resulting in evaluation of results from selected optical devices and conventional test procedures.

3. OBJECTIVES OF THE STUDY

The specific objectives of the study are to:

1. Conduct a review and evaluation of available optical gradation analysis devices that are in use and/or being investigated by other agencies.
2. Prepare physical samples and conduct gradation tests on a range of materials using current ASTM/AASHTO procedures.
3. Repeat tests on physical samples using two new optical devices being made available to the researchers.
4. Analyze the data.
5. Identify additional devices that should be used in Phase-2 evaluation and repeat the gradation tests.

Ultimately, the results of this study will help to prepare recommendations to ODOT on specification changes and equipment to purchase based on the capability, precision, and durability of the equipment evaluated.

4. BACKGROUND AND SIGNIFICANCE OF WORK

The particle size distribution, or gradation, of an aggregate is one of the most influential characteristics in determining how it will perform as a pavement material. In Hot Mix Asphalt (HMA) applications, gradation can be used to determine almost every important property including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage. In PCC, gradation helps to determine durability, porosity, workability, cement and water requirements, strength, and shrinkage. Because of this, gradation is a primary concern in HMA and PCC mix design. Most agencies specify allowable aggregate gradations for both [3].

Gradation tests are routinely performed by State agencies and paving contractors during mix design and QC/QA processes. Considerable amount of technician time is expended for performing the gradation tests. Typically, each test consumes 30 to 60 minutes of technician time. The need to reduce this time arises from the fact that grading tests of aggregate samples is used for process control during the production of HMA. If the test time for gradation tests can be reduced by about 50 percent, improved plant production rate can be achieved while saving several hours of testing time [4].

In the recent years, several researchers [5, 6, 7, 8] have conducted studies to develop optical devices for the evaluation of physical properties of aggregates. A review of these studies reveal that while optical devices have potential application in gradation tests, more research is needed to validate the repeatability, reliability, precision and durability of these devices. The present study will provide an opportunity to further evaluate the ability of available equipment to accurately measure gradation of aggregates in a much shorter time.

5. WHAT ARE OPTICAL GRADATION DEVICES?

An optical device is an instrument used for producing and controlling light. Optical instruments either process light waves to enhance an image for viewing, or analyze light waves to determine one of a number of characteristic properties. A camera could be considered a type of optical device for viewing, capturing and storing an image.

In the last 25 to 30 years, since the inception of personal computers, analysis of digital images has become a common task. Concurrent with the development of the personal computer has been the development of digital cameras and optical devices. As the digital imaging technology has become more refined, the demands for more precise and accurate measurements from the resulting images have followed [9].

Digital images are electronic snapshots taken of an object. The digital image is sampled and mapped as a grid of dots or picture elements (pixels). Each pixel is assigned a tonal value (black, white, and shades of gray or color), which is represented in binary codes (zeros and ones). The binary digits (bits) for each pixel are stored in a sequence by a computer and often reduced to a mathematical expression. The bits are then interpreted and read by the computer to produce an analog version for display and/or printing [10].

Digital images are produced by optical and electronic devices, which accurately record image data. A number of industries such as pharmaceutical, agricultural, and food processing, have successfully deployed optical devices in their quality control and quality assurance programs. It is evident that the primary benefits derived with the use of optical devices include accurate, consistent and faster test results, reduced technician time, better use of existing manpower and improved production rate.

In the recent years, there has been a growing interest in the highway industry to develop optical devices for the analysis of particle size and shape of aggregates used in highway construction. A review of literature identified following six devices:

1. Aggregate Image Analyzer - University of Illinois
2. Aggregate Imaging System - Texas A&M University
3. Image Acquisition setup - West Virginia University
4. VDG40 - LCPC (French Research Lab)
5. WipFrag - Wipware Systems
6. Computerized Particle Analyzer (CPA) – WS Tyler

The University of Illinois Aggregate Imaging System (Figure 1) uses three cameras in orthogonal directions to capture three dimensional view of each aggregate particle. Coarse aggregate particles are placed on a conveyor belt, one at time. The belt moves at a uniform rate of 8cm/second and brings the particles within the field of view of the cameras. Then the cameras capture the front, top and side views of each particle. The cameras are in turn connected to a computer which assists in storing the images on a real time basis. The data is processed to obtain flat and elongated ratio, angularity and surface texture of each particle [11].

The Texas A&M and West Virginia University devices are conceptually similar. A known number of coarse aggregate particles are manually placed on a light-emitting source. A high resolution camera takes two dimensional images of the particles and stores the information on a computer (Figures 2 and 3). A computer algorithm analyzes shape and size of individual particles. These devices are not dynamic, meaning they can not be used with in-line production systems [5, 12]. It should be recognized that the University of Illinois, Texas A&M and Weat Virginia University three devices are not yet available for commercial uses.

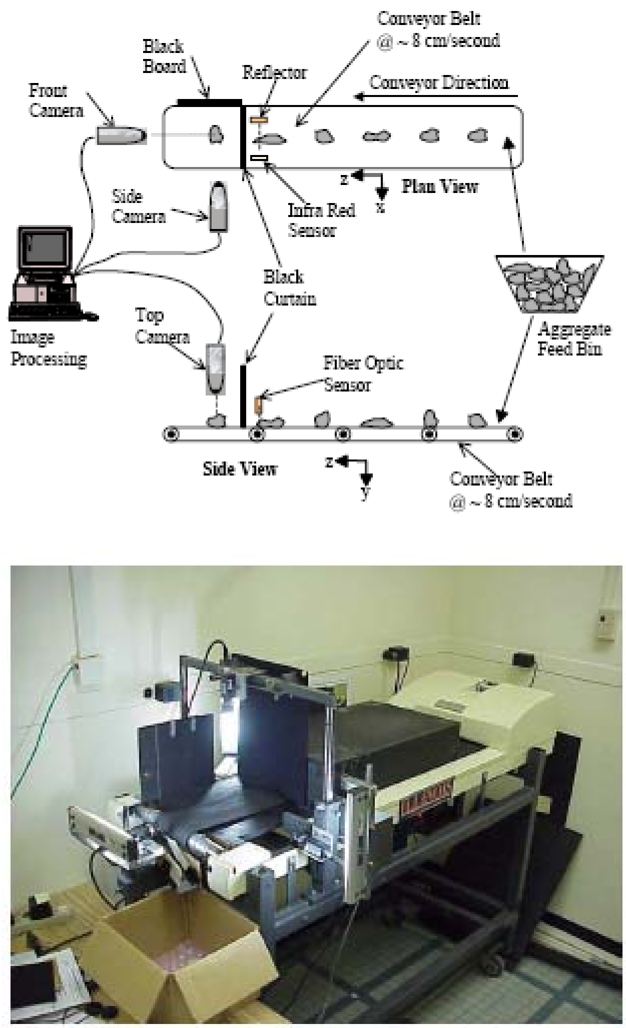


Figure 1. University of Illinois Aggregate Image Analyzer [11]

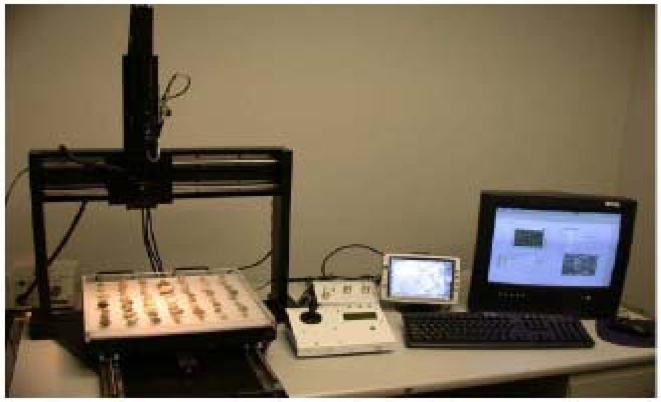


Figure 2. Texas A&M University Aggregate Imaging System [12]

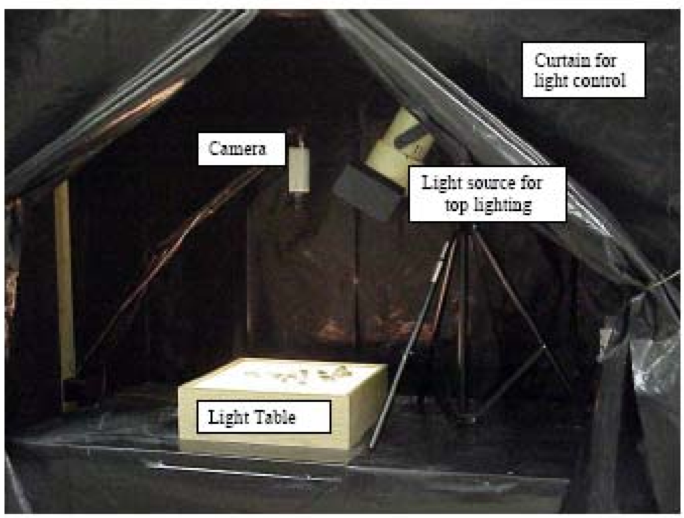


Figure 3. West Virginia University Image Acquisition Setup [5]

The other three devices (VDG-40, WipFrag and CPA) mentioned above are commercial products. The WipFrag device is being extensively used in quarrying and mining applications to obtain information on size, uniformity and fragment shapes of rocks. This device is best suited for quality control of stock piles. The system is fairly versatile and accepts digital images as well as video clips. A modified version of the unit is being developed to determine particle size and shape as required in the highway industry [6]. This equipment is routinely used in the mining industry across the world. However, the literature does not indicate its use in the highway industry for gradation and/or shape analysis.

Perhaps, the first commercial device that was specifically developed for the particle size analysis of aggregates is VDG-40 Videogranulometer (Figure 4). In using this device, the aggregate sample is fed into the hopper. The materials travel along a conveyor, onto to a cylindrical drum, and fall into a collector bin. During this process, a line scan camera captures the images of aggregate particles. The data is stored in a computer and analyzed to obtain gradation curve [13]. The literature however, could not establish the extent of use of this device in the United States and elsewhere.

Figure 4. VDG-40 Videogranulometer [13]

The Computerized Particle Analyzer (CPA) [14] is a commercial optical device that is being used for particle size and shape analysis, primarily in the agricultural industry. Thirty one units are currently in operation in North America. Nearly 50% of the units are being used in the agricultural industry to measure the particle sizes of fertilizers. Figure 5 illustrates a view of

CPA. Marketed by W.S. Tyler Company, based in Mentor, Ohio, this device has been designed to examine particles as they freely fall in front of a light source, while a sophisticated camera capable of making 10,000 scans per second captures images. The finalized data is stored and sorted into 250 classes. In other words, this amounts to an analysis equivalent to 250 test sieve measurements. The information is then finally presented in the size analysis fractions or shape calculations chosen by the user. This is all accomplished in about three minutes. The CPA is operated by a Windows-based user-friendly program. The device allows the user the option to select any sieve size classification in either ASTM or ISO designations. This would allow analysis equal to a select stack of test sieves.

Figure 5. Computerized Particle Analyzer

According to the manufacturers of this device, the CPA process has been researched, developed, and continuously tested throughout the 1990's. The repeatability of the machine is remarkable and the variances from traditional sieving data versus CPA correlated results are minimal.

In addition, a device known as Sedigraph (Figure 6) is available to analyze particle sizes of fine fractions using sedimentation technique. The device can measure particles ranging from 300 to 0.10 μm equivalent spherical diameter. It utilizes a modern pumping system that is silent, reliable, and easy to maintain. A maintenance reminder, based on the number of analyses performed, alerts the user when it is time for routine maintenance. A computer controlled mixing chamber temperature improves repeatability and reproducibility. A highly versatile and interactive reporting system provides a wide range of custom data presentation options including dynamic reformatting of plots and cut-and-paste graphics and tables. Particle settling velocity is reported as graphical and tabular data. The device runs up to 18 samples unattended. One test can be completed in 15 minutes or less. Literature indicates extensive use of this system in pharmaceutical and food industry [15]. Some paving contractors in Ohio routinely use this device for the size analysis of fine fractions.

Figure 6. Sedigraph [15]

6. DEVICES EVALUATED IN THE PRESENT STUDY

Development and/or customization of a device to the industry's needs is in the best interest of the industry as well as the developers. Generally, the product developers take an active role to research the industry's needs, issues and concern. This action can help the developers to understand and incorporate the necessary details in the development process. The VDG40 device has been specifically developed for particle size analysis of aggregates. On the other hand, CPA and WipFrag systems have been developed for different applications (agricultural, food processing, mining industry etc.). However, with some effort, it may be possible to customize these two devices for the determination of size and shape of aggregates. With this intent, the researchers contacted the developers of CPA and WipFrag systems. The

VDG40 system does not appear to have representation in the United States. However, the researchers are communicating with the developers of VDG-40 to obtain additional information.

The CPA product engineers readily agreed to actively participate in the research program and to loan a unit for the investigation. Although the WipFrag system developers also showed interest, they were neither willing to make their system available or to actively participate in the research program. The CPA device has been available since February 2006. The product engineer has made several visits to the test lab to set up the device, train the technicians, and to review test results. During the course of testing, several issues have been brought to the attention of the product engineer and the company is considering making necessary hardware and software changes.

In addition, the Valley Asphalt Corporation has made Sedigraph equipment available for the study.

7. WORKING PRINCIPLE AND CURRENT CAPABILITIES OF CPA

Figure 7 graphically illustrates the working principle of CPA. The aggregate sample is placed in the hopper (1). Upon starting the interactive computer program, the conveyor (2) begins to vibrate at a predefined rate causing the aggregate particles to move and fall into a collector bin. Images of individual particles are captured by a high resolution camera (4) against the backdrop of a high intensity light source (3). A computer algorithm (5) helps to store and process the data.

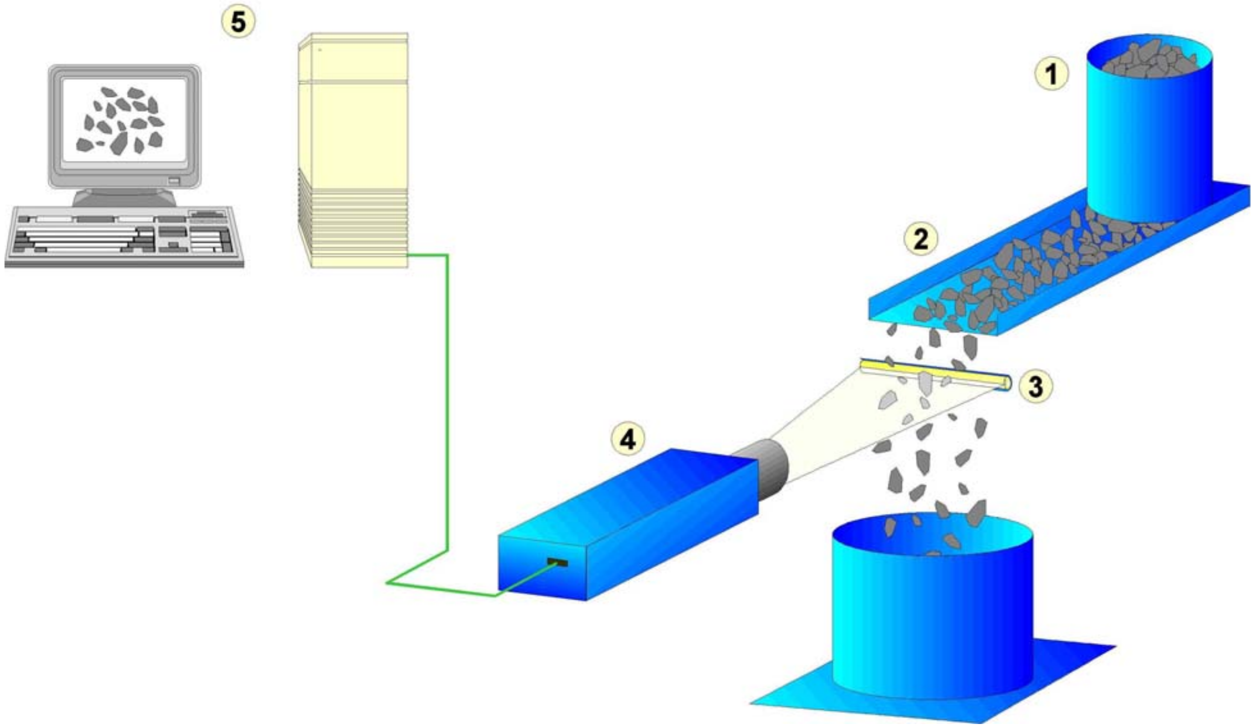


Figure 7. Working Principle of CPA [14]

The on-screen display of the image capturing process allows the users to view the entire process on real-time basis. The processed information is readily available to view in various formats. Figure 8 shows a snapshot of screen display. In its current format, CPA delivers the following processed information:

- Particle count
- Particle size distribution, in conformity with AASHTO/ASTM specifications
- Flat and elongation
- Sphericity

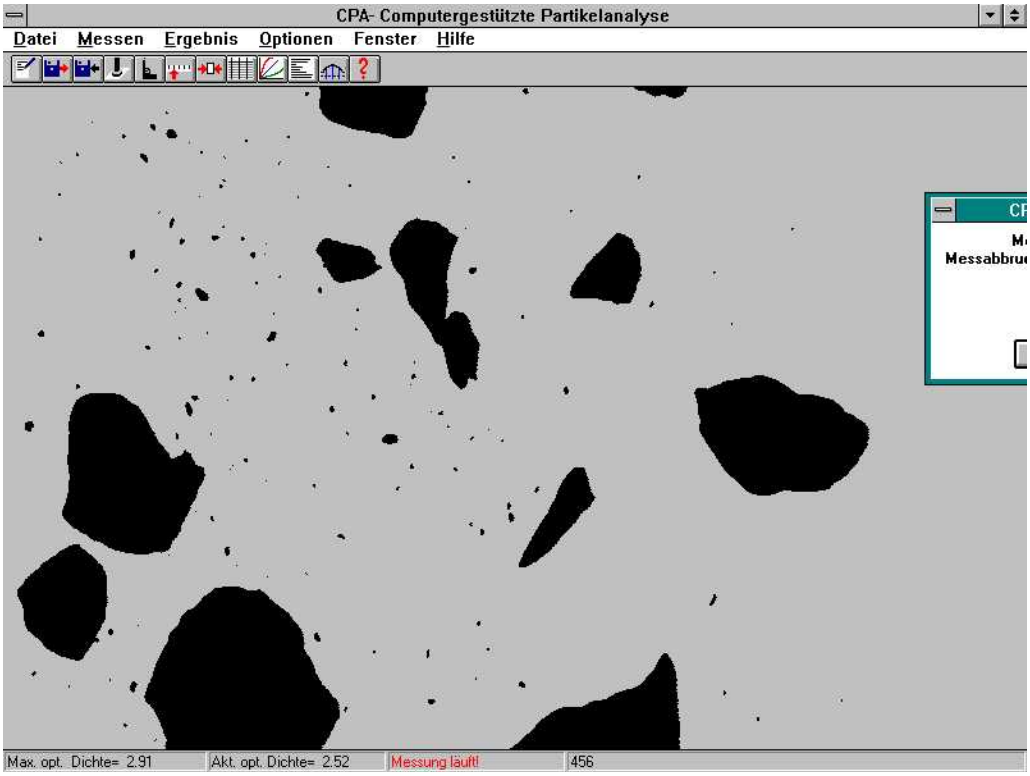


Figure 8. Snapshot of Interactive Screen

8. THE EXPERIMENT AND OBSERVATIONS

The first step in conducting the experiment was to identify aggregate sources and types to be included in testing. In association with ODOT's project liaison and Valley Asphalt Corporation, the researchers finalized a list of aggregate sources and collected adequate samples from each source. Table 1 provides the list of aggregate sources. The sources, in general, included the following:

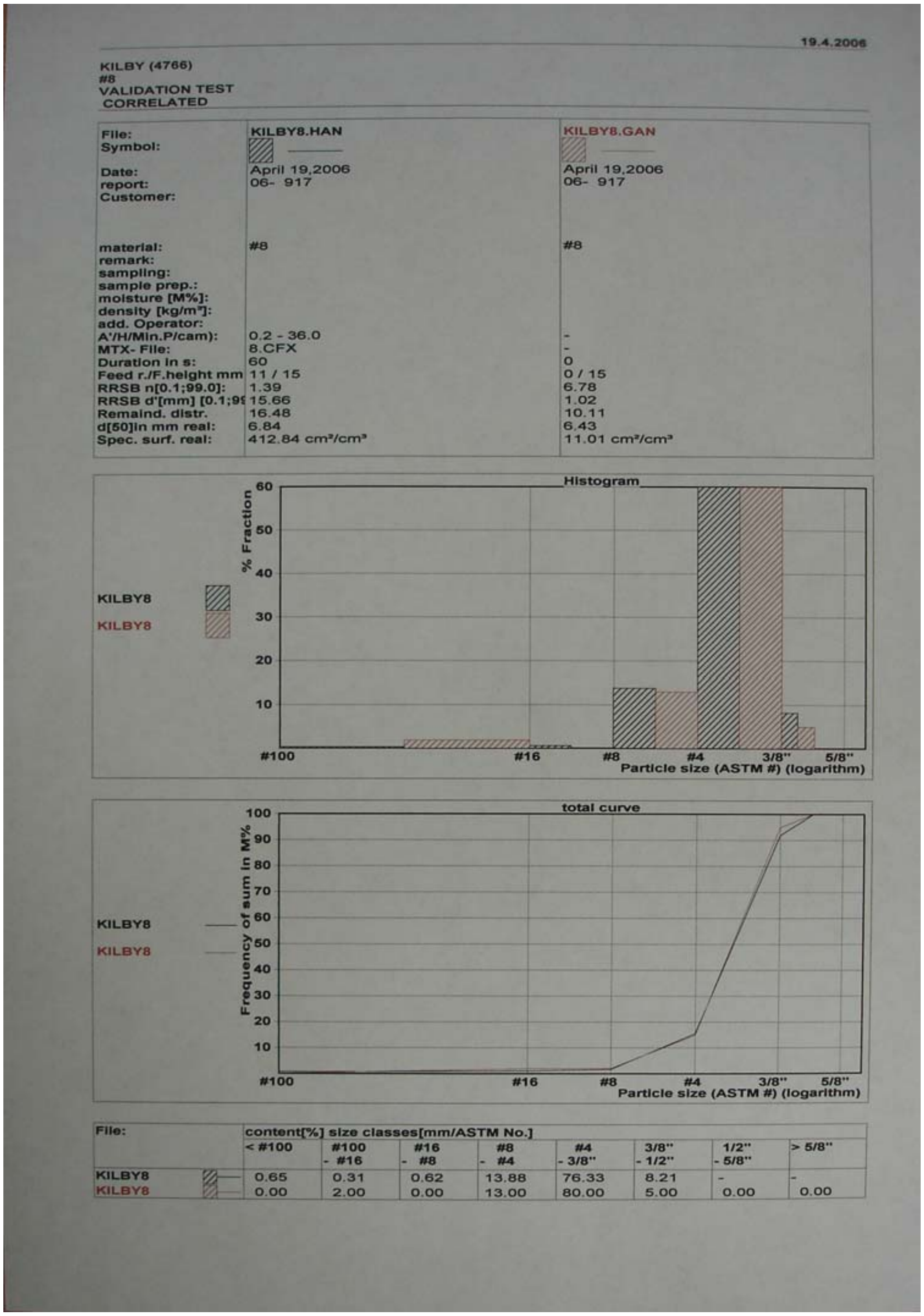
- 100% crushed gravel, #8,
- 100% crushed gravel, #57
- 40% crushed gravel, #8
- 40% crushed gravel, #57
- Natural sand
- Limestone, sand
- Limestone,#8
- Limestone, #57
- Slag, #8/#9
- Slag, sand

Table 1. Aggregate Sources and Types included in the Test Program

ODOT Source #	Aggregate Type	Plant	#4	#57	#78	#8	#9	Sand
4364	Limestone	East Fairfield Coal						
4511	Gravel	Melvin Stone (Williamsport)						
4526	Gravel	Melvin Stone (Circleville)						
4601	Gravel	Martin Marietta(Fairborn)						
4602	Limestone	Walls Mtl's (Fort Jefferson)						
4604	Limestone	Martin Marietta (Phillipsburg)						
4607	Gravel	Martin Marietta						
4611	Gravel	Enon Sand & Gravel						
4615	Limestone	Piqua Materials						
4622	Limestone	Stoneco						
4623	Limestone	Miami River Stone						
4624	Gravel	Spring Creek Gravel						
4628	Gravel	Urbana Materials						
4631	Limestone	C F Poeppleman						
4637	Gravel	Mechanicsburg Sd&Gr						
4703	Gravel	Martin Marietta						
4705	Gravel	Martin Marietta						
4706	Gravel	Martin Marietta						
4707	ACBF	Olympic						
4711	Gravel	Martin Marietta						
4715	Gravel	Martin Marietta						
4719	Gravel	Hilltop Basic Resources						
4721	Limestone	Melvin Stone (Melvin)						
4723	Gravel	Morrow Sand & Gravel						
4724	Gravel	Oeder Sand & Gravel						
4725	Gravel	Phillips Sand & Gravel						
4726	Gravel	Shamrock Materials						
4729	Gravel	Watson Gravel						
4737	Limestone	Martin Marietta						
4741	Limestone	Caremuse Materials						
4745	Gravel	Northern Kentucky Aggregates						
4749	Gravel	Martin Marietta						
4766	Gravel	Southern Ohio Aggregates						
4772	Gravel	Hanson Aggregates (Powell Bunnel)						
4777	Limestone	Melvin Stone (Bowersville)						
4781	Gravel	Harrison Sd&Gr (New Trenton)						
4804	Gravel	Shelly Mtls/Melvin Stone (Chillicothe)						
4813	Gravel	Valley Materials						
4814	Limestone	Martin Marietta						
4820	Limestone	Hanson Aggregates (Plum Run)						
4825	Limestone	Martin Marietta						
4833	Limestone	Hanson Aggregates (Eagle Winchester)						
4836	Limestone	Melvin Stone (Plano Rd)						
5027	Gravel	Oster						
5113	Gravel	Sidley Inc						
	Limestone	Rush County						

To begin with, 10 sources were randomly selected from the list. Samples were collected from these sources and gradation tests were performed according to standard AASHTO procedure. These samples were then tested in CPA. Gradation data from the two test procedures was compared for each of the 10 tests. The results were not consistent meaning, the discrepancy was relatively high (>25%) in some cases. Additional tests conducted produced similar test results. This variation is primarily due to the fact that CPA measures absolute dimensions of the particles. Wire screens used in standard laboratory sieves have precisely defined square openings through which particles can pass. In a sieve analysis, the size of a particle is defined by the size of the smallest opening through which it **can** pass and the size of the next smaller opening through which it **cannot** pass. Thus, theoretically, a 50 mm (2") long, 6.1 mm (0.24") thick particle can pass through a 6.25 mm (0.25") opening. It was then decided to use the correlation feature provided in the interactive computer program. This feature assists in knowing the amount of variation between the two tests for each sieve size and to develop correction factors to narrow the differences. Additional tests revealed improvement in the results. The results were further improved by setting up one correlation file for each material type. This entire process (including approximately 100 tests) can be stated as *customizing* CPA for sieve analysis of aggregates. Figure 9 shows a sample output.

The Request for Proposal for this project had suggested a 2-phase approach. Tasks suggested for Phase 1 included identification of available optical devices and conducting preliminary tests. Phase 2 would entail a detailed investigation of the equipment selected in Phase 1. The efforts presented in this report relate to Phase 1 study.



19.4.2006

KILBY (4766)
#8
VALIDATION TEST
CORRELATED

File:	KILBY8.HAN	KILBY8.GAN
Symbol:		
Date:	April 19,2006	April 19,2006
report:	06- 917	06- 917
Customer:		
material:	#8	#8
remark:		
sampling:		
sample prep.:		
moisture [M%]:		
density [kg/m³]:		
add. Operator:		
A'/H/Min.P/cam):	0.2 - 36.0	-
MTX- File:	8.CFX	-
Duration in s:	60	0
Feed r./F.height mm	11 / 15	0 / 15
RRSB n[0.1;99.0]:	1.39	6.78
RRSB d'[mm] [0.1;9§	15.66	1.02
Remaind. distr.	16.48	10.11
d[50]in mm real:	6.84	6.43
Spec. surf. real:	412.84 cm²/cm³	11.01 cm²/cm³

Histogram
% Fraction
60
50
40
30
20
10
KILBY8
KILBY8
#100 #16 #8 #4 3/8" 5/8"
Particle size (ASTM #) (logarithm)

total curve
Frequency of sum in M%
100
90
80
70
60
50
40
30
20
10
KILBY8
KILBY8
#100 #16 #8 #4 3/8" 5/8"
Particle size (ASTM #) (logarithm)

File:	content[%] size classes[mm/ASTM No.]							
	< #100	#100 - #16	#16 - #8	#8 - #4	#4 - 3/8"	3/8" - 1/2"	1/2" - 5/8"	> 5/8"
KILBY8	0.65	0.31	0.62	13.88	76.33	8.21	-	-
KILBY8	0.00	2.00	0.00	13.00	80.00	5.00	0.00	0.00

Figure 9. Comparing ASTM and CPA test results

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Gradation analysis of aggregates is a test that is routinely performed by the departments of transportation, paving contractors and test labs to determine the particle size distribution of aggregate samples. This test is useful to the highway agencies in many ways including design of hot mix asphalt concrete mixtures, determination of durability and workability of asphalt and concrete mixes, and assessment of various pavement performance attributes. Consequently, the testing agencies invest a considerable amount of time and effort for gradation analysis of aggregate samples.

Traditionally, gradation tests are done by following the ASTM or AASHTO test procedures. These test procedures require the use of a set of sieves, a sieve shaker and a weighing scale. The sieves are first arranged in a given order with a sieve having the largest opening at the top and one with the smallest opening at the bottom. The goal of the procedure is to determine the amount of material retained on each sieve, after they are subjected to shaking. This information is used to generate a gradation curve – the end product. This procedure has been in use for several years. With very little training, technicians can adopt to the procedure. Although the test results are found to be consistent, precise and repeatable, it is possible for some errors to creep in. The sources of error can be from faulty screens, sieves not calibrated after repeated use, or human errors entering the data into a spreadsheet. The amount of time consumed (30 to 60 minutes) for each test can also be a factor for large operations. As a result, the industry would welcome an alternate method that can improve the state-of-the-practice. Needless to say, even an incremental improvement may derive significant benefit to the highway industry.

Certain agricultural, food and pharmaceutical industries appear to have similar needs. They often control the size of materials in production to maintain the quality of their product and to obtain optimal performance. These industries have made headway by adopting innovative technologies for the determination of particle size. For example, Agrium Corporation, based in Western Canada, routinely uses optical devices at many of their facilities to control particle size of fertilizers [16]. Although the exact nature and operational characteristics of these devices may be different from what is needed for the highway industry, perhaps, with some modification, it is possible to customize such devices for gradation analysis of aggregates.

The primary goal of the present study is to conduct a thorough review of currently available optical devices for gradation analysis of aggregates. The literature review revealed two major initiatives, one at the University of Illinois and the other at Texas A&M University. Researchers at these universities have designed and constructed optical devices specifically for gradation analysis of aggregates. The primary difference between the two systems is that the University of Illinois system utilizes three cameras in orthogonal directions while Texas A&M University device uses a single camera. Researchers at West Virginia University have also attempted to develop a system very similar to the Texas A&M device. These devices are currently undergoing extensive in-house evaluations and as such, they are not commercially available. The review also revealed availability of three commercial optical devices namely VDG-40, WipFrag and Computerized Particle Analyzer (CPA). While VDG-40 was developed specifically for gradation analysis, WipFrag and CPA were developed for use in mining and agricultural industries, respectively.

In the present study, the CPA device became available for laboratory evaluation to determine its suitability for gradation analysis. Typical aggregate samples were collected from various sources in Ohio. Gradation of these samples was first determined using the traditional ASTM procedure. The same samples were then tested in CPA. The initial test results showed considerable variation between the two test procedures. However, after continued evaluation of the device that included over 100 tests on various types and sizes of aggregate samples, researchers were able to identify and implement appropriate modifications to the computer algorithm and narrow the differences.

Based on the efforts, test results, and experience gained, it is observed that the CPA device has potential to produce gradation results comparable to the traditional ASTM and AASHTO procedures. The device is capable of producing consistent and repeatable test data. It is computer-controlled and user-friendly. Two primary benefits noted during the evaluation are: (i) time savings, and (ii) generation of additional information. One gradation test can be completed in less than five minutes, compared to 30 to 60 minutes for the conventional procedure. More importantly, the same data can also be used to obtain additional information about elongation index and angularity.

While the results so far show promise, they should only be deemed preliminary. Additional efforts are needed to ascertain the preliminary findings and truly establish the capabilities of CPA. The researchers recommend that ODOT initiate the Phase 2 program and expand the scope of services. The Phase 2 study may include additional tests as below:

Aggregate Size	Type	Sample size	Tests
#4	Limestone and Gravel	Total of 150 samples. These samples will be collected from various aggregate sources in Ohio and represent different texture, color and other physical properties	Fractured count (D5821), Flakiness and Elongation (digital caliper), Sieve Analysis, CPA
#57			
#8			

Upon completion of the additional tasks mentioned above, conclusions about the capabilities of CPA and recommendations to ODOT on specification changes, equipment to purchase based on the capability, precision, durability and cost of the equipment can be made.

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