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INFRASTRUCTURE MANAGEMENT AND ENGINEERING

A COMPARISON OF OPTICAL GRADATION ANALYSIS DEVICES TO CURRENT TEST METHODS

FINAL REPORT

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16. Abstract:

Optical devices are being developed to deliver accurate size and shape of aggregate particles with, less labor, less consistency error, and greater reliability. This study was initiated to review the existing technology, and generate basic data to determine when and where such devices are appropriate from the standpoint of both economies and performance. The study was taken up in two phases. Phase-1 incorporated a review of the existing devices for gradation analysis. 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 examines particles as they freely fall in front of a light source, while a camera capable of making 10,000 scans per second captures 2-D images. Aggregate samples were collected from 46 different sources in Ohio. These sources included various sizes of lime stone and gravel with varying amounts of crushed faces. Gradation tests were first performed according to standard ASTM/AASHTO procedures. The samples were then tested in CPA. The results of the tests showed that the maximum difference between the test results was less than 1%.

Phase-2 was initiated: (i) to validate the gradation results derived from CPA, and (ii) to investigate its suitability for the measurement of shape characteristics of aggregates such as % *Fractured Face* (ASTM D5821) and *Flakiness and Elongation Index* (ASTM D4791). The fractured face test is subjective and requires visual inspection of aggregate surface to estimate percent of fractured surface. The CPA device is not configured to directly output this property. However, the device measures another property termed 'Sphericity'. The researchers attempted to establish a correlation between %FF and the Spherecity values. To pursue this goal, a total of 202 aggregate samples (78 gravel and 204 limestone) were tested. Flat and elongated test requires the measurement of largest and least dimension of each particle. A free falling particle always falls with its largest dimension exposed to the camera. However, the width exposed to the camera may not always correspond to the least dimension. This is particularly true for flaky particles which lie on their flat surface. In order to overcome this limitation and to capture the least dimension, the feeder bin was redesigned so as to allow only one particle to fall at a time. The effort culminated in the redesign of feeder so as to allow only one particle to fall at a time. The study led to the following conclusions:

1. CPA device is capable of producing *gradation* results with great repeatability, reproducibility, reliability, and precision. The results clearly demonstrate the capability of CPA in matching traditional sieve analysis results.
2. The device is rugged, durable, and user friendly.
3. A primary advantage of CPA is its capability to be installed as in-line systems for continuous monitoring at the crusher and/or asphalt plant. With such systems, the results are continuously transferred to the control plant for making necessary adjustments for process control. However, the present study focused on the use of CPA device in the laboratory environment.
4. In its current format, the CPA is not capable of determining *%FF* and *F/E index*.

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A COMPARISON OF OPTICAL GRADATION ANALYSIS DEVICES TO CURRENT TEST METHODS

1. INTRODUCTION

The sieve analysis, commonly known as the "gradation analysis" is routinely performed by the paving contractors, departments of transportation and private test laboratories to determine the particle size distribution of aggregate samples. The test 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. The gradation data can be used to calculate relationships between various aggregate or aggregate blends, to check compliance with such blends, and to predict trends during production by plotting gradation curves graphically, to name just a few uses. 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 while the procedures for a wet (washed) sieve analysis are given in ASTM C117. When an aggregate sample consists of an appreciable amount of materials finer than No. 200 sieve, wet sieving is performed.

1.1 Extent of Gradation Tests Conducted in Ohio

The Ohio Department of Transportation (ODOT) [2] has established specifications in developing tests required for the design of Portland Cement Concrete (PCC), Hot Mix Asphalt (HMA), and special aggregate bases in Ohio. In addition to providing information necessary for design work, sieve analysis of aggregates is required by ODOT in its Quality Control (QC) and Quality Assurance (QA) Programs. QC tests are those tests necessary to control the quality of a product and are conducted by the contractors. QA tests are acceptance tests, performed by the owner. At a hot mix asphalt production facility, QC/QA 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 facility. As an example, the total number of gradation tests conducted by a HMA production facility in Ohio which produces approximately 250,000 tons of asphalt concrete mix in a year is as follows:

- Gradation tests during 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 HMA is produced in Ohio in a year, it is possible that a total of (16,000,000 x 950/250,000) = 60,800 tests are conducted in Ohio in a year. This includes the tests conducted only by the asphalt industry.

1.2 ODOT's Efforts

In the recent times, new methods are being devised to expedite and rationalize the aggregate test results. Most notable among the new technologies are optical test methods that use computer controlled video enhancement pictures. The primary intent of using the optical devices is to obtain faster results with, less labor, less consistency error, and greater reliability.

In its continuing efforts to improve its material testing practices in Ohio, the OMM initiated a study to conduct a critical review of the available optical devices and provide basic data to determine when and where such devices are appropriate from the standpoint of both economies and performance. The basic focus of this study was on 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?

1.3 Present Study: Significance and Scope

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

Gradation tests are routinely performed by State agencies, aggregate producers 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].

The present study was taken up in two phases. Phase-1 focused on optical devices pertaining to gradation tests. The Phase-1 study was extended into Phase-2 to further research the applicability of the devices for Flakiness and Elongation Index (ASTM D4791), and Angularity (ASTM D5821) tests. This report combines the tasks of Phases 1 and 2 and presents a) a review of the available optical devices, b) an experimental plan to conduct lab studies on a range of aggregate samples that resulted in evaluation of selected optical device and conventional test procedures, and c) subsequent conclusions and recommendations.

2. 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 selected optical device,
4. Investigate the applicability of the device to determine Flakiness and Elongation Index (F/E) and angularity,

5. Analyze the data,
6. Prepare recommendations to ODOT on specification changes and equipment to purchase based on the capability, precision, and durability of the equipment evaluated.

3. WHAT ARE OPTICAL DEVICES?

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 [5].

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, a unit of measure, 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 [6].

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 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.

4. OPTICAL DEVICES FOR AGGREGATE SIZE AND SHAPE ANALYSIS

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 [7]
2. Aggregate Imaging System - Texas A&M University [8]
3. Image Acquisition setup - West Virginia University [9]
4. VDG40 - LCPC (French Research Lab) [10]
5. WipFrag - Wipware Systems [11]
6. Computerized Particle Analyzer(CPA) – WS Tyler [12]

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 8 cm/s 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.

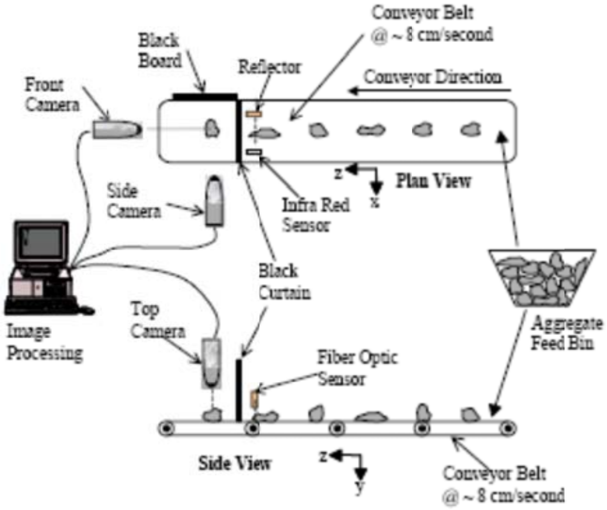


Figure 1 Schematic of the University of Illinois Aggregate Image Analyzer [7]

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 (Figure 2 and 3).

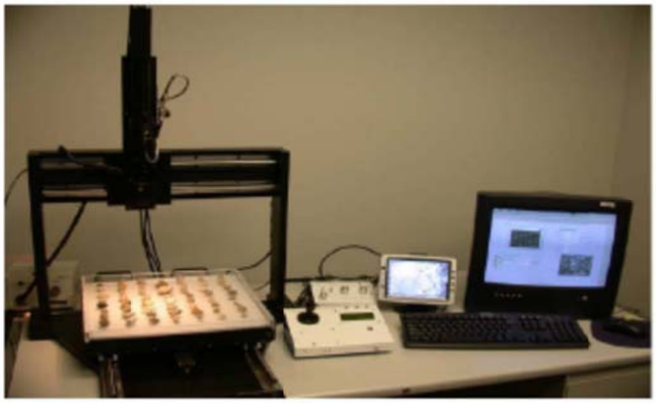


Figure 2 Texas A&M Aggregate Imaging System [8]

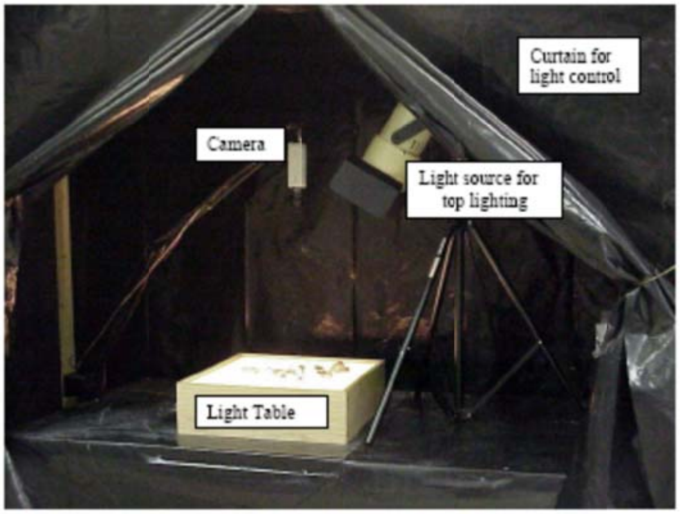


Figure 3 West Virginia Image Acquisition Setup [9]

A computer algorithm analyzes shape and size of individual particles. These devices are not dynamic, meaning they cannot be used with in-line production system. The Texas device was modified from its earlier version by Pine Instruments [13]. The modified device is capable of measuring particle size, shape, angularity and texture. The system, as shown in Figures 4 and 5, has an integrated hardware/software system that automates the process of measurement. Interactive software designed to remove operator influence assists the users in conducting tests and generating reports. The device has been tested by several DOTs, universities and private laboratories under Federal Highway's Highways for Life program of study [14].

Figure 4 Aggregate Imaging System Modified by Pine Instruments

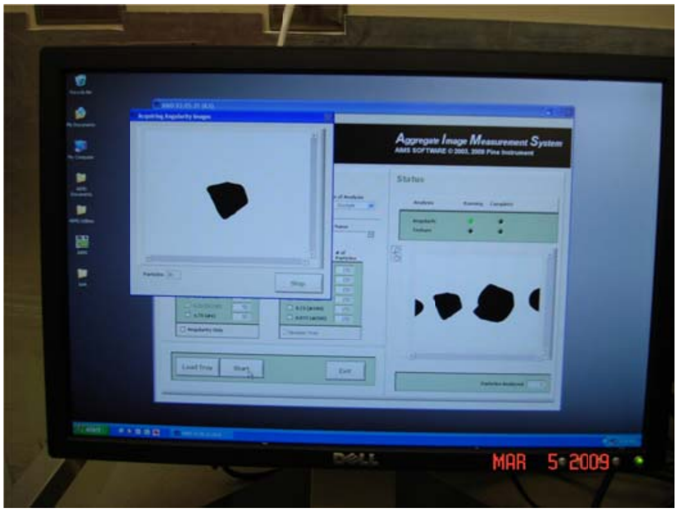


Figure 5 Interactive Software for the Aggregate Imaging System

The other three devices (VDG-40, WipFrag and CPA) 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 stockpiles. 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. This device is routinely used in the mining industry across the world.

Perhaps, the first commercial device that was specifically developed for the particle size analysis of aggregates is VDG-40 Videogranulometer (Figure 6). In using this device, the aggregate sample is first 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. The literature however, could not establish the extent of use of this device in the United States and elsewhere.

Figure 6 VDG-40 Videogranulameter [10]

The Computerized Particle Analyzer (CPA) 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 and shapes of fertilizers [15]. Figure 7 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 18,000 scans per second captures images. The data obtained during the analysis 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 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. There are several variants of the system depending on the maximum particle size. Figures 8 and 9 show the systems that can handle particles up to 2” and 3” respectively.

Figure 7 CPA 4 Dual Range

Figure 8 CPA 3.2

Figure 9 CPA 4

According to the manufacturers of this device, the CPA process has been researched, developed and continuously tested throughout the 1990s. The repeatability of the machine is remarkable and the variances from traditional sieving data versus CPA correlated results are minimal [16].

5. DEVICE EVALUATED IN THE PRESENT STUDY

Development and/or customization of a device to the industry's needs are in the best interest of industry as well as developers. Generally, the product developers take an active role to research 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 was developed for particle size analysis of aggregates in response to industry needs to improve the existing procedure. On the other hand, CPA and WipFrag systems have been developed for different applications (agricultural, food processing, mining industry). 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 these systems. The VDG40 system does not appear to have representation in the United States. The CPA product engineers readily agreed to actively participate in the research program and to make a unit available for the investigation [15]. 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 [17].

6. WORKING PRINCIPLE AND CURRENT CAPABILITIES OF CPA

Figure 10 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). The free falling objects are detected and registered against the light by the camera. Using the computer algorithm (5), the particles are scanned line by line and reconstructed. A special memory handling enables to measure all particles of the sample. The device is capable of measuring the particle size distribution and shape of all dry and flowing bulk materials between 0.0016” and 1.5”.

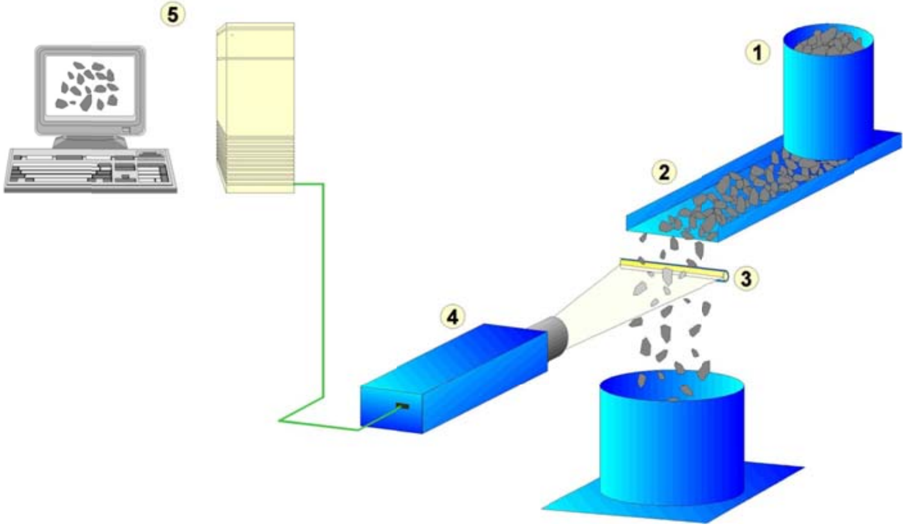
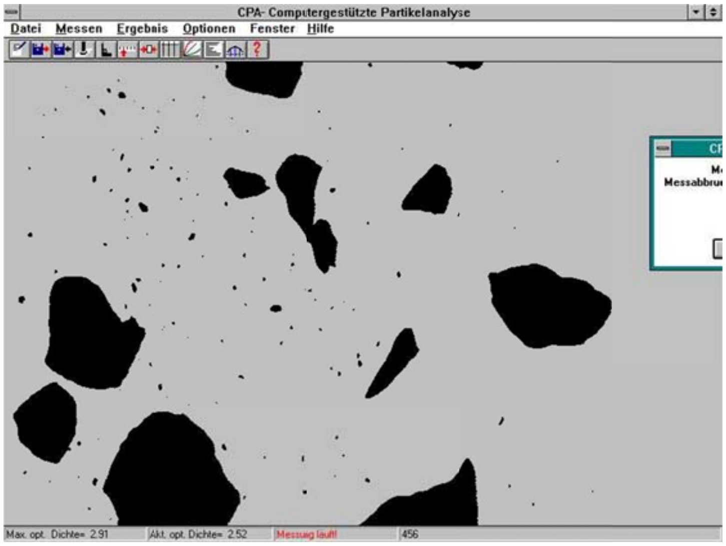


Figure 10 Working Principle of CPA [15]

The on-screen display of 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 11 shows a snapshot of screen display.



Max. opt. Dichte= 2.91

Akt. opt. Dichte= 2.52

Messuag läuft!

456

Figure 11 Snapshot of Interactive Screen

7. THE EXPERIMENT AND OBSERVATIONS

The CPA device used for evaluation in the present study is shown in Figure 9. This device, CPA4, can handle particles sand sized to 1.5”. 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, the researchers finalized a list of aggregate sources and collected adequate samples from each source. Table 1 provides the list of aggregate sources.

Table 1 Aggregate Sources and Types included in the Experiment

ODOT Source #	**Plant**	**Aggregate Type**	**Particle Size**		
			#4	#8	#57
4602	Walls Mtl's (Fort Jefferson)	Limestone	✓		✓
4604	Martin Marietta (Phillipsburg)			✓	✓
4615	Piqua Materials			✓	✓
4622	Stoneco		✓	✓	
4623	Miami River Stone		✓	✓	✓
4721	Melvin Stone (Melvin)			✓	✓
4825	Martin Marietta			✓	✓
4833	Hanson Aggregates (Eagle Winchester)		✓		
4836	Melvin Stone (Plano Rd)			✓	✓
4777	Melvin Stone (Bowersville)				✓
4737	Martin Marietta		✓	✓	✓

ODOT Source #	**Plant**	**Aggregate Type**	**Particle Size**		
			#4	#8	#57
4611	Enon Sand & Gravel	Gravel	✓	✓	✓
4637	Mechanicsburg Sd&Gr		✓		
4526	Melvin Stone (Circleville)			✓	✓
4601	Martin Marietta(Fairborn)			✓	✓
4607	Martin Marietta			✓	✓
4703	Martin Marietta			✓	
4705	Martin Marietta			✓	
4711	Martin Marietta			✓	✓
4715	Martin Marietta			✓	✓
4723	Morrow Sand & Gravel			✓	✓
4726	Shamrock Materials			✓	
4745	Northern Kentucky Aggregates			✓	
4766	Southern Ohio Aggregates			✓	✓
4628	Urbana Materials				✓
4749	Martin Marietta				✓

7.1 Comparison of Grain Size Analysis using CPA and ASTM C136 Test Procedures

To begin with, 10 sources were randomly selected from the above list. It should be recognized that, for all the tests conducted in this study, air-dried samples were used. Gradation tests were performed according to standard ASTM C136 procedure [18] and then analyzed using the CPA. The results of the gradation analysis from the two test procedures were compared for each source. The results were not consistent, meaning, the discrepancy in percent passing of the material was relatively high (>25%) in some cases. Additional testing was conducted and produced similar test results.

The inconsistency between the two test procedures was discovered to be primarily due to the fact that CPA measures the absolute dimensions of the aggregate particles. This highlighted the fundamental difference in the way the traditional sieve analysis and the CPA interpret the measurement of aggregate particles. Wire screens used in standard laboratory sieves for performing the standard ASTM C169 test procedure have precisely defined square openings through which particles can pass. Thus, in a sieve analysis, the size of a particle is defined by the size of the smallest square opening through which it **can** pass and the size of the next smaller square opening through which it **cannot** pass. Theoretically, a 2” long, 0.24” thick particle can pass through a 0.25” square opening while the optical analysis classifies this particle as finer than 0.25”.

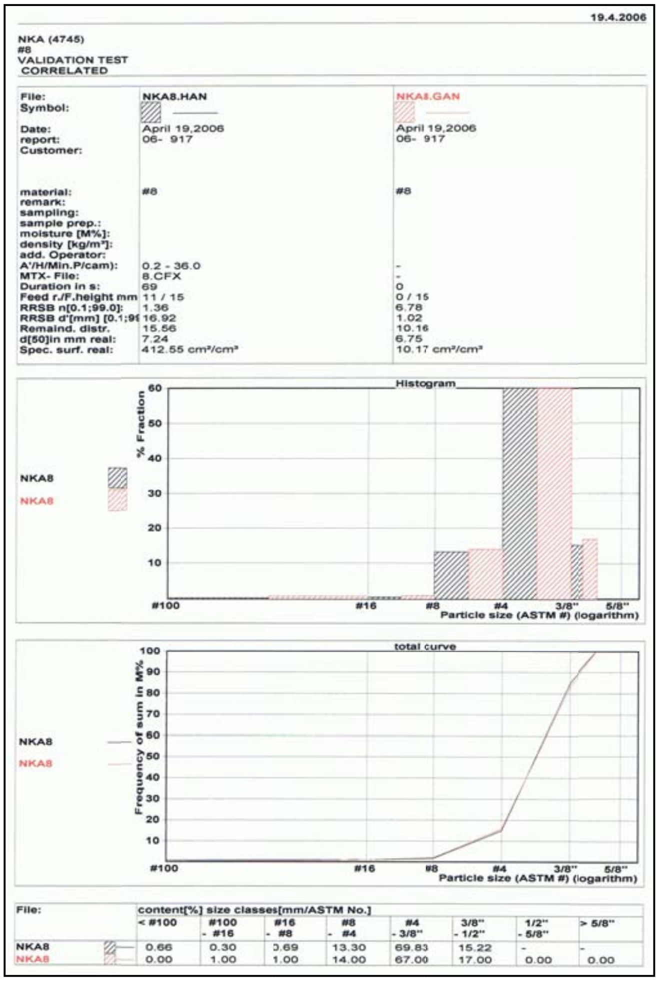
To overcome the inconsistency problem mentioned above, the CPA system incorporates a calibration feature. The calibration feature assists in knowing the amount of variation between the two test procedures for each sieve size and develops correction factors to narrow the differences. Before reporting gradation analysis results from a CPA, a technician is required to run this calibration (during the initial setup) and also required to verify the calibration periodically, particularly when the shape and size of particles changes.

Ten aggregate samples, representing the complete range of materials collected, were selected. Calibration tests were run as required by the interactive program and appropriate constants were developed. This entire process that included three tests on each sample can be stated as customizing a CPA for sieve analysis of aggregates.

Following this, comparative gradation analysis between the ASTM procedure [18] and CPA were continued. The results from this comparative gradation analysis revealed a difference in test results between the procedures that was significantly lower. The results of the calibration procedure were then applied on all the samples listed in Table 1.

The sieve analysis results using both the test procedures for all the 46 samples are graphically presented in Appendix A. As can be seen, the difference between the two test results for each material was either very small or none. The maximum difference between the test results was less than 1%, indicating excellent comparison between the two test procedures.

A typical graphic output showing charts of percentage fraction and cumulative percent passing is presented in Figure 12. Prior to the beginning of the test, the software allows the user to enter the gradation values obtained from the traditional sieve analysis. The output can be formatted to produce graph of particle size distribution from the two tests simultaneously allowing direct comparison. For each of the sample tested, gradation test results from the sieve analysis were first entered and then tests were conducted using the CPA device. An example of the graphic output is shown in Figure 12.



19.4.2006

NKA (4745)
#8
VALIDATION TEST
CORRELATED

File:	NKA8.HAN	NKA8.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:	69	0
Feed r./F.height mm	11 / 15	0 / 15
RRSB n[0.1;99.0]:	1.36	6.78
RRSB d'[mm] [0.1;9	16.92	1.02
Remaind. distr.	15.56	10.16
d[50]in mm real:	7.24	6.75
Spec. surf. real:	412.55 cm²/cm³	10.17 cm²/cm³

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"
NKA8 ▨ ——	0.66	0.30	.69	13.30	69.83	15.22	-	-
NKA8 ▨ ——	0.00	1.00	1.00	14.00	67.00	17.00	0.00	0.00

Figure 12 Comparing ASTM C136 and CPA Test Results

The principal of operation is different between the two techniques. In using the sieves, the user will collect a known weight of dry sample and process the material through a set of sieves. Weight of the particles retaining on each sieve is measured in order to calculate percent of material passing through each sieve size. Two important steps to note here are: sample size and weight of sample. The sample size used in sieve analysis is usually ranges from 3500 to 10000 g for the coarse aggregate gradation analysis and around 300 g for the fine aggregate gradation analysis

[19]. Particle size distribution is determined based on the weight of the size fractions retained on each sieve in proportion to the total weight. On the contrary, the CPA device derives particle size distribution based on number of individual particles, not weight. Although the principal of operation is different between the two techniques, CPA offers distinct advantage in terms of significant reduction in testing time. An added strength of CPA is its capability to be installed as in-line and on-line systems for continuous monitoring at the aggregate and/or asphalt plant. The on-line systems offer an automated method for collecting and testing samples at predetermined intervals. The results can be helpful in monitoring production and making necessary adjustments. The in-line systems allow continuous monitoring. With such systems, the results are continuously transferred to the control plant. According to the manufacturers of CPA, on-line systems are best suited for installations at aggregate plant. Fourteen installations made in North America and Europe have been in operation [15, 20]. Figures 13, 14, and 15 show typical CPA on-line systems.

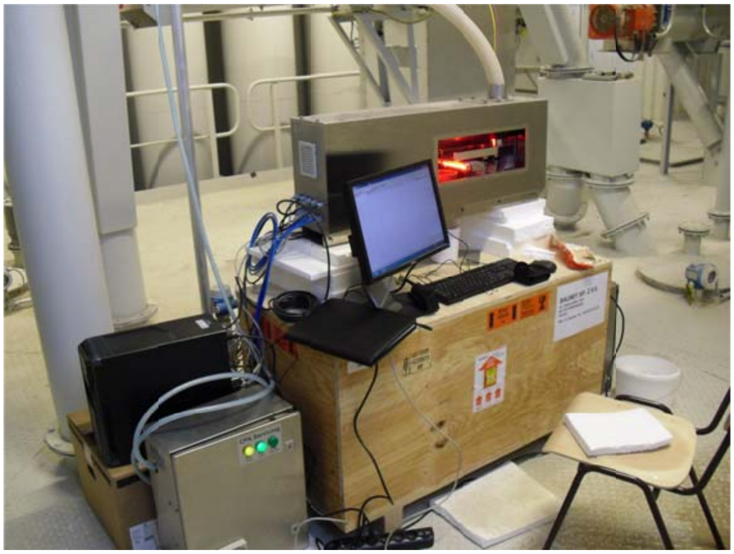


Figure 13 CPA On-Line System at a Building Construction Materials Production Facility in Poland

Figure 14 CPA On-Line System to check the Roundness of Plastic Granules

Figure 15 CPA 4-2 Housed in a Container at an Aggregate Crusher

The system shown in Figure 13 is an on-line system installed in early 2011 at a facility producing building construction materials such as screed, plaster and stucco in Poland. Samples are taken at 5 to 10 minute intervals and processed by the CPA unit. This unit is devised primarily to measure sand sized particles. The unit shown in Figure 14 has been installed in a chemical industry to check the roundness of plastic granules in the range 0.1” to 0.15”. Figure 15 shows CPA 4-2 unit housed in a container for an outdoor installation. The device can handle particles between 0.08” and 1.2”.

Performance review of on-line systems have shown the ability of these systems to monitor the particle sizes of various types of materials under varied conditions, transfer the data to the control office, and provide the necessary data for process control [21]. With these capabilities, the CPA devices meet the performance expectations for gradation analysis both in a laboratory environment and on-site installations.

7.2 Evaluating Repeatability of CPA

Repeatability testing establishes whether or not a device is capable of repeating its outcome within a certain limit under the same set of conditions. In order to evaluate the repeatability capability of CPA device, the following three representative samples (Table 2) were selected.

Table 2 Aggregates Used for Evaluating Repeatability of CPA

Size	**Type**	**# of tests repeated (on the same physical sample)**
#57	Gravel crushed	6
#8	Natural gravel	5
Sand	Natural Sand	4

Gradation analysis using the CPA was conducted on the same physical sample from each of the three different materials as indicated above. The gradation analysis procedure was repeated multiple times on the sample physical sample as shown in table 2. The results of the repeated gradation analysis for the three different types of materials are presented (in terms of % retained) in Tables 3, 4 and 5. A graphical representation of all the test data for the three materials is plotted as the cumulative distribution of percent passing and percent retained on each sieve versus the sieve size in figures 16, 17, and 18.

Table 3 Repeatability of CPA Showing % Material Retained on Indicated Sieves for #57 Crushed Gravel

Sieve Size	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
1-1/2"	0.00	0.00	0.00	0.00	0.00	0.00
1"	0.67	0.65	0.83	0.84	0.30	0.00
3/4"	14.88	16.96	16.82	16.04	17.99	13.00
1/2"	33.50	32.46	32.12	31.52	30.91	35.00
3/8"	15.67	15.31	14.88	15.28	15.41	17.00
#4	24.52	24.26	24.86	25.50	24.62	24.00
#8	10.29	9.89	9.98	10.28	10.21	10.40

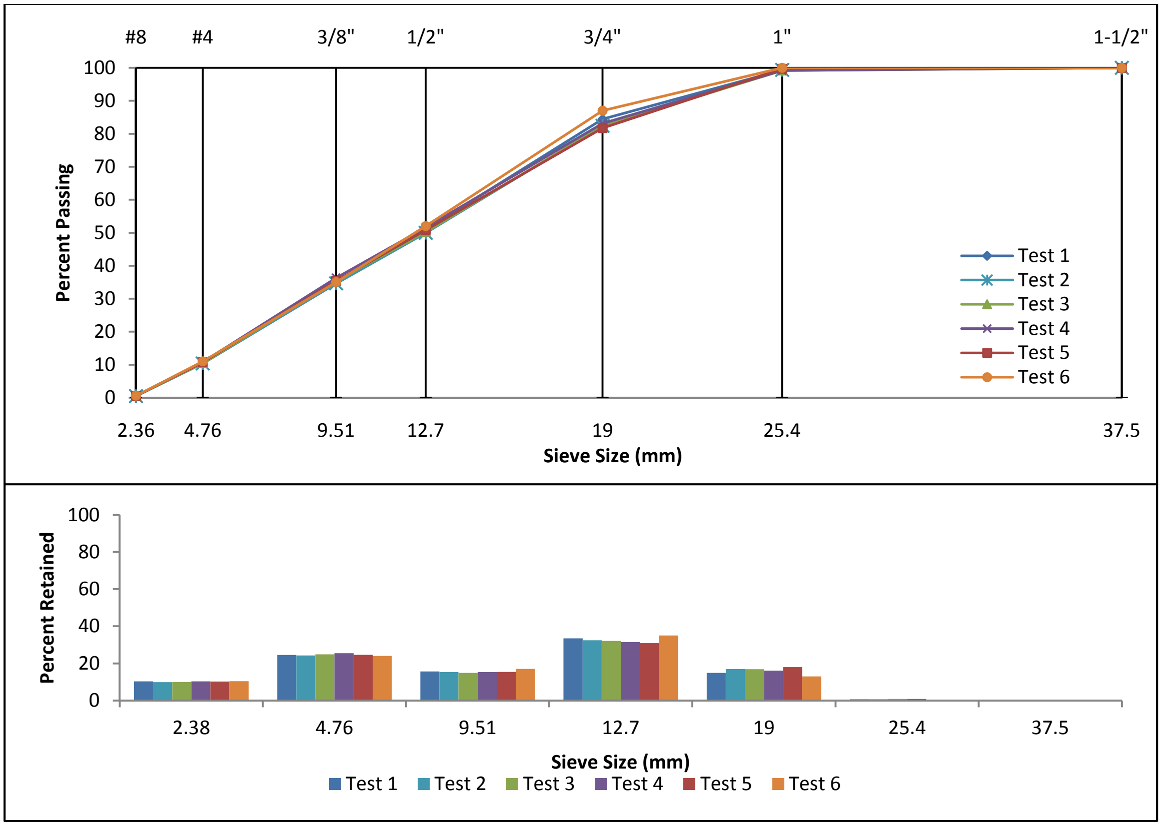


Figure 16 Grain Size Test Data Plotted as Cumulative % Passing and % Retained on Individual Sieves for a Representative Sample of #57 Crushed Gravel

Table 4 Repeatability of CPA Showing % Material Retained on Indicated Sieves for #8 Natural Gravel

Sieve Size	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
1-1/2"	3.50	3.50	3.51	3.36	3.41	0.00
3/8"	19.59	16.96	19.13	19.82	18.37	14.00
#4	61.76	64.03	62.34	61.90	62.63	69.00
#8	14.85	15.21	14.66	14.63	15.28	16.00
#16	0.29	0.27	0.32	0.28	0.29	1.00
#100	0.01	0.03	0.04	0.01	0.02	0.00

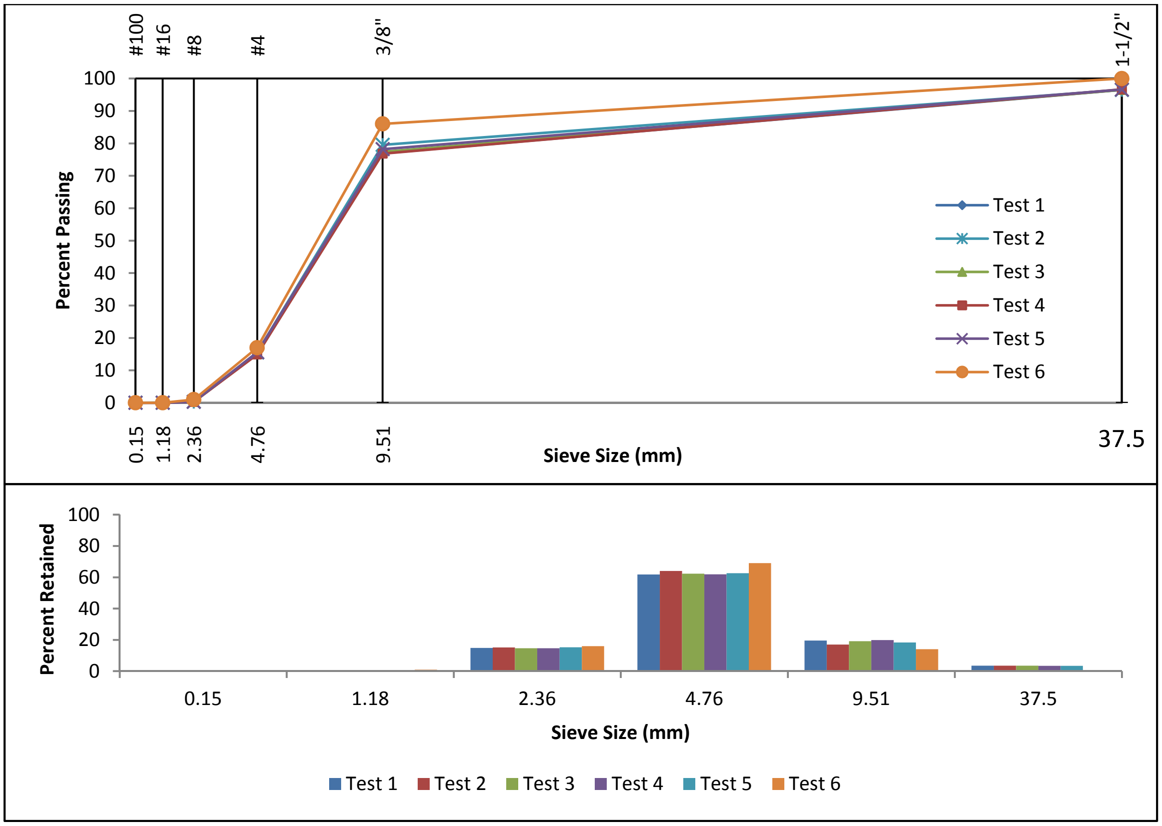


Figure 17 Grain Size Test Data Plotted as Cumulative % Passing and % Retained on Individual Sieves for a Representative Sample of #8 Natural Gravel

Table 5 Repeatability of CPA Showing % Material Retained on Indicated Sieves for Natural Sand

Sieve Size	Test 1	Test 2	Test 3	Test 4
3/8"	0.00	0.00	0.00	0.00
#4	6.22	6.28	5.47	6.18
#8	12.59	12.6	12.19	11.37
#16	11.29	11.5	11.31	10.97
#30	28.46	26.95	26.97	26.32
#50	37.41	38.17	39.26	40.1
#100	3.58	4.05	4.31	4.56
#200	0.44	0.44	0.48	0.49

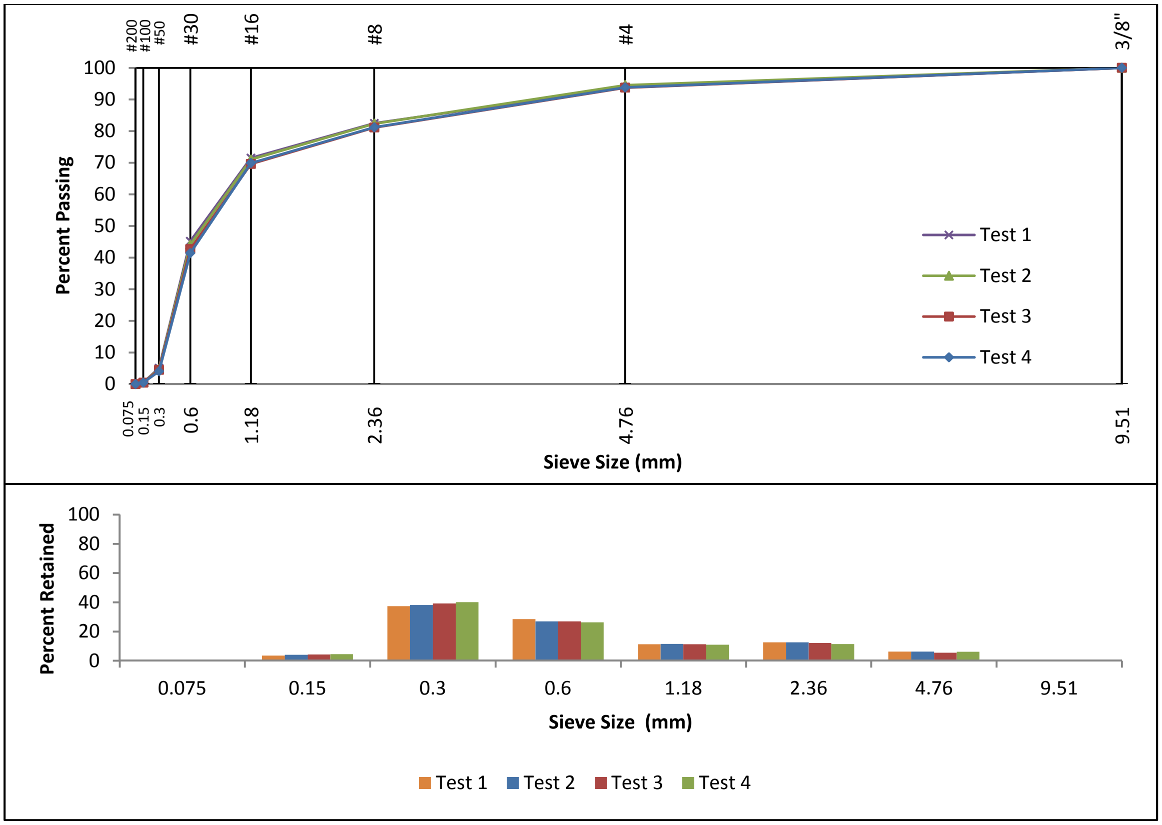


Figure 18 Grain Size Test Data Plotted as Cumulative % Passing and % Retained on Individual Sieves for a Representative Sample of Natural Sand

A cursory view of the results suggests the CPA device is repeatable. However, to conclusively and objectively state whether or not the CPA device is capable of repeatedly performing the grain size analysis, it is essential to statistically validate the test results. In order to statistically validate the repeatability of the CPA device, control charts were used. Control charts are an efficient way of analyzing performance data to evaluate a process. Typically, a control chart has (i) Center Line (CL); (ii) Upper Control Limit (UCL); and (iii) Lower Control Limit (LCL). If the individual test results produced by the device lie between UCL and LCL, then the device is deemed repeatable. The CL, UCL, and LCL are calculated as follows:

$$\text{Center Line} = \text{Mathematical Average of all the samples}$$

$$\text{Upper Control Limit} = \text{Center Line} + \text{L} * \text{SD}$$

$$\text{Lower Control Limit} = \text{Center Line} - \text{L} * \text{SD}$$

Where: L is the distance of the control limits from the center line and SD is the standard deviation of all the samples. The distance, L, is generally chosen based on the 68-95-99.7 rule, which states, for a normally distributed data, nearly all values fall within 3 standard deviations of the mean. In other words, about 68% of the values fall within 1 standard deviation of the mean, about 95% of the values fall within 2 standard deviations of the mean, and about 99% of the values fall within 3 standard deviations of the mean.

The test results were methodically analyzed using the percent retained fraction on each of the sieves used. The results of the grain size analysis tests – in terms of percent of material retained on sieves – and the three components of control charts are presented in Table 6, 7, and 8.

Table 6 Verification of Repeatability of CPA for #57 Crushed Gravel

Sieve Size	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Mean	SD	UCL (CL+3*SD)	CL	LCL (CL-3*SD)
1-1/2"	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1"	0.67	0.65	0.83	0.84	0.30	0.00	0.55	0.33	1.55	0.55	-0.45
3/4"	14.88	16.96	16.82	16.04	17.99	13.00	15.95	1.78	21.28	15.95	10.62
1/2"	33.50	32.46	32.12	31.52	30.91	35.00	32.59	1.47	37.00	32.59	28.17
3/8"	15.67	15.31	14.88	15.28	15.41	17.00	15.59	0.74	17.80	15.59	13.38
#4	24.52	24.26	24.86	25.50	24.62	24.00	24.63	0.52	26.19	24.63	23.06
#8	10.29	9.89	9.98	10.28	10.21	10.40	10.18	0.20	10.77	10.18	9.58

Table 7 Verification of Repeatability of CPA for #8 Natural Gravel

Sieve Size	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Mean	SD	UCL (CL+3*SD)	CL	LCL (CL-3*SD)
1-1/2"	3.50	3.50	3.51	3.36	3.41	0.00	2.88	1.41	7.12	2.88	-1.36
3/8"	19.59	16.96	19.13	19.82	18.37	14.00	17.98	2.21	24.60	17.98	11.36
#4	61.76	64.03	62.34	61.90	62.63	69.00	63.61	2.76	71.90	63.61	55.32
#8	14.85	15.21	14.66	14.63	15.28	16.00	15.11	0.52	16.65	15.11	13.56
#16	0.29	0.27	0.32	0.28	0.29	1.00	0.41	0.29	1.28	0.41	-0.46
#100	0.01	0.03	0.04	0.01	0.02	0.00	0.02	0.01	0.06	0.02	-0.03

Table 8 Verification of Repeatability of CPA for Natural Sand

Sieve Size	Test 1	Test 2	Test 3	Test 4	Mean	SD	UCL (CL+3*SD)	CL	LCL (CL-3*SD)
3/8"	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
#4	6.22	6.28	5.47	6.18	6.04	0.40	7.20	6.00	4.90
#8	12.59	12.6	12.19	11.37	12.19	0.60	13.90	12.20	10.50
#16	11.29	11.5	11.31	10.97	11.27	0.20	11.90	11.30	10.60
#30	28.46	26.95	26.97	26.32	27.18	0.90	29.90	27.20	24.50
#50	37.41	38.17	39.26	40.1	38.74	1.20	42.30	38.70	35.20
#100	3.58	4.05	4.31	4.56	4.13	0.40	5.40	4.10	2.90
#200	0.44	0.44	0.48	0.49	0.46	0.00	0.50	0.50	0.40

As can be seen in the above tables, UCL and LCL have been calculated with L being equal to 3 and all the individual values fall within UCL and LCL. This illustrates with 99.7% confidence that the CPA device is able to produce repeatable gradation test results.

Encouraged by the results of Phase-1 investigation, ODOT decided to further evaluate the additional capabilities CPA.

8. INVESTIGATING ADAPTABILITY OF CPA TO MEASURE ANGULARITY, % FRACTURED FACE, AND ELONGATION INDEX (F/E)

In additional to gradation analysis, two additional tests namely, fractured face (ASTM D5821) and Flat and elongated (ASTM D4791) are required to be conducted before aggregate can be used in HMA in Ohio. A fractured face is defined as an "angular, rough or broken surface of an aggregate particle created by crushing, by other artificial means, or by nature" [22]. A minimum of 25% of the maximum cross-sectional area of the particle should have a rough (fractured) face to be quantified as fractured particle. The test is subjective and requires visual inspection of aggregate surface to estimate percent of fractured surface. Flat and elongated particles are determined as a ratio of maximum to minimum dimension. The test is conducted on representative sample using a mechanical caliper to measure the maximum and minimum dimensions of each particle. The limestone, dolomite, and slag sources are assumed to be 100% fractured (due to the method in which they are manufactured). Thus the fractured face test is particularly important for the gravel sources.

8.1 Adaptability of CPA Device to Measure Angularity

Tests were conducted to investigate the capability of CPA to measure angularity of aggregate particles. Angularity is a shape characteristic of aggregates. The CPA device is not configured to directly output this property. However, a review of the results showed that the device measures another property termed 'sphericity'. Sphericity represents how closely an aggregate particle resembles a sphere. It is defined as the ratio of the surface area of a sphere having the same volume as the particle in question to the surface area of the particle [23]. Sphericity values range between 0 and 1; a perfect sphere has a value of 1. An interesting question is thus raised: Can the sphericity values of aggregate calculated by the CPA also be used to determine or infer the angularity of aggregate?

CPA calculates spherecity using the relation:

$$\psi = \frac{U}{2 * \sqrt{\pi . A}}$$

Where:

Ψ – Sphericity

U – Circumference of the projection area

A – Content of the projection area

ASTM D5821 is a subjective test that requires the testing operator to visually evaluate whether the aggregate has fractured faces. If this test can be made objective, the results can be more rational, consistent, and operator independent. One such effort towards making the ASTM

D5821 test objective is reported in NCHRP Report 405 [24]. This report details the project NCHRP 4-19, wherein the percent fractured faces of aggregate have been correlated to uncompacted voids in coarse aggregate.

The uncompacted void content of coarse aggregates (AASHTO T326) [25] is an objective test which is known to relate void content to aggregate's angularity, sphericity, and surface texture. This test is simple, inexpensive, and more importantly, consumes significantly less time to perform. Figure 19 shows the uncompacted void content device in operation.

The uncompacted void content test procedure involves taking a specified size and amount of coarse aggregate and dropping it into a cylinder of known volume. Given the specific gravity and weight of aggregates in the cylinder, the volume of voids as a percentage of total volume is calculated. The loose uncompacted void content, known as Coarse Aggregate Angularity (CAA), is related to angularity and surface texture of the sample.

Figure 19 Uncompacted Void Content Device

The focus of this part of the study was to investigate if there is a correlation between sphericity and fractured count as obtained from CAA (AASHTO T326). If a relationship can be established, then the CPA device could be used to generate angularity, and thus, percent fractured face results in an objective, quick, and simple way.

A total of 202 aggregate samples were tested for sphericity. The CAA values for these samples were provided by ODOT. The list of the samples along with the CAA and other information is presented in Table B1 of Appendix B.

Figure 20 shows the correlation between sphericity and CAA for gravel and limestone. As seen from the figure, a good correlation exists between the two parameters for both types of materials.

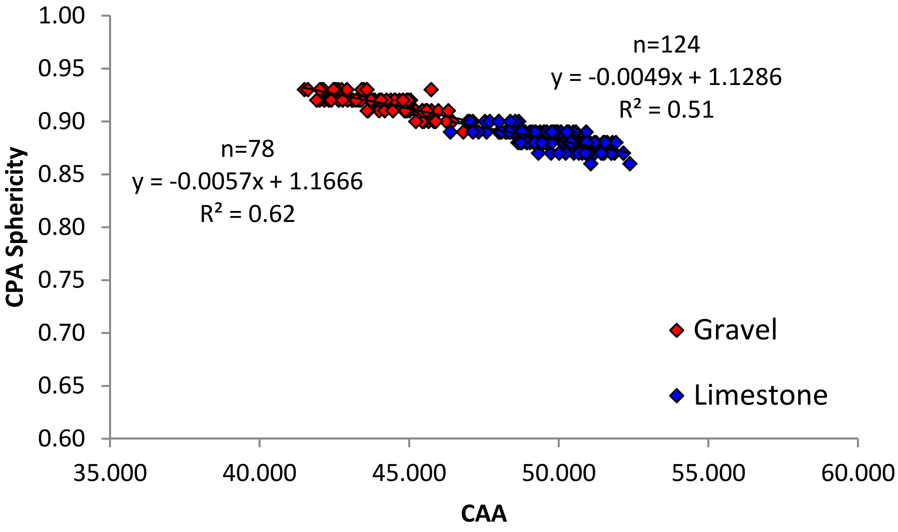


Figure 20 Correlation between CPA Sphericity and CAA

The spherecity values used in the above correlation were calculated using the equation described earlier and embedded in the CPA software. However, a review of literature regarding spherecity reveals that, in fact, there are different formulations that can be used to estimate the sphericity of an aggregate. It is seemed prudent to verify the correlation with respect to other formulations of spherecity. In doing so, the spherecity computation by the CPA device would get validated. The additional formulations (including CPA) for spherecity used for validation are as below (Table 9).

Table 9 Sphericity Formulations Evaluated in this Study

Model	Formulation	Parameters	Remarks
CPA	$\psi = \frac{U}{2 * \sqrt{\pi . A}}$	Ψ – Sphericity U – Circumference of the projection area A – Content of the projection area	
Wadell [26]	$\psi = \sqrt[3]{\frac{dI.ds}{dL^2}}$	Ψ – Sphericity dL – Maximum axis length dI – Intermediate axis length ds – Short axis length	
Sneed and Folk [27]	$\psi = \sqrt[3]{\frac{ds^2}{dL.dI}}$	Ψ – Sphericity dL – Maximum axis length dI – Intermediate axis length ds – Short axis length	
Lees [28]	$\psi = \frac{12.8 * (\sqrt[3]{p^2 q})}{1 + p(1+q) + 6\sqrt{1 + p^2(1+q^2)}}$	Ψ – Sphericity p – Flatness ratio = $\frac{ds}{dL}$ q – Elongation ratio = $\frac{dI}{dL}$	
Mora et al [29, 30]	$\text{Mean thickness} = ds = \lambda * \text{breadth}$ $\lambda = \frac{M}{\rho * \sum_1^n(\text{area} * \text{breadth})}$	ds – Short axis length λ is a parameter dependent on the flakiness of the aggregate particle M – Total mass of the sample	The third dimension required to estimate sphericity values for Wadell, Sneed

		ρ – Density of the material n – Total number of particles	and Folk, and Lees is estimated using this method.

The aggregate size parameters used in the above formulations are presented in Figure 21.

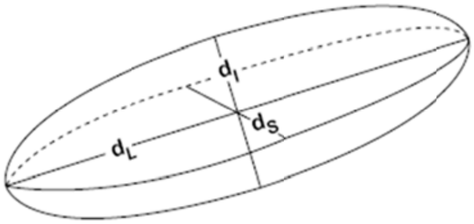


Figure 21 Axes of Aggregate Particles [31]

Wadell defined sphericity as the ratio of the diameter of a sphere with volume equal to that of the particle to the diameter of the sphere which will circumscribe the particle.

Sneed and Folk defined the sphericity of an aggregate particle as the ratio of the maximum projection area of a sphere with volume equal to that of the particle to the maximum projection area of the particle.

Lees formulated the sphericity based on the flatness and elongation ratios of an aggregate particle.

Each of the three additional formulations presented in Table 9 require three dimensions to determine the sphericity of an aggregate particle. The problem arises when using the CPA device, which only captures and measures the 2D projection of the particles. Consequently, the third dimension, i.e., thickness of the particle is not obtainable from the results of the CPA device.

Mora et al presented a method to determine the third dimension (thickness) of an aggregate in situations when only two dimensional measurements are available. Under the assumption that aggregate particles from the same source have more or less the same shape characteristics, the third dimension was estimated using the following equations.

$$\text{Mean thickness} = \lambda * \text{breadth}$$

Where:

λ is a parameter dependent on the flakiness of the aggregate particle

Estimating the mean thickness using the above equation and knowing the other two dimensions, the volume of an aggregate particle can be calculated as,

$$\text{Volume} = \text{Mean thickness} * \text{area} = \lambda * \text{breadth} * \text{area}$$

Using the total volume of all the particles, n, and the material's density, ρ, the total mass, M, of the aggregate sample can be formulated:

$$M = \rho * \lambda * \sum_{i=1}^{n} (\text{breadth} * \text{area})$$

Rearranging the above formulation, the value of λ can be calculated as follows.

$$\lambda = \frac{M}{\rho} * \sum_{i=1}^{n} (\text{breadth} * \text{area})$$

Knowing the total mass of the sample, density of aggregates, and two dimensions of an aggregate particle, it is now possible to determine the third dimension. Applying the above equations to the 2D data generated by CPA device, sphericity values for all additional formulations listed in Table 9 can be determined. The sphericity values calculated using Wadell, Sneed and

Folk, and Lees equations are presented in Table B2 of Appendix B. The correlations between the newly estimated sphericity values and CAA are presented in Figures 22 through 24. Table 10 summarizes the R^2 values from all of the above described formulations for both types of materials.

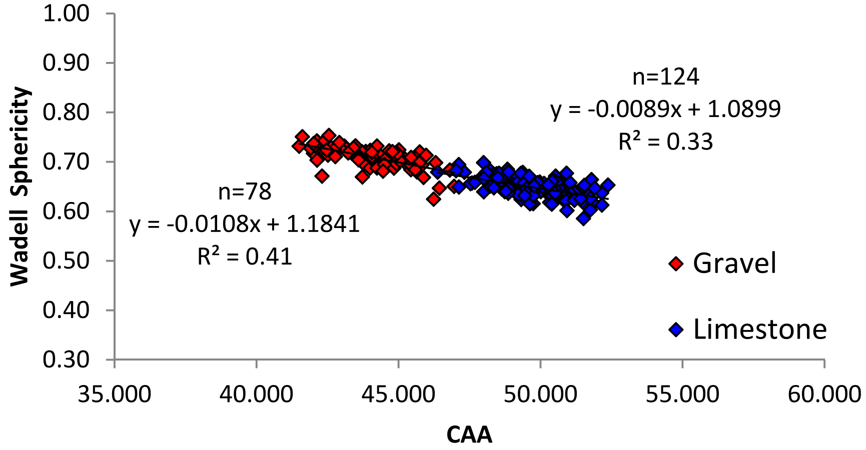


Figure 22 Correlation between Wadell Sphericity and CAA

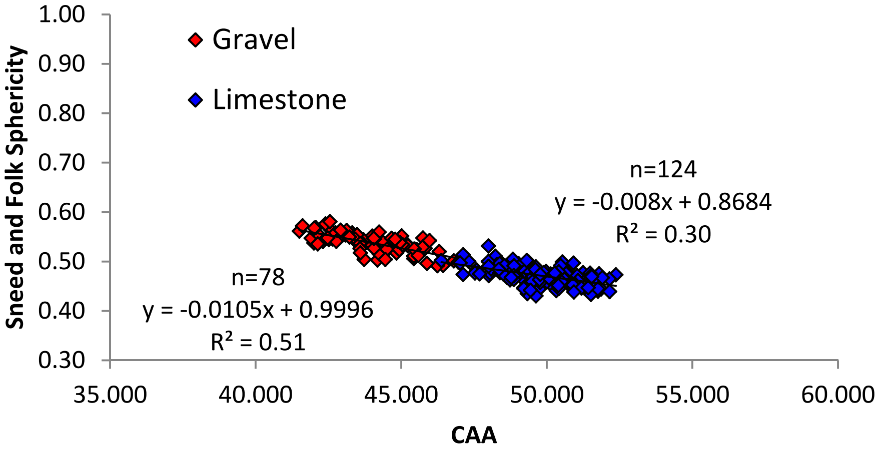


Figure 23 Correlation between Sneed & Folk Sphericity and CAA

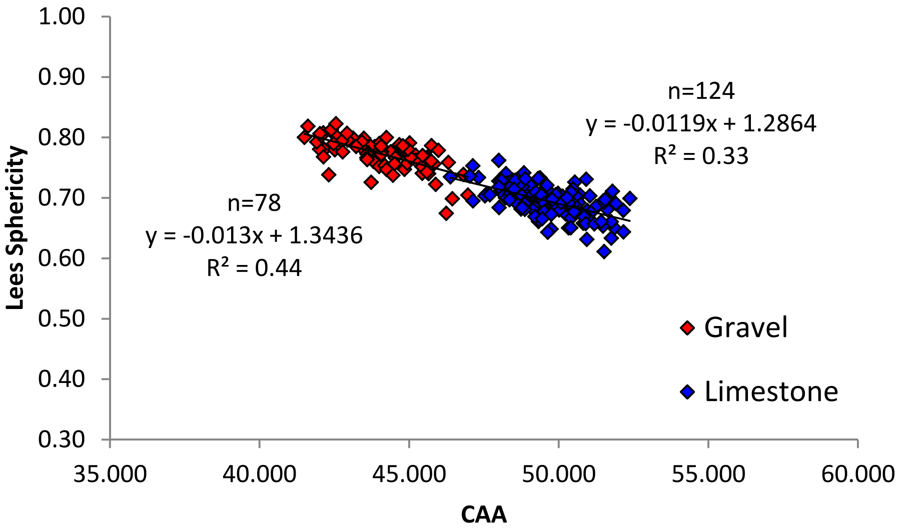


Figure 24 Correlation between Lees Sphericity and CAA

Table 10 Summary of Correlations between Sphericity and CAA

Comparison Between	**R^2 (Gravel)**	**R^2 (Limestone)**
CPA ψ and CAA (AASHTO T326)	0.62	0.51
Wadell ψ and CAA (AASHTO T326)	0.41	0.33
Sneed and Folk ψ and CAA (AASHTO T326)	0.51	0.30
Lees ψ and CAA (AASHTO T326)	0.44	0.33

The above results assist not only to further establish a strong correlation between spherecity and CAA but go on to validate the spherecity computations from CPA.

8.2 Adaptability of CPA Device to Measure Percent Fractured Faces

Encouraged by the correlation results between sphericity and CAA, a similar effort was initiated to investigate a possible correlation between sphericity and percent fractured faces. According to ASTM D5821, an aggregate particle could be separated into one of the following three categories i) percent fractured with one or more faces ii) percent fractured with two or more faces, and iii) uncrushed particles. The percent fractured faces data for a total of 110 aggregate samples were collected from ODOT. Corresponding sphericity values were obtained using the CPA, Wadell, Sneed and Folk, and Lees models. Figures 25 through 32 show correlation between sphericity values calculated using different methods and percent of fractured faces. The results are summarized in Table 11.

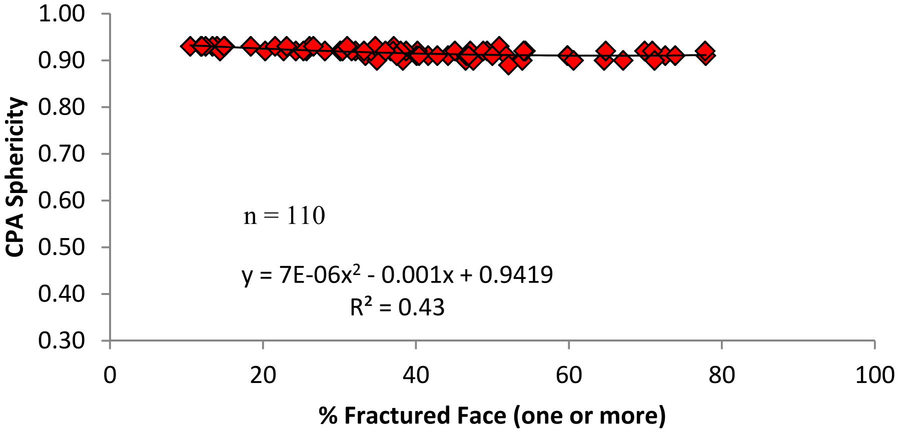


Figure 25 Correlation between CPA Sphericity vs. % Fractured Face (>1)

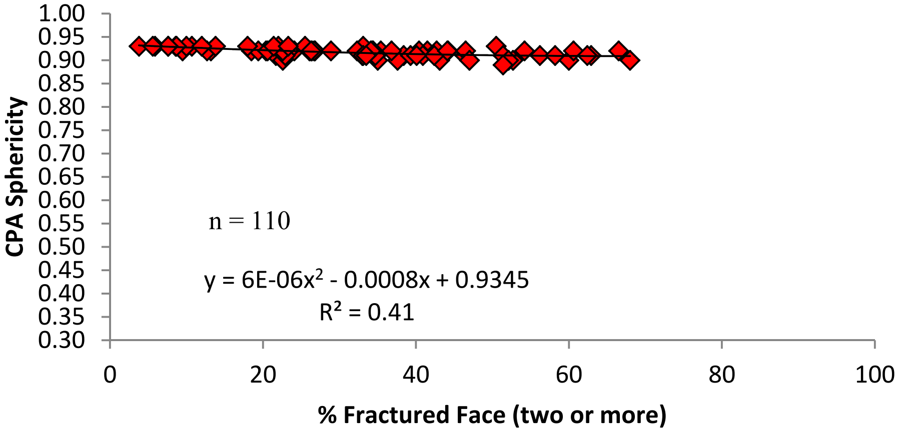


Figure 26 Correlation between CPA Sphericity vs. % Fractured Face (>2)

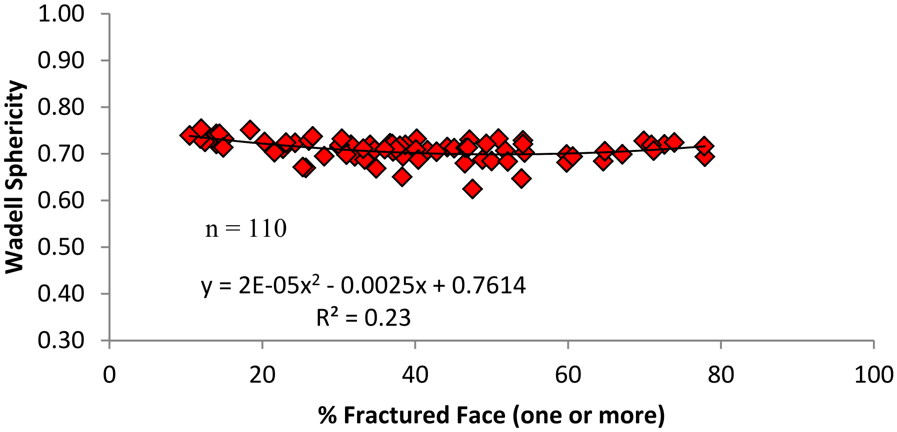


Figure 27 Correlation between Wadell Sphericity vs. % Fractured Face (>1)

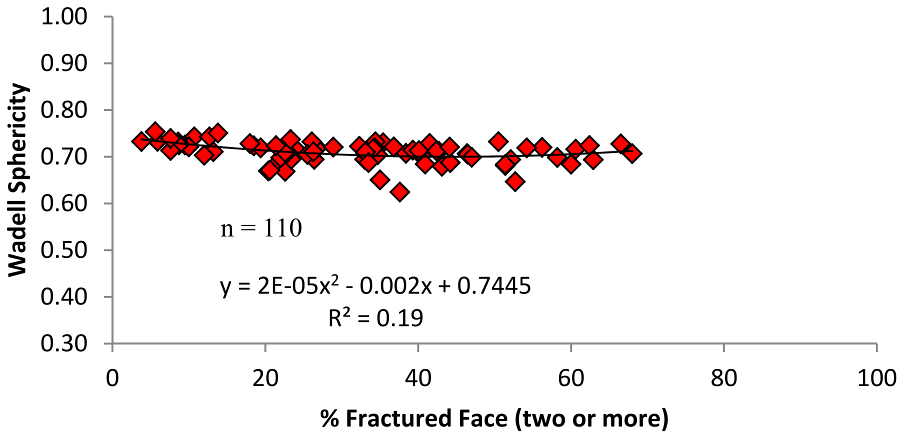


Figure 28 Correlation between Wadell Sphericity vs. % Fractured Face (>2)

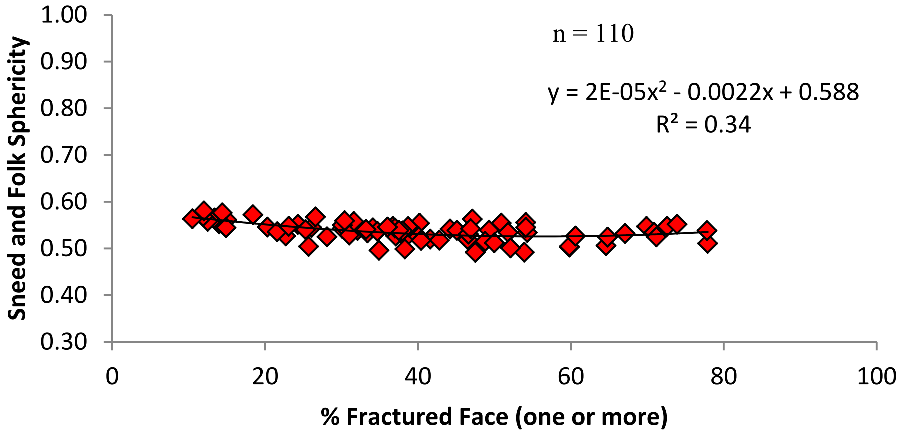


Figure 29 Correlation between Sneed and Folk Sphericity vs. % Fractured Face (>1)

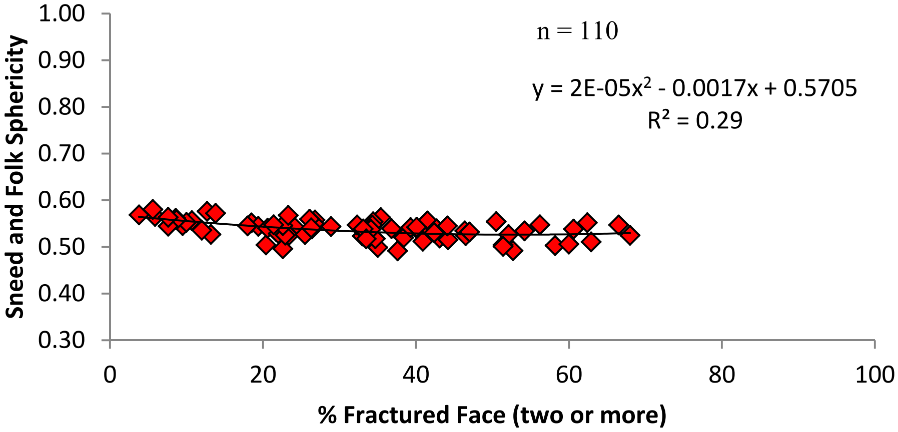


Figure 30 Correlation between Sneed and Folk Sphericity vs. % Fractured Face (>2)

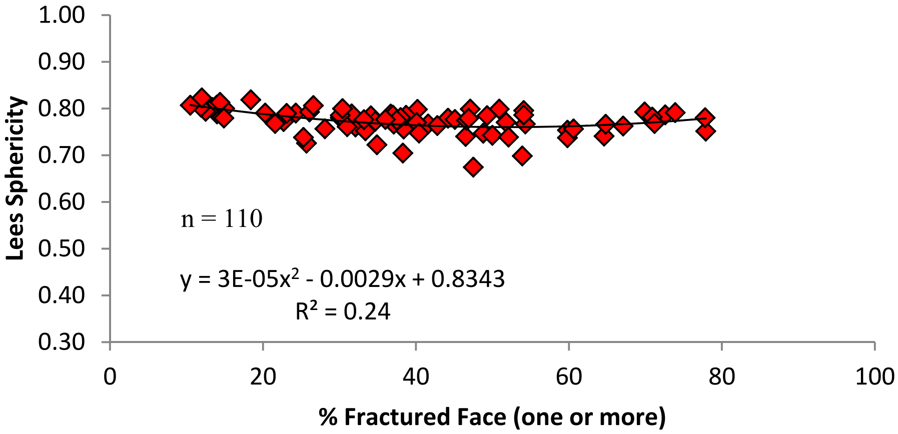


Figure 31 Correlation between Lees Sphericity vs. % Fractured Face (>1)

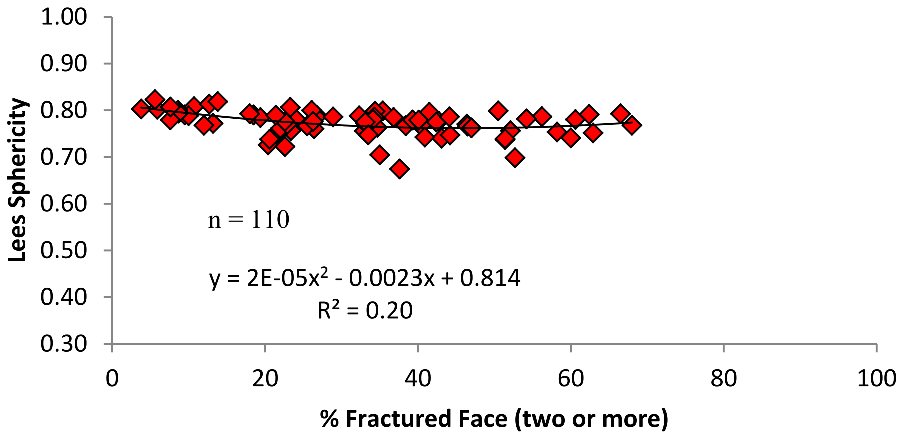


Figure 32 Correlation between Lees Sphericity vs. % Fractured Face (>2)

Table 11 Summary of Correlations between Sphericity and % Fractured Faces

Comparison Between	**R^2**	
	% Fractured Face (>1)	**% Fractured Face (>2)**
CPA and ASTM D5821	0.43	0.41
Wadell (1932) and ASTM D5821	0.23	0.19
Sneed and Folk (1958)	0.34	0.28
Lees (1964)	0.24	0.20

It can be observed from the table that the correlation between sphericity calculated using CPA and ASTM D5821 is relatively higher compared to other methods.

8.3 Adaptability of CPA Device to Measure F/E

The study was further extended to verify the ability of CPA device to determine the F/E of aggregate particles. At this point, while working with the 2-dimensional images, the limitation of the CPA device became evident.

By definition, flat and elongated particles require the measurement of largest and least dimension of each particle. A free falling particle always falls with its largest dimension exposed to the camera. However, the width exposed to the camera may not always correspond to the least dimension. This is particularly true for flaky particles which lie on their flat surface.

In order to overcome this limitation and to capture the least dimension, the feeder bin was redesigned so as to allow only one particle to fall at a time. The effort culminated in the redesign of feeder so as to allow only one particle to fall at a time. Several designs that would allow reading and recording the least dimension were attempted as shown in Figures 33, 34, 35, and 36, based primarily on the experience of developers.

Figure 33 Feeder redesign with Rounded Walls

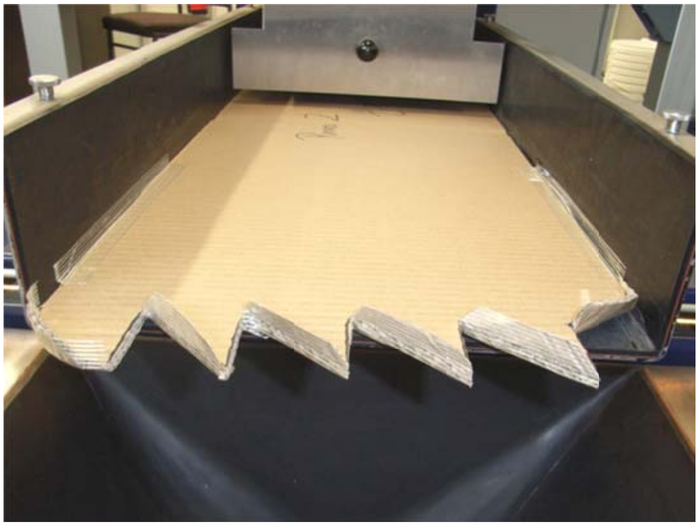


Figure 34 Feeder with Diagonal Openings

Figure 35 Feeder with Combination of Round and Square Walls

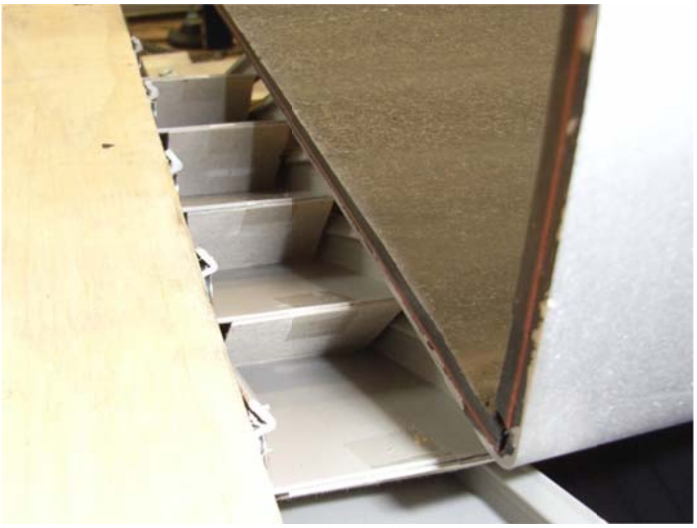


Figure 36 Oblique Chutes

The goal of this effort was to ensure the particles rotate and fall while exposing the least and largest dimension simultaneously. This is in sharp contrast to the earlier design where a number of particles were exposed at the same time. Preliminary tests conducted to test the rotation of particles are presented in Figure 37.

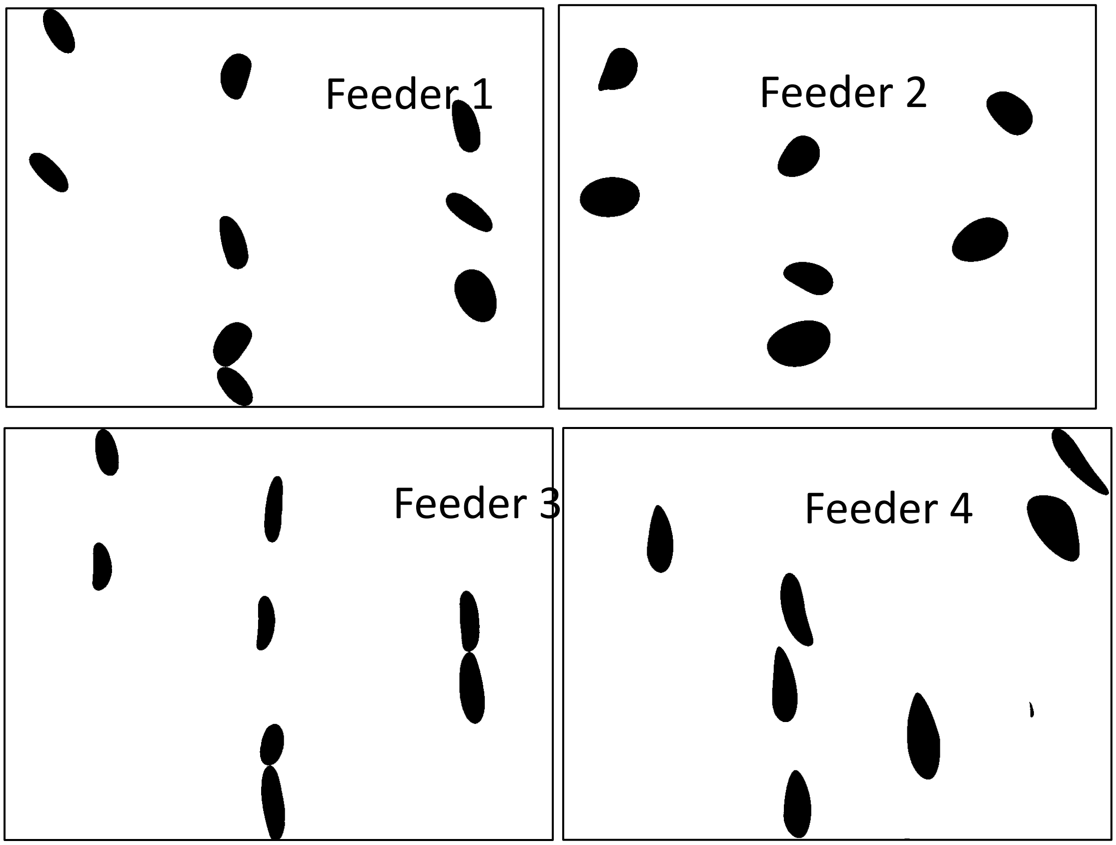


Figure 37 Preliminary Tests Using New Feeders

The results produced by none of these feeders were found to be satisfactory for the research team. Feeder 1 offered less rotation of particles. As a result, smallest dimension was not visible. Also, some particles were in contact with each other. Feeder 2 displayed significant rotation of particles. The particles were not in contact. However, the smallest dimension was not always visible. In using Feeder 3, the smallest dimension was visible. However, the length of the particles was exaggerated. With Feeder 4, smallest dimension was not always visible and length was exaggerated.

Based on this experience further changes were made in the feeder design and a prototype was developed for material testing. Figure 38 shows the feeder used for further testing.

Figure 38 Feeder Used for Detailed Tests

Even with this design, measuring the least dimension of individual particles did not provide satisfactory results. It can be stated that CPA in its current format is not capable of generating F/E results to match with the standard testing procedure.

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

Sieve analysis, also known as gradation analysis, is a process of determining the particle size distribution of a granular material. The results of sieve analysis provide the basic data needed for the design and analysis of cement concrete and asphalt concrete mixes. Traditionally, sieve analysis is conducted by processing a sample of granular material through a set of sieves. Data analysis is performed by calculating the percentage material retained on each sieve. The results are presented in the form of a graph of cumulative percentage of material passing through each sieve size. It is generally felt that sieve analysis test is rather time consuming as well.

Lately, optical devices are being introduced for gradation analysis in the road construction industry. Such devices have been in practice in pharmaceutical and agricultural industries since the 1990s. The optical gradation devices utilize a camera (or a set of cameras) to capture the image of individual particles. The shape and size characteristics are analyzed and displayed in real time using a computer algorithm. The performance claims of optical devices include repeatable, reliable, and quick results. The devices can also be used in such a way as to continuously record and monitor the particle size distribution in a production facility. This feature can be of significance as it can result in strict quality and process control.

Realizing an opportunity to improve the current practices of determining the particle size analysis, the Ohio Department of Transportation's Office of Material Management initiated a study. The first task of the study was to review optical gradation devices available for gradation analysis of coarse and fine aggregates. Although much is heard about such devices, no department of transportation seems to have incorporated such a device in their specification. This means, all the agencies are still using the traditional sieve analysis procedure. However, the literature pointed efforts by some universities, in association with respective state DOTs and Federal Highway Administration, to develop optical devices. A thorough review of these devices indicated the primary emphasis of these agencies has been to derive shape characteristics such as angularity, texture, fractured count and flat and elongated ratio. Continued search for optical devices for gradation revealed two devices specifically designed for the purpose of gradation analysis. These two devices – VDG 40 Granulameter and Computerized Particle Analyzer (CPA) – are European development and designed exclusively to analyze the particle size distribution of given materials. The first of the two abovementioned devices, VDG 40, was developed in France to process aggregates used in road construction. The CPA, a German development, has been used primarily in chemical and agricultural industry with a minor representation in construction material industry. Although these devices have been in the market for over 10 years, much is not heard about them in the US because most of the units sold are operating in parts of Europe and Canada.

Since the primary objective of the present study was to review optical gradation devices currently available, the researchers contacted the developers of VDG 40 and CPA for particulars about the equipment and their desire to participate in the study. The CPA developers readily agreed to actively participate in the research program. Participation included making one unit available and providing technical assistance. The first question before beginning the evaluation was: “is there a need to evaluate the device for optical gradation”? The CPA device has been tested and many units are in operation for over 10 years. However, it became apparent that most of the sales are in chemical and agricultural applications and as such it was thought a good idea to verify how the device will adopt to paving industry. With this in mind, an experiment was designed to evaluate the validity of CPA for gradation analysis of representative coarse and fine aggregate samples from various sources in Ohio.

CPA is a friendly and easy to use device. This photo-optical device is designed for measuring the particle size distribution and shape of dry materials between 0.015” and 1.5”. In using this device, the aggregate sample is first placed in a hopper. Upon starting the interactive computer program, the material will begin to move and fall into a collector bin. A camera placed in the control box will capture images of individual particles against the backdrop of a high intensity light source. A computer algorithm helps to store and process the data.

In consultation with OMM, 46 aggregate samples (sand sized to 1") comprising of limestone and gravel from various sources in Ohio were collected. Gradation analysis of all the aggregate samples were first performed using traditional sieve analysis procedure. The same physical samples were tested using CPA device. Obviously the goal of the study was to ensure good comparison between the two test procedures. The early results showed considerable variation. Discussion with the device developers led to the need for calibration of the device prior to making runs. Ten representative samples were used to develop calibration constants. The results obtained after calibration of the system showed significant improvement in test results. The maximum difference in test results was less that 1%. A total of 46 aggregate samples comprising of limestone and gravel were collected from different aggregate sources in Ohio were tested. The test results showed excellent comparison between the CPA and sieve analysis results.

The ability of CPA to produce consistent and repeatable test results was tested by conducting repeated tests on representative samples. The test results validated using control charts showed all the test results fall within the upper and lower control limits, indicating CPA was capable of producing repeatable results.

The investigation was further pursued to examine the CPA device's ability to derive shape parameters such as Percent Fractured Face (FF) and Flat and Elongation Index (F/E). Percent FF, also known as 'crushed count', and F/E tests are routinely performed in Ohio by the paving contractors to verify material compliance with ODOT's specifications. These parameters essentially require mapping 3-dimensions of individual aggregate particles. However, the CPA is equipped with a single camera and only captures 2-dimensions. In order to obtain the third dimension, the researchers made two efforts:

1. Establish a cross-correlation between %FF, an objective test termed Uncompacted Void Content of coarse aggregates, CAA, and, Spherecity values derived from CPA.
2. Initiated hardware modification to the CPA device to capture the third dimension.

9.2 Conclusions

Based on the results obtained and experience gained in this study, the following conclusions were drawn:

- The results obtained in this study clearly demonstrate the capability of CPA in matching traditional sieve analysis results.
- CPA device is capable of producing gradation results that are repeatable, reproducible, reliable, and precise.
- A good correlation exists between the sphericity obtained from the CPA device and Coarse Aggregate Angularity, and a moderate correlation was found between sphericity and percent fractured faces.
- The CPA device in its current format is not capable of producing F/E results to match with the standard test procedure.
- The device is rugged, durable, and user friendly.
- A primary advantage of CPA is its capability to be installed as in-line systems for continuous monitoring of particle size distribution at the crusher and/or asphalt plant. With such systems, the results are continuously transferred to the control plant for making necessary adjustments for process control. However, the present study focused on the use of CPA device in the laboratory environment.

9.3 Recommendation

1. It is recommended that ODOT include the CPA device in the specification for gradation analysis.
2. It is recommended that ODOT will use the CPA device for the determination of %FF provided appropriate modifications are made to improve its capability to produce %FF with greater confidence.
3. In its current design, the CPA device is not recommended for the determination of F/E ratio.

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APPENDIX A

Charts showing comparative sieve analysis results between ASTM C136 and CPA procedures

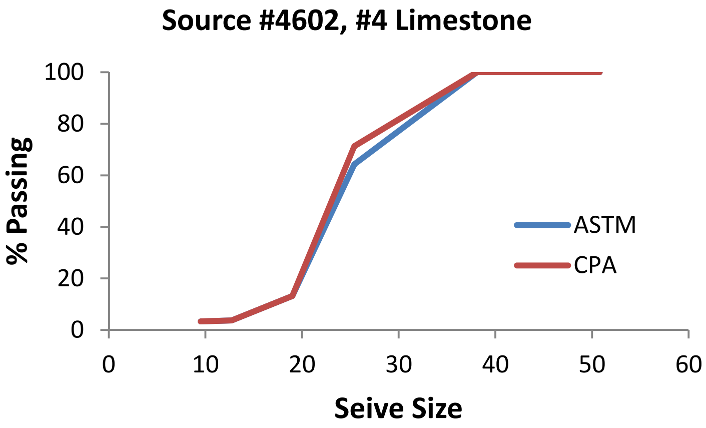


Figure A1 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

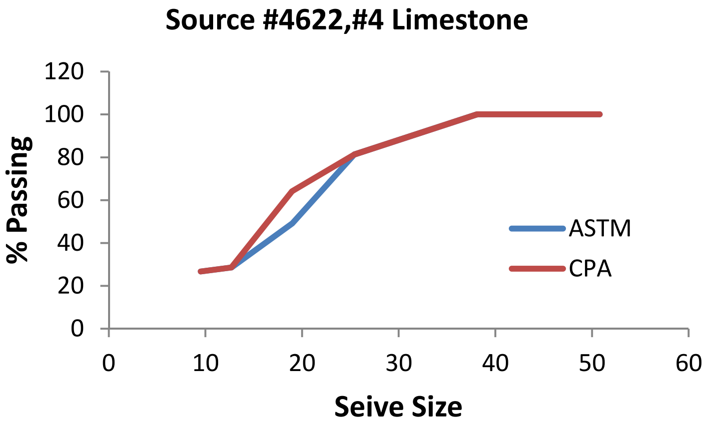


Figure A2 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

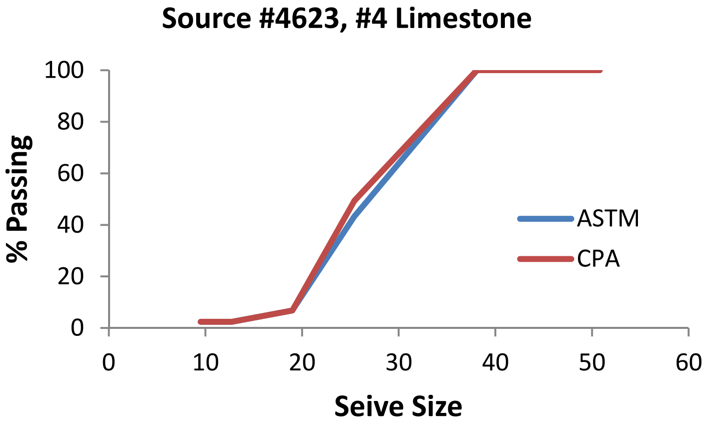


Figure A3 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

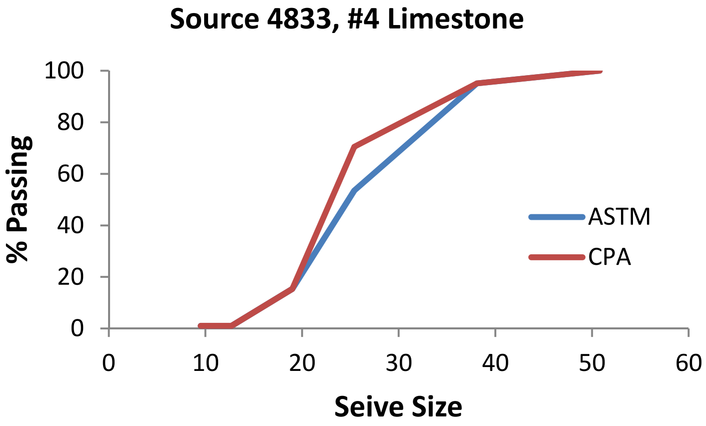


Figure A4 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

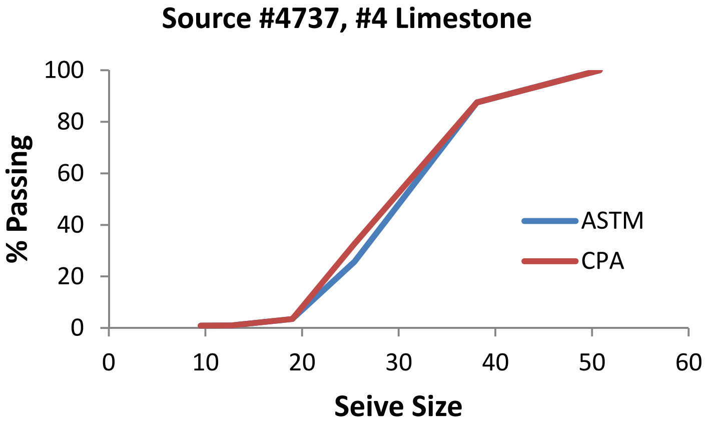


Figure A5 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

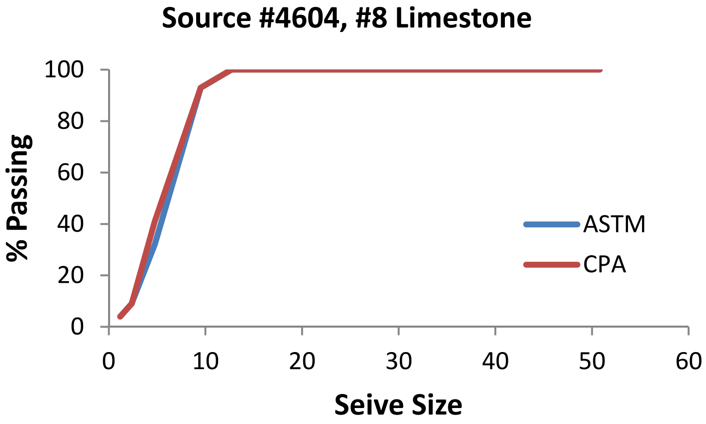


Figure A6 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

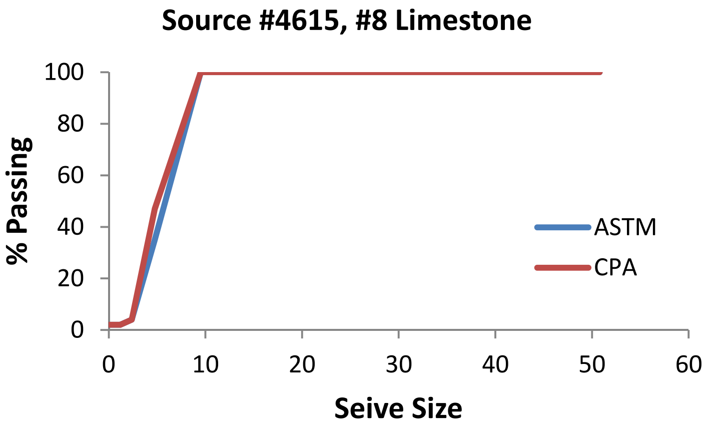


Figure A7 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

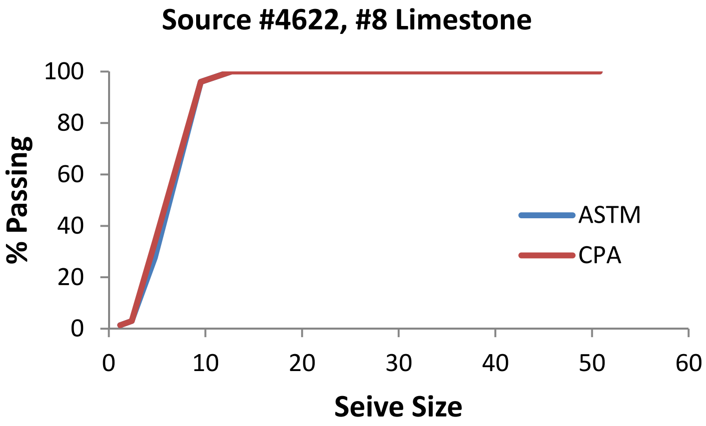


Figure A8 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

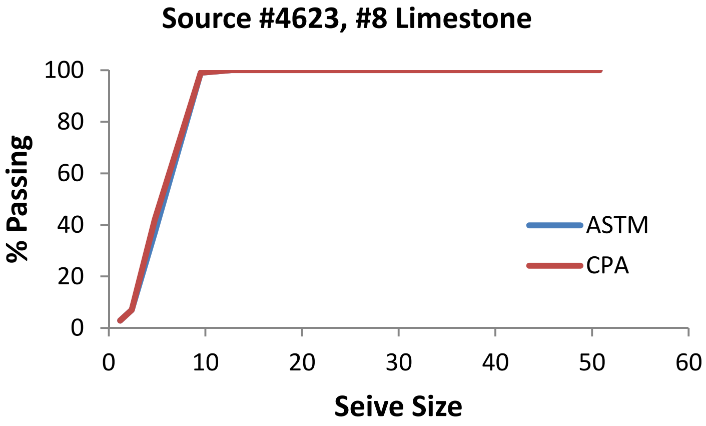


Figure A9 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

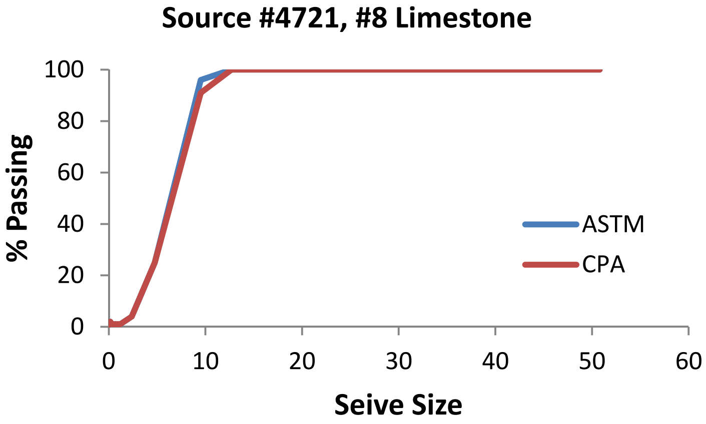


Figure A10 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

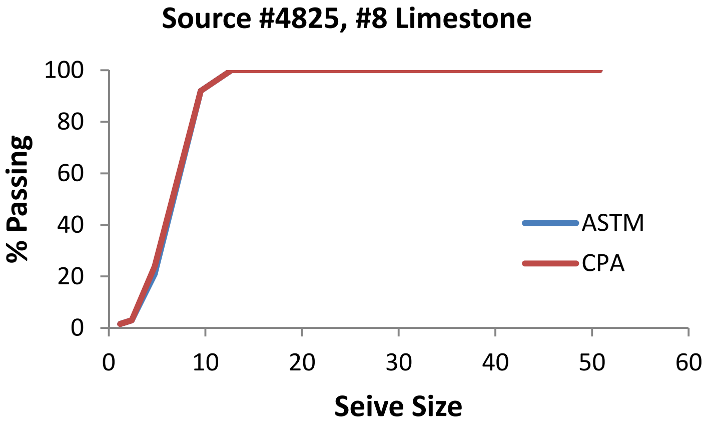


Figure A11 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

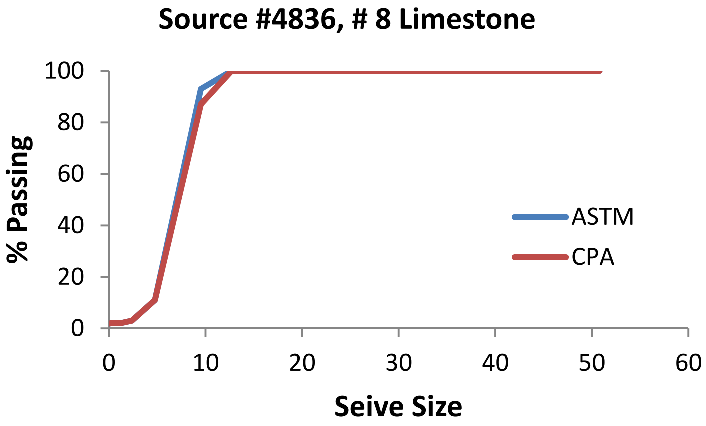


Figure A12 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

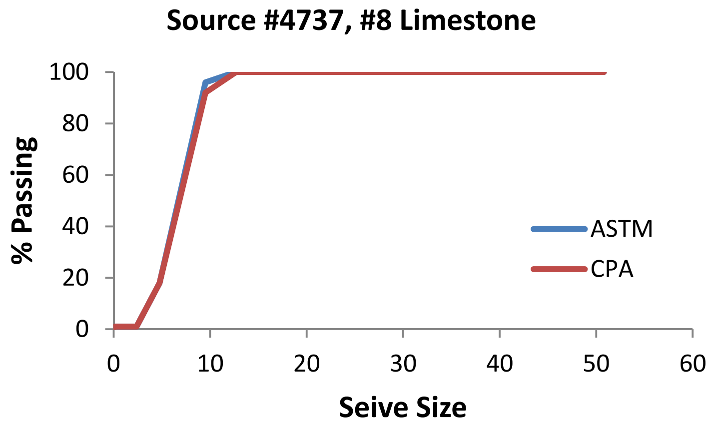


Figure A13 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

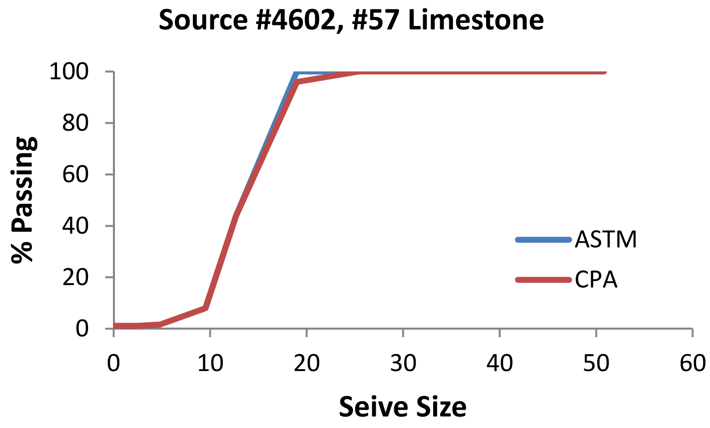


Figure A14 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

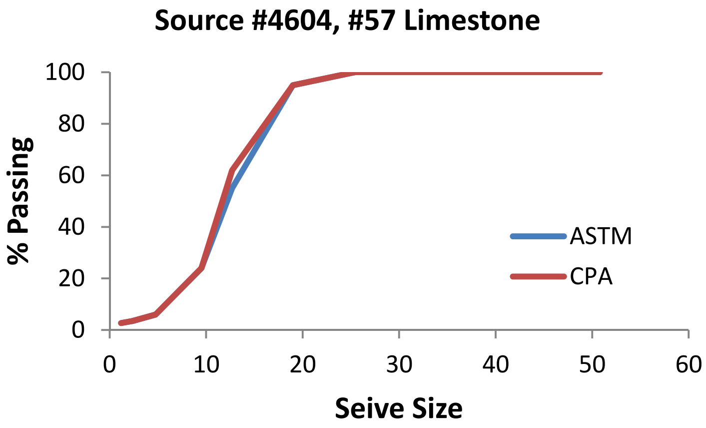


Figure A15 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

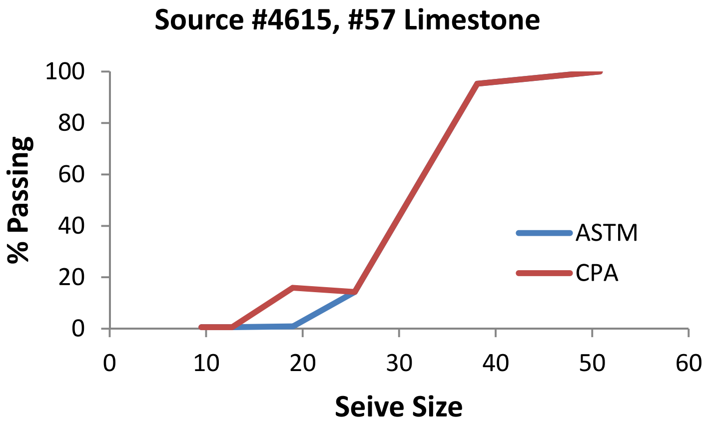


Figure A16 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

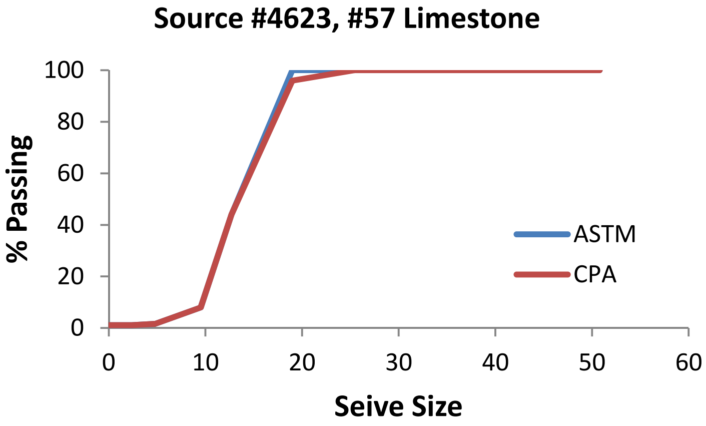


Figure A17 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

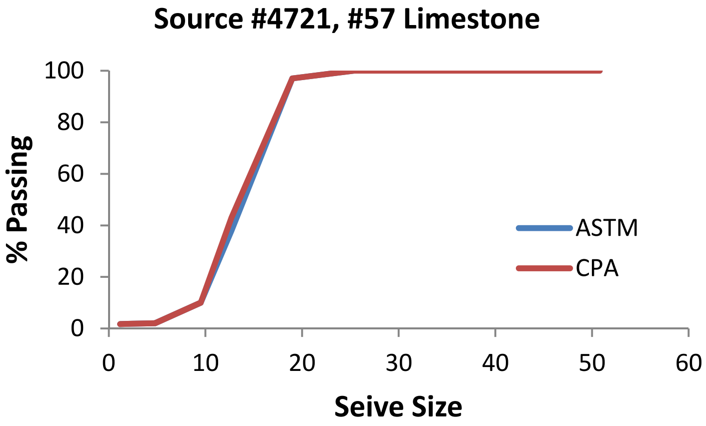
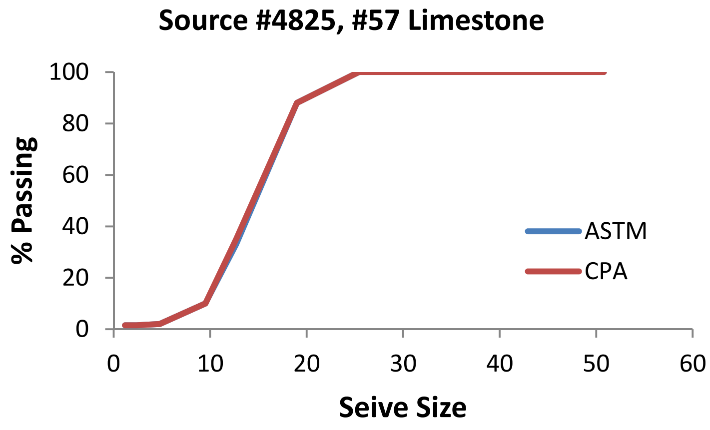


Figure A18 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures



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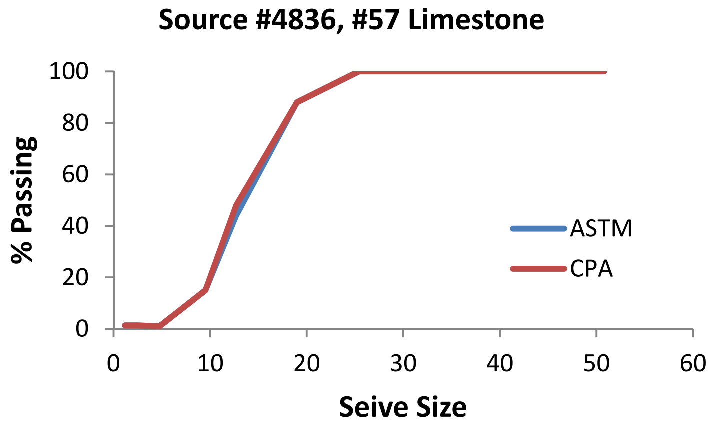

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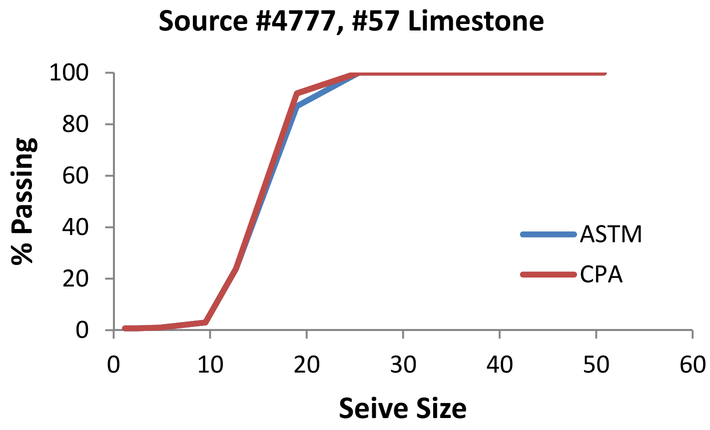

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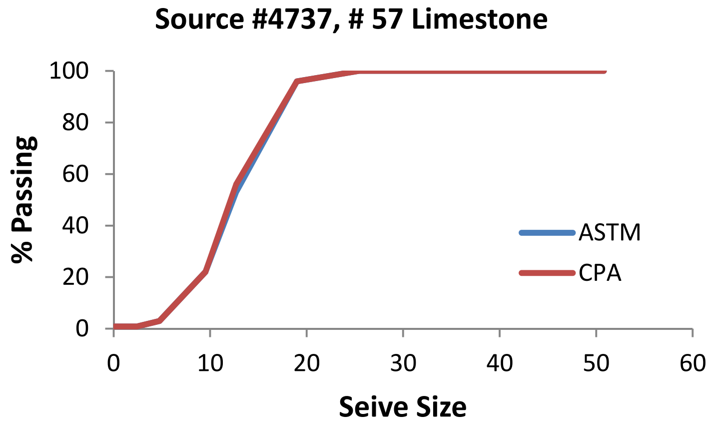

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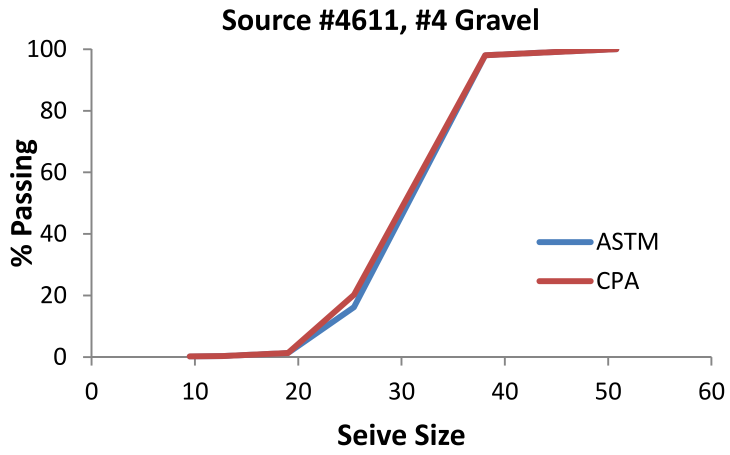

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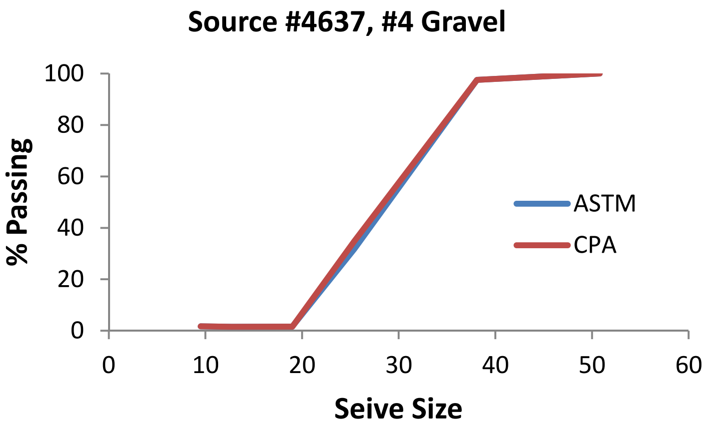

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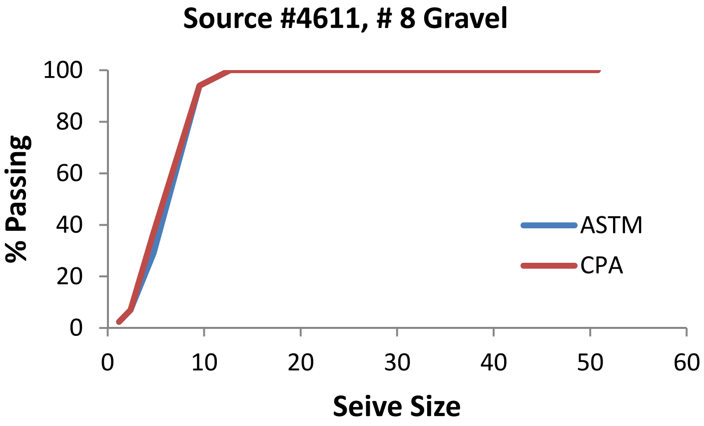

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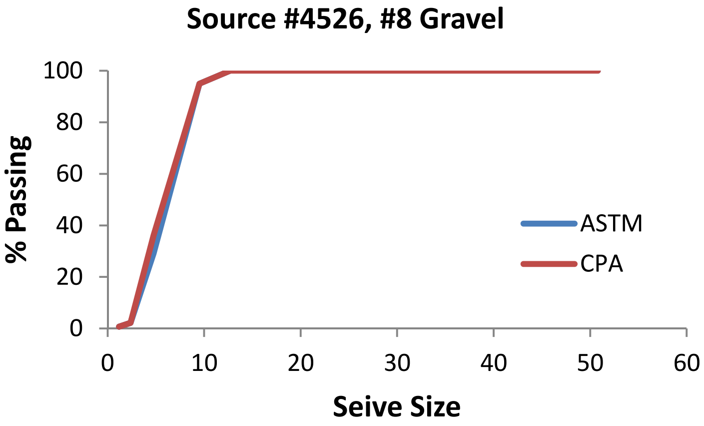

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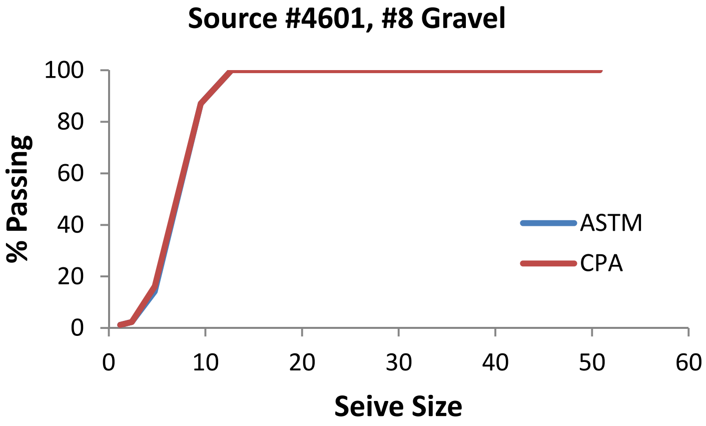

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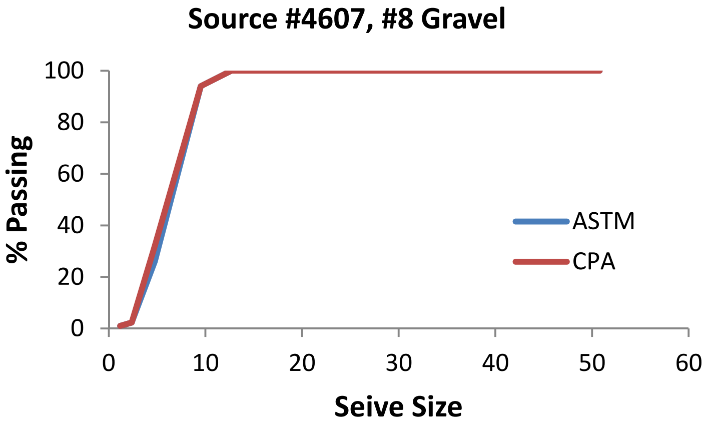

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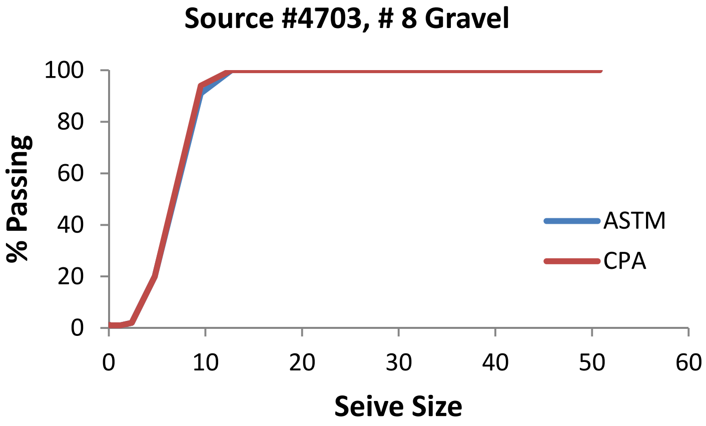

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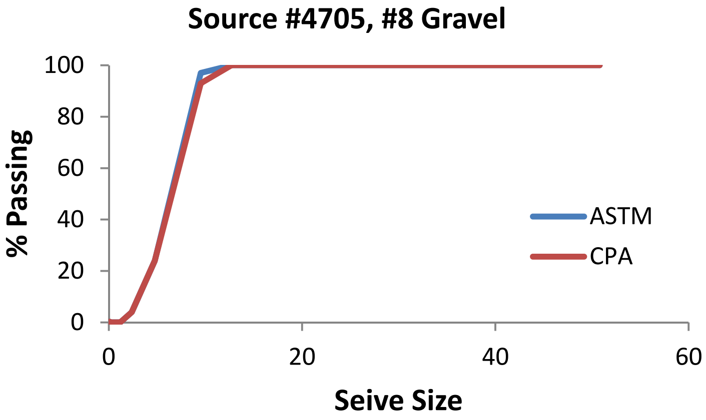

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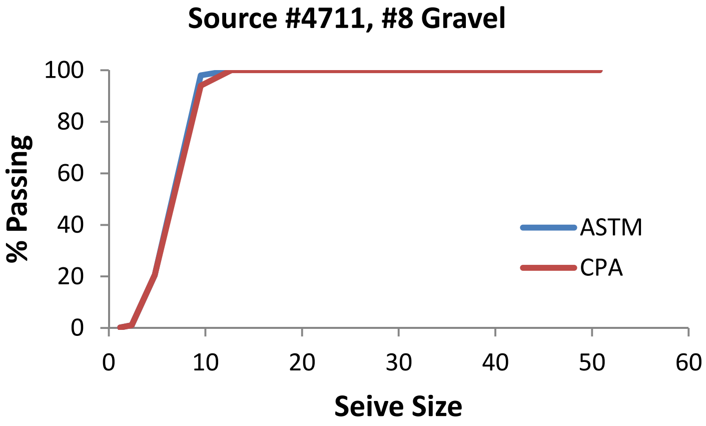

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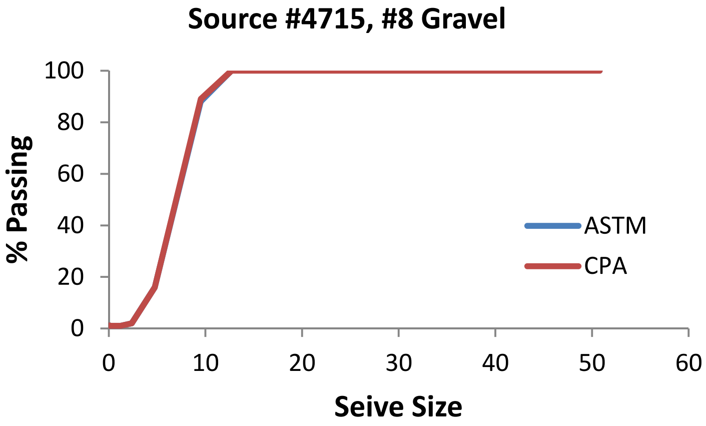

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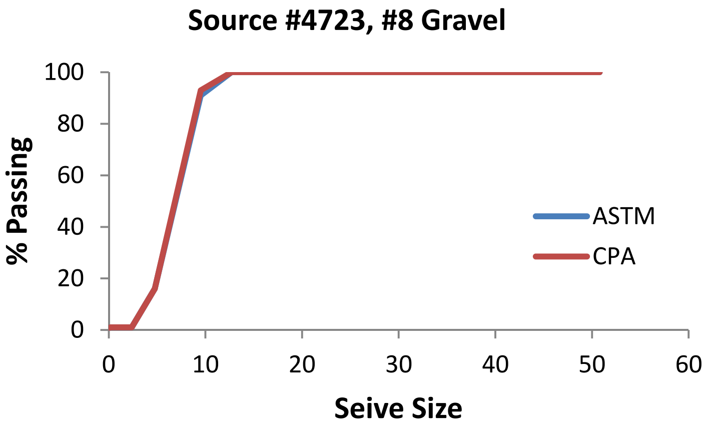

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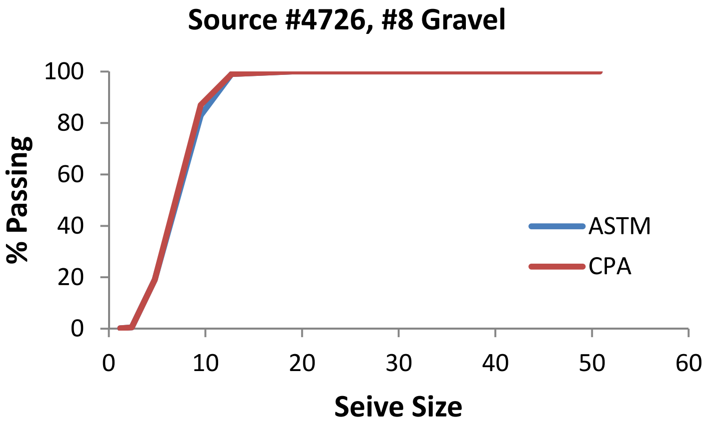

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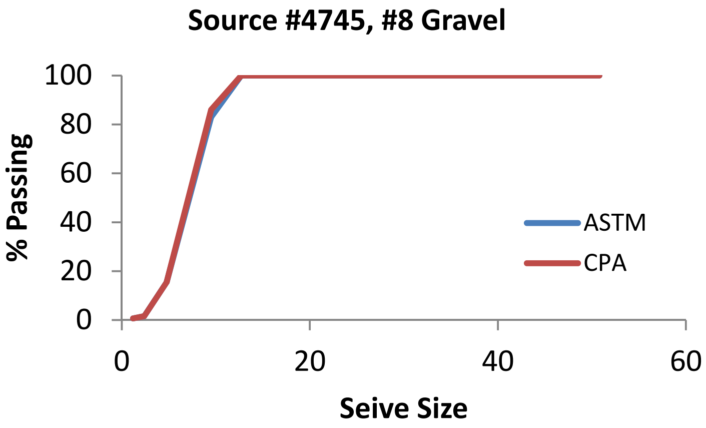

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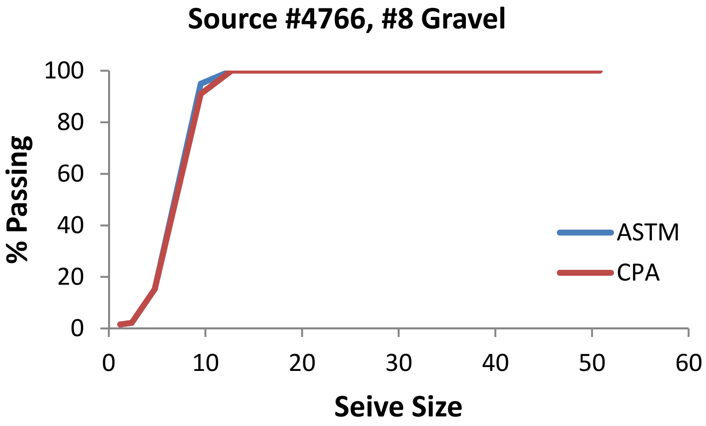

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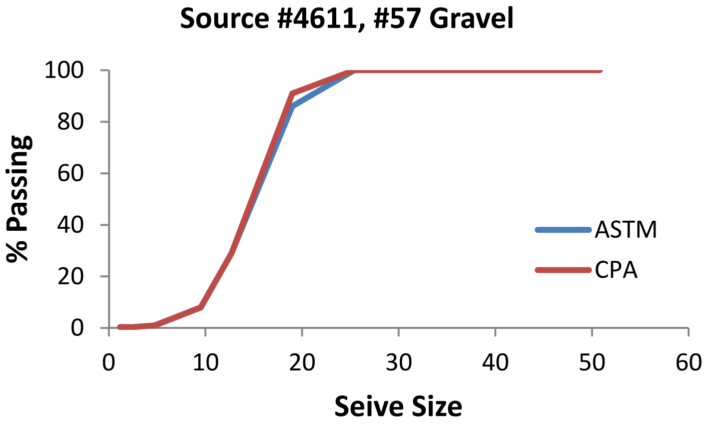

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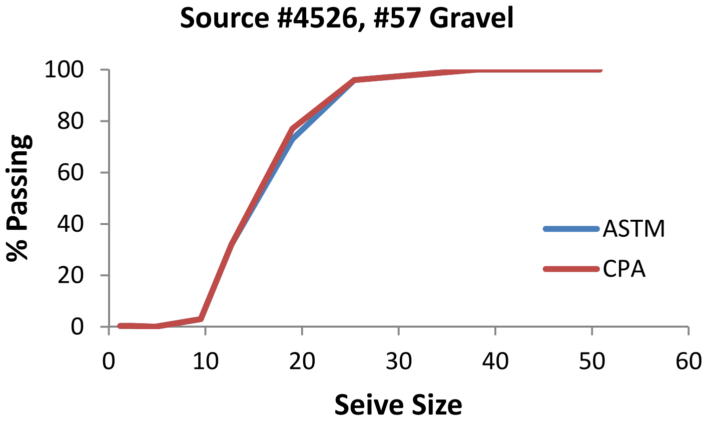

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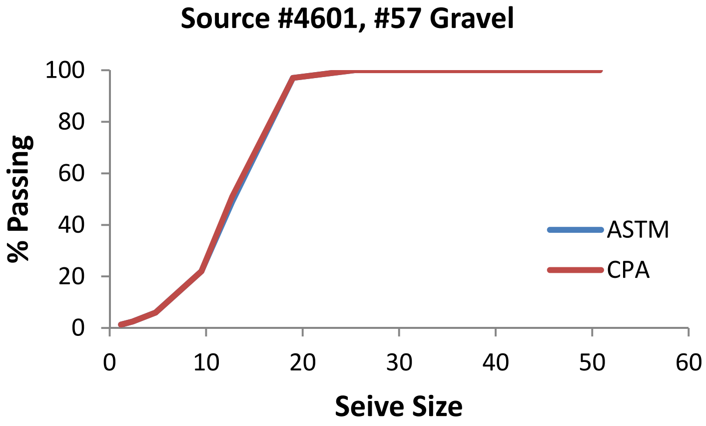

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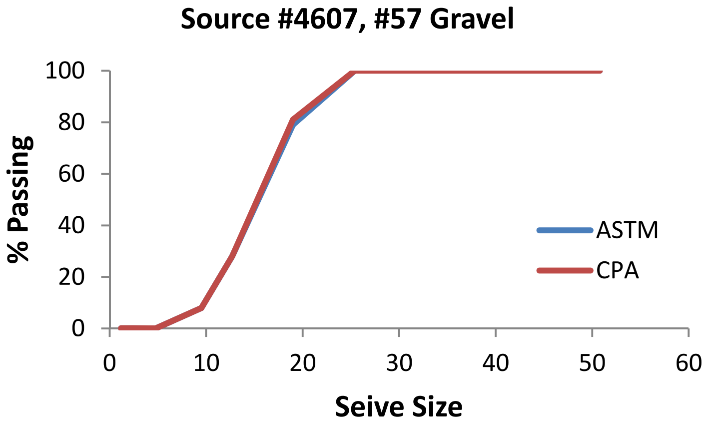

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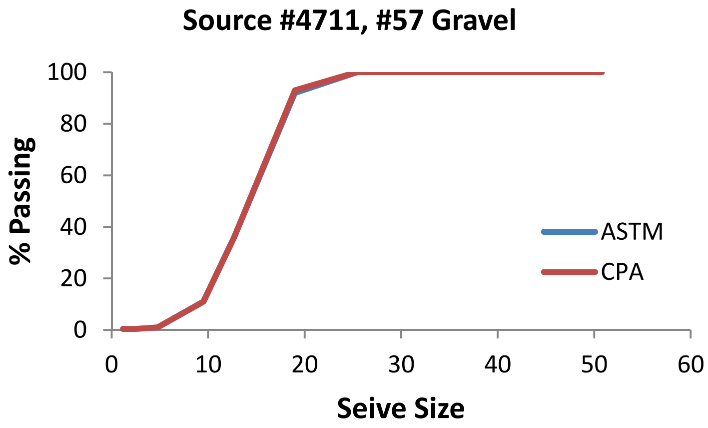

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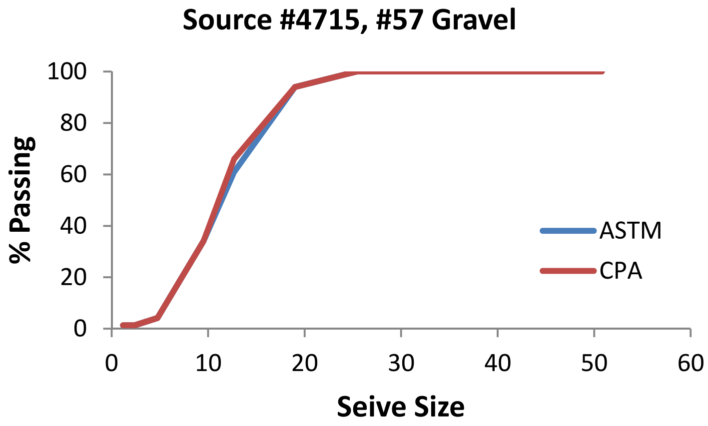

Figure A42 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

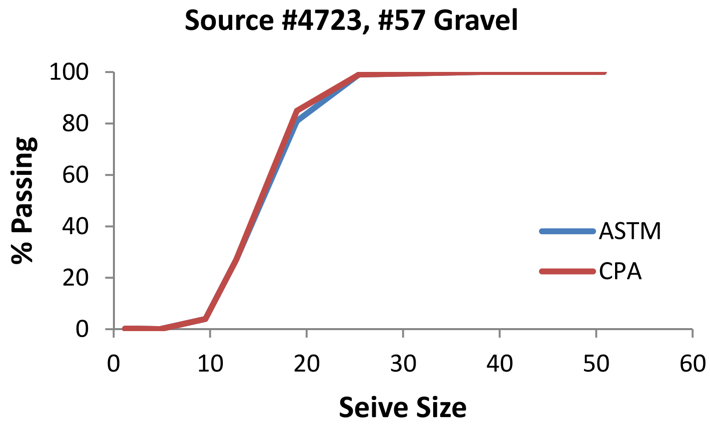

Figure A43 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

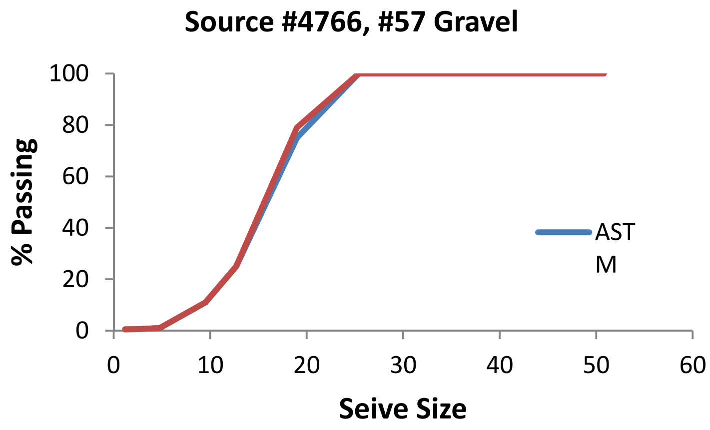

Figure A44 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

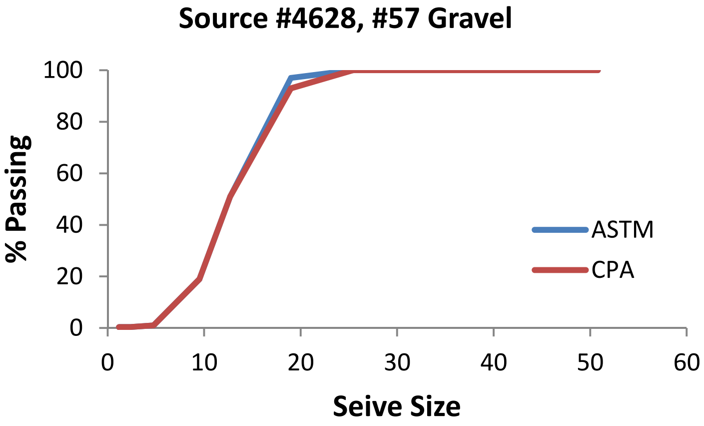

Figure A45 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

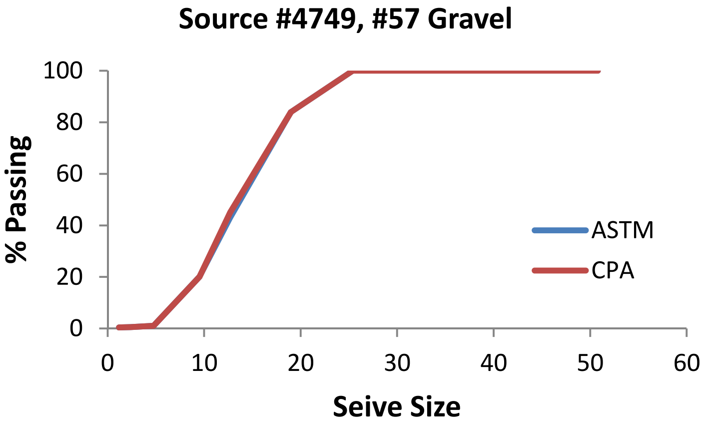

Figure A46 Comparative Sieve Analysis Results between ASTM C136 and CPA Procedures

APPENDIX B

Tables showing CAA, Percent Fractured Faces, and sphericity values

Table B1 Sphericity, CAA, and Percent Fractured Face of Aggregate Samples

P/S CODE	LOCATION	G#	MATL TYPE	CPA	CAA	% FF (>1)	% FF (>2)
4512	National L&S @ Marion	3499	57 LS	0.88	49.39		
4512	National L&S @ Marion	5390	57 LS	0.89	47.59		
4907A	Clinton @ S. Wellston	5391	8 LS	0.88	49.34		
4907A	Clinton @ S. Wellston	5394	8 LS	0.88	50.82		
4201	Young's @ Loudonville	5395	57 LS	0.87	50.51		
4945	Shelly @ Reedsville	5396	8 GR	0.92	43.73	25.7	20.40
4958	Shelly @ Portland	5404	57 GR	0.92	43.81	32.1	26.40
4807	Mar-Zane @ Chillicothe	5405	57 GR	0.91	44.00	33.4	21.70
4807	Mar-Zane @ Chillicothe	5411	8 GR	0.93	43.49	50.9	50.50
5111	Drummond @ Drummond	5412	57 GR	0.92	44.01	24.3	18.50
5106	O-N Mineral @ Pt. Inland	5425	57 LS	0.89	48.01		
5106	O-N Mineral @ Pt. Inland	5426	57 LS	0.89	49.22		
4211	Seville @ Lodi	5431	8 LS	0.90	48.67		
4118	Stansley @ Genoa	5435	8 GR	0.90	45.89	34.9	22.60
4003	Shelly @ Kenton	5436	57 LS	0.87	50.96		
4394	Subtropilis @ Petersburg	5437	57 LS	0.88	49.17		
4505	National @ Delaware	5454	8 LS	0.89	49.95		
4513	Shelly @ York Center	5459	57 LS	0.89	49.12		
4330	Mar-Zane @ Barberton	5460	57 LS	0.88	49.76		
4839	Ervin Hill @ Hillsboro	5462	8 GR	0.92	44.07	22.7	13.20
4840	Shelly @ Chillicothe-2	5464	57 GR	0.92	42.65	20.3	9.50
4376	Allegheny @ Slippery Rock	5465	8 GR	0.92	41.91	69.9	66.50
4385	Allegheny @ Harrisville	5487	57 LS	0.87	49.75		
4376	Allegheny @ Slippery Rock	5488	57 LS	0.87	49.32		
4385	Allegheny @ Harrisville	5490	8 LS	0.87	51.00		
4214	Rupp @ Marshallville	5491	8 LS	0.87	51.87		
4844	Three Locks @ Chillicothe	5502	57 GR	0.91	45.56	38.4	33.00
4105	Lafarge @ Marblehead	5504	8 GR	0.93	42.13	14	10.70
4112	Hanson @ Flat Rock	5535	8 LS	0.90	47.70		
4804	Shelly @ Chillicothe-1	5554	8 LS	0.88	50.42		
4373	Mar-Zane #16 @ Ravenna	5558	57 GR	0.90	45.65	46.5	43.10
4110	Hanson @ Waterville	5563	8 LS	0.87	51.48		
4373	Mar-Zane #16 @ Ravenna	5570	8 GR	0.92	43.40	34.1	19.40
4106	Martin Marietta @ Woodville	5580	57 LS	0.88	49.63		
9552	Stocker @ Gnadenhutten	5592	57 GR	0.92	42.17	30.1	24.10
5114	Lafarge @ Manatoulin	5593	57 LS	0.89	49.98		
5116	O-N Minerals @ Rogers City	5599	8 GR	0.92	43.13	47.1	35.40
5116	O-N Minerals @ Rogers City	5602	8 SL	0.88	53.59		
4523	Shelly @ Lockbourne	5622	8 LS	0.89	50.58		
4352	Massillon #2 @ Massillon	5624	57 LS	0.89	49.38		
4118	Stansley @ Genoa	5625	8 LS	0.89	49.52		
4352	Massillon #2 @ Massillon	5628	8 LS	0.87	51.76		

P/S CODE	LOCATION	G#	MATL TYPE	CPA	CAA	% FF (>1)	% FF (>2)
4205A	Hanson @ Sandusky	5643	8 LS	0.88	49.77		
4205A	Hanson @ Sandusky	5645	8 GR	0.92	42.95	54.1	41.50
4325	Oster @ Massillon	5652	8 GR	0.93	42.64	14	10.00
4007	National @ Findlay	5654	57 GR	0.91	45.22	51.8	46.40
4007	National @ Findlay	5668	57 GR	0.92	43.32	31.6	26.80
4820	Hanson @ Peebles	5670	57 LS	0.89	48.24		
4833	Hanson @ Winchester	5690	57 GR	0.91	45.75	72.6	56.20
4108	Macritchie @ W. Millgrove	5692	8 GR	0.92	44.92	70.9	54.20
5027	Oster @ Bolivar #2	5694	57 LS	0.87	50.23		
4652	Shelly @ Springfield	5699	57 LS	0.89	47.32		
4004	Olen Corporation @ Upper Sandusky	5700	8 LS	0.90	48.00		
4743	Barrett @ Medway	5702	57 LS	0.88	49.04		
4819	Ohio Asphaltic @ Hillsboro	5703	8 LS	0.89	50.50		
4204A	Wagner @ Sandusky	5704	8 LS	0.87	52.16		
4204A	Wagner @ Sandusky	5715	8 LS	0.89	49.51		
4501	Agg Rok @ Columbus	5716	8 LS	0.89	50.33		
4501	Agg Rok @ Columbus	5718	8 LS	0.88	51.80		
4621	Miami River Stone @ Sidney GR	5722	57 LS	0.87	51.20		
4103	Stoneco @ Portage	5730	57 LS	0.87	50.78		
5017	Menuez @ Millersburg	5741	8 GR	0.91	45.60	41.6	38.40
5052	Anthony @ Wintersville	5742	8 GR	0.90	46.96	38.3	35.00
4414A	Sidwell @ Zanesville	5745	57 LS	0.89	49.04		
4414	Sidwell @ Zanesville	5747	8 LS	0.89	48.87		
4414A	Sidwell @ Zanesville	5749	57 LS	0.88	50.13		
4414	Sidwell @ Zanesville	5764	8 LS	0.88	50.84		
4413	Shelly @ E. Fultonham	5771	8 GR	0.93	43.42	26.1	18.00
4626	Shelly @ Belle Center	5773	8 GR	0.92	44.51	28.1	23.40
4020	Shelly @ Forest	5776	57 GR	0.91	44.19	59.8	58.20
4624	Barrett @ Sidney (GR)	5777	57 GR	0.90	45.50	71.2	68.00
4205C	Hanson @ Sandusky	5785	57 GR	0.90	46.44	53.9	52.70
5029	Midvale @ Midvale	5792	57 LS	0.90	47.13		
4624	Barrett @ Sidney (GR)	5811	57 LS	0.89	48.84		
4730	Moraine Materials @ Germantown	5814	8 LS	0.89	49.61		
4815	Hanson @ Hillsboro	5817	8 GR	0.93	42.56	13.4	5.90
4815	Hanson @ Hillsboro	5819	8 LS	0.89	49.83		
5064	J.D. Mining @ Magnolia	5820	57 LS	0.89	48.22		
5115	O-N Minerals @ Cedarville	5838	8 GR	0.91	44.94		
4788	Evans @ Cincinnati	5840	8 LS	0.88	51.62		
4003	Shelly @ Kenton	5841	57 LS	0.88	51.25		
4307	Canton Agg. @ Canton	5856	57 GR	0.92	42.31	25.3	20.60
4811	Hanson @ Sargents	5859	8 LS	0.90	48.55		
4743	Barrett @ Medway	5865	57 LS	0.89	48.46		
5115	O-N Minerals @ Cedarville	5865	57 LS	0.89	48.28		
4015	National @ Delphos	5876	57 GR	0.92	43.09	40.2	34.40

P/S CODE	LOCATION	G#	MATL TYPE	CPA	CAA	% FF (>1)	% FF (>2)
4004	Olen Corporation @ Upper Sandusky	5881	8 CR GR	0.91	45.43	77.9	62.90
4123	Stoneco @ Maumee	5884	57 LS	0.88	49.51		
4526	Melvin @ Circleville	5896	8 GR	0.92	45.05	54.3	40.40
5068	Kimble @ E. Sparta	5897	8 GR	0.92	43.23	30.1	26.70
4636	National @ Buckland	5898	57 GR	0.90	46.24	47.5	37.60
4005	Meshberger @ Portland	5907	57 GR	0.90	45.44	64.6	60.00
5114	Lafarge @ Manatoulin	5918	57 LS	0.89	49.50		
4512	National @ Marion	5920	8 LS	0.89	49.21		
4833	Hanson @ Winchester	5930	8 GR	0.92	43.85	49.3	36.80
4103	Stoneco @ Portage	5951	8 LS	0.89	48.39		
5027	Oster @ Bolivar #2	5952	8 LS	0.88	50.55		
4116	Clay Center @ Clay Center	5953	57 LS	0.88	49.47		
4025	Hanson @ Woodburn	5968	8 GR	0.91	46.31		
4622	Stoneco @ Celina	5971	8 GR	0.92	44.24	30.4	26.10
4202	National @ Bucyrus	5976	8 GR	0.91	44.88	44.2	39.30
4202	National @ Bucyrus	5977	8 GR	0.93	43.59	34.7	33.10
4838	Tow Path Materials @ Lucasville	5978	57 GR	0.92	44.38	45.1	42.70
4838	Tow Path Materials @ Lucasville	5988	57 GR	0.93	41.50	15	8.60
4631	Poeppleman @ Bradford	5990	8 GR	0.91	44.46	59.8	51.40
4638	Duff @ Huntsville	5993	8 LS	0.89	48.88		
4833	Hanson @ Winchester	5998	57 LS	0.89	48.47		
4413	Shelly @ E. Fultonham	5999	8 LS	0.88	50.51		
4106	Martin Marietta @ Woodville	6009	57 LS	0.88	49.58		
5057	Holmes Supply @ Holmesville	6010	57 LS	0.89	48.00		
4512	National @ Marion	6012	8 LS	0.90	48.38		
4730	Moraine Materials @ Germantown	6015	57 LS	0.88	48.71		
4730	Moraine Materials @ Germantown	6016	57 LS	0.89	49.23		
4839	Ervin Hill @ Hillsboro	6017	57 LS	0.88	48.64		
4807	Mar-Zane @ Chillicothe	6031	57 LS	0.88	50.54		
5106	O-N Minerals @ Pt. Inland	6035	8 CR GR	0.92	44.67	36.7	32.30
4118	Stansley @ Genoa	6046	8 SL	0.88	52.65		
4840	Shelly @ Chillicothe - 2	6049	8 LS	0.88	51.49		
4509	Olen @ Columbus 100%	6052	8 LS	0.89	49.75		
4509A	Olen @ Columbus 40%	6058	57 GR	0.92	44.25	48.8	44.20
4206	Erie Materials @ Sandusky	6069	8 GR	0.92	44.06	38.7	34.30
4523	Shelly @ Lockbourne	6073	8 GR	0.93	42.75	12.5	8.70
5020	Newton @ Dover	6076	8 GR	0.93	43.59	37.1	25.50
4519	Shelly @ Ostrander	6099	8 GR	0.92	42.40	14.4	12.70
4611	Enon Sd & Gr @ Enon	6101	8 LS	0.88	50.40		
4201	Young's @ Loudonville	6120	57 LS	0.88	50.72		
5111	Drummond @ Drummond	6122	57 LS	0.88	50.19		
4628	Urbana Materials @ Urbana	6125	8 LS	0.88	51.52		
4403	Shelly @ Coshocton	6133	8 LS	0.87	51.52		
4837	Hanson @ Grayson	6149	57 LS	0.88	49.69		

P/S CODE	LOCATION	G#	MATL TYPE	CPA	CAA	% FF (>1)	% FF (>2)
4402	Shelly @ Dresden	6163	8 LS	0.89	50.08		
4212	Mar-Zane #14 @ Melco	6165	8 LS	0.88	49.21		
4614	Miller Bros. @ Vandalia	6166	57 LS	0.90	47.54		
5114	Lafarge @ Manatoulin	6172	8 GR	0.93	45.74	31	22.00
4111	Hanson @ Sylvania - 1	6173	57 LS	0.88	48.78		
4008	National @ Lima	6175	57 GR	0.93	42.52	14.9	7.60
4604	Martin Marietta @ Phillipsburg	6176	8 GR	0.93	42.07	11.9	3.80
4013	Stoneco @ Scott	6212	57 LS	0.89	48.79		
4844	Three Locks @ Chillicothe	6220	57 LS	0.89	50.92		
4020	Shelly @ Forest	6236	8 LS	0.88	50.41		
4804	Shelly @ Chillicothe - 1	6245	8 GR	0.93	42.92	10.5	7.60
4212	Mar-Zane #14 @ Melco	6267	57 LS	0.89	48.38		
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6270	8 GR	0.91	43.60	42.8	34.70
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6284	57 GR	0.92	43.71	37	28.90
4822	Waterloo @ Oak Hill	6310	8 GR	0.91	45.45	40.1	22.90
4206	Erie Materials @ Sandusky	6311	57 GR	0.92	44.54	64.8	46.50
5116	O-N Minerals @ Rogers City	6316	57 LS	0.89	48.71		
5038	Stocker @ Pt. Washington	6317	8 LS	0.89	48.50		
4106	Martin Marietta @ Woodville	6331	8 LS	0.88	51.91		
5052	Anthony @ Wintersville	6340	57 GR	0.93	41.62	18.4	13.80
4114	Hanson @ Bloomville	6348	57 LS	0.88	51.04		
4205A	Hanson @ Sandusky	6359	57 LS	0.89	48.05		
4205D	Hanson @ Sandusky	6361	8 LS	0.89	48.36		
4820	Hanson @ Peebles	6366	8 GR	0.93	42.14	21.6	12.00
4820	Hanson @ Peebles	6378	8 LS	0.88	51.55		
4785	Martin Marietta @ Sabina	6379	8 GR	0.91	45.59	50	40.90
4628	Urbana Materials @ Urbana	6380	57 GR	0.90	45.83	60.6	52.10
4110	Hanson @ Waterville	6383	57 GR	0.92	42.01	38	34.10
4638	Duff @ Huntsville	6385	8 LS	0.87	51.76		
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6388	57 LS	0.86	52.38		
5038	Stocker @ Pt. Washington	6389	8 LS	0.87	50.90		
4027	National @ Rimer	6392	57 GR	0.91	43.64	37.5	33.10
4215A	Wooster Aggregate @ Wooster	6403	57 LS	0.88	50.48		
4519	Shelly @ Ostrander	6408	8 LS	0.88	51.19		
4208	Stein @ Lorain	6409	8 LS	0.88	49.45		
4002	Hanson @ Paulding	6410	57 LS	0.89	47.13		
4608	Barrett @ Fairborn	6413	57 LS	0.88	49.55		
4601	Martin Marietta @ Fairborn 40% CRGR	6431	57 GR	0.91	44.88	46.6	42.40
4738	Carmeuse @ Maysville	6432	8 LS	0.89	49.90		
4002	Hanson @ Paulding	6434	57 CR GR	0.89	46.81	52.1	51.40
4132	Stoneco @ Ottawa Lake	6436	8 GR	0.92	44.96	77.8	60.60
4030	National @ Carey (W)	6437	57 GR	0.91	45.02	73.9	62.40
4513	Shelly @ York Center	6440	57 LS	0.88	48.94		
4027	National @ Rimer	6442	8 LS	0.89	49.78		

P/S CODE	LOCATION	G#	MATL TYPE	CPA	CAA	% FF (>1)	% FF (>2)
4411	Shelly @ Lancaster	6453	57 LS	0.89	48.39		
5109	Lafarge @ Presque Isle	6464	8 LS	0.89	48.87		
4105	Lafarge @ Marblehead	6465	57 LS	0.90	48.00		
5116	O-N Minerals @ Rogers City	6480	8 LS	0.87	51.42		
4607	Martin Marietta @ Troy	6481	8 LS	0.88	50.94		
4915	Martin Marietta @ Applegrove	6482	8 GR	0.92	42.78	33.2	26.30
4205C	Hanson @ Sandusky	6484	57 LS	0.86	51.07		
4509A	Olen @ Columbus 40%	6485	57 LS	0.87	50.67		
4416	Mar-Zane #1 @ Zanesville	6489	8 LS	0.87	52.16		
4132	Stoneco @ Ottawa Lake	6503	57 LS	0.88	49.31		
4123	Stoneco @ Maumee	6508	57 LS	0.88	48.93		
4316	Jefferson @ Steetsboro	6511	57 LS	0.89	50.29		
4842	Mountain @ Greenup, KY	6542	57 GR	0.90	45.23	67.1	47.00
5031	Tube City @ Mingo Jct.	6562	57 LS	0.89	48.09		
4101	Stoneco @ Lime City	6564	8 LS	0.90	47.03		
4158	Cardinal @ Perrysburg	6567	8 GR	0.93	42.55	12	5.60
4158	Cardinal @ Perrysburg	6578	57 GR	0.91	45.98	46.9	40.10
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6590	57 LS	0.88	49.63		
4614	Miller Bros. @ Vandalia	6591	57 GR	0.92	44.09	36	22.60
5038	Stocker @ Pt. Washington	6603	8 GR	0.92	44.79	54.1	44.10
4516	Tuffco Sd & Gr @ Plain City	6606	8 LS	0.89	48.78		
4025	Hanson @ Woodburn	6607	57 LS	0.89	46.38		
4632	Con-Ag @ St. Mary's	6610	57 LS	0.87	50.01		
4523	Shelly @ Lockbourne	6634	8 GR	0.93	42.48	23.1	21.40
4523	Shelly @ Lockbourne	6671	57 GR	0.91	44.84	40.4	33.50
4509A	Olen @ Columbus 40%	6674	8 LS	0.89	50.28		
4005	Meshberger @ Portland	6684	8 GR	0.93	42.02	26.6	23.30
4111	Hanson @ Sylvania - 1	6692	57 LS	0.88	48.74		
4703	Martin Marietta @ Fairfield	6729	57 LS	0.88	50.33		
4110	Hanson @ Waterville	6735	57 LS	0.88	49.42		

Table B2 Sphericity Values Calculated Using Wadell, Sneed and Folk, and Lees Equations

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
4512	National L&S @ Marion	3499	57 LS	2.657	5000	0.65	0.47	0.69
4512	National L&S @ Marion	5390	57 LS	2.600	5000	0.66	0.48	0.71
4907A	Clinton @ S. Wellston	5391	8 LS	2.586	5000	0.63	0.44	0.66
4907A	Clinton @ S. Wellston	5394	8 LS	2.624	5000	0.62	0.45	0.66
4201	Young's @ Loudonville	5395	57 LS	2.664	5000	0.64	0.48	0.69
4945	Shelly @ Reedsville	5396	8 GR	2.585	5000	0.67	0.50	0.73
4958	Shelly @ Portland	5404	57 GR	2.539	5000	0.69	0.54	0.76
4807	Mar-Zane @ Chillicothe	5405	57 GR	2.534	5000	0.69	0.53	0.75
4807	Mar-Zane @ Chillicothe	5411	8 GR	2.594	5000	0.73	0.55	0.80
5111	Drummond @ Drummond	5412	57 GR	2.600	5000	0.72	0.55	0.79
5106	O-N Mineral @ Pt. Inland	5425	57 LS	2.803	5000	0.64	0.47	0.68
5106	O-N Mineral @ Pt. Inland	5426	57 LS	2.669	5000	0.64	0.47	0.69
4211	Seville @ Lodi	5431	8 LS	2.665	5000	0.67	0.49	0.72
4118	Stansley @ Genoa	5435	8 GR	2.603	5000	0.67	0.50	0.72
4003	Shelly @ Kenton	5436	57 LS	2.693	5000	0.64	0.46	0.68
4394	Subtropilis @ Petersburg	5437	57 LS	2.687	5000	0.64	0.47	0.69
4505	National @ Delaware	5454	8 LS	2.684	5000	0.65	0.47	0.70
4513	Shelly @ York Center	5459	57 LS	2.577	5000	0.64	0.47	0.68
4330	Mar-Zane @ Barberton	5460	57 LS	2.696	5000	0.65	0.47	0.70
4839	Ervin Hill @ Hillsboro	5462	8 GR	2.540	5000	0.71	0.53	0.77
4840	Shelly @ Chillicothe-2	5464	57 GR	2.634	5000	0.73	0.55	0.79
4376	Allegheny @ Slippery Rock	5465	8 GR	2.596	5000	0.73	0.55	0.79
4385	Allegheny @ Harrisville	5487	57 LS	2.699	5000	0.62	0.44	0.65
4376	Allegheny @ Slippery Rock	5488	57 LS	2.718	5000	0.62	0.45	0.66

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
4385	Allegheny @ Harrisville	5490	8 LS	2.686	5000	0.63	0.45	0.67
4214	Rupp @ Marshallville	5491	8 LS	2.699	5000	0.62	0.44	0.65
4844	Three Locks @ Chillicothe	5502	57 GR	2.573	5000	0.69	0.52	0.76
4105	Lafarge @ Marblehead	5504	8 GR	2.603	5000	0.74	0.56	0.81
4112	Hanson @ Flat Rock	5535	8 LS	2.525	5000	0.66	0.48	0.71
4804	Shelly @ Chillicothe-1	5554	8 LS	2.549	5000	0.63	0.45	0.67
4373	Mar-Zane #16 @ Ravenna	5558	57 GR	2.629	5000	0.68	0.52	0.74
4110	Hanson @ Waterville	5563	8 LS	2.695	5000	0.62	0.45	0.65
4373	Mar-Zane #16 @ Ravenna	5570	8 GR	2.564	5000	0.72	0.54	0.78
4106	Martin Marietta @ Woodville	5580	57 LS	2.729	5000	0.62	0.43	0.64
9552	Stocker @ Gnadenhutten	5592	57 GR	2.564	5000	0.71	0.54	0.78
5114	Lafarge @ Manatoulin	5593	57 LS	2.703	5000	0.66	0.48	0.71
5116	O-N Minerals @ Rogers City	5599	8 GR	2.580	5000	0.73	0.56	0.80
5116	O-N Minerals @ Rogers City	5602	8 SL	2.510	5000	0.65	0.47	0.69
4523	Shelly @ Lockbourne	5622	8 LS	2.707	5000	0.66	0.47	0.70
4352	Massillon #2 @ Massillon	5624	57 LS	2.635	5000	0.68	0.50	0.73
4118	Stansley @ Genoa	5625	8 LS	2.654	5000	0.65	0.47	0.69
4352	Massillon #2 @ Massillon	5628	8 LS	2.665	5000	0.60	0.44	0.63
4205A	Hanson @ Sandusky	5643	8 LS	2.719	5000	0.65	0.46	0.69
4205A	Hanson @ Sandusky	5645	8 GR	2.643	5000	0.73	0.56	0.80
4325	Oster @ Massillon	5652	8 GR	2.563	5000	0.72	0.55	0.79
4007	National @ Findlay	5654	57 GR	2.554	5000	0.71	0.53	0.77
4007	National @ Findlay	5668	57 GR	2.614	5000	0.72	0.56	0.79
4820	Hanson @ Peebles	5670	57 LS	2.810	5000	0.68	0.51	0.74
4833	Hanson @ Winchester	5690	57 GR	2.656	5000	0.72	0.55	0.79
4108	Macritchie @ W. Millgrove	5692	8 GR	2.631	5000	0.72	0.53	0.78

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
5027	Oster @ Bolivar #2	5694	57 LS	2.690	5000	0.64	0.45	0.67
4652	Shelly @ Springfield	5699	57 LS	2.591	5000	0.68	0.50	0.73
4004	Olen Corporation @ Upper Sandusky	5700	8 LS	2.577	5000	0.67	0.49	0.72
4743	Barrett @ Medway	5702	57 LS	2.604	5000	0.66	0.48	0.70
4819	Ohio Asphaltic @ Hillsboro	5703	8 LS	2.573	5000	0.65	0.47	0.69
4204A	Wagner @ Sandusky	5704	8 LS	2.659	5000	0.64	0.46	0.68
4204A	Wagner @ Sandusky	5715	8 LS	2.675	5000	0.64	0.46	0.68
4501	Agg Rok @ Columbus	5716	8 LS	2.730	5000	0.65	0.46	0.69
4501	Agg Rok @ Columbus	5718	8 LS	2.658	5000	0.66	0.48	0.71
4621	Miami River Stone @ Sidney GR	5722	57 LS	2.734	5000	0.64	0.47	0.68
4103	Stoneco @ Portage	5730	57 LS	2.701	5000	0.63	0.46	0.67
5017	Menuez @ Millersburg	5741	8 GR	2.683	5000	0.71	0.52	0.77
5052	Anthony @ Wintersville	5742	8 GR	2.570	5000	0.65	0.50	0.70
4414A	Sidwell @ Zanesville	5745	57 LS	2.650	5000	0.67	0.50	0.72
4414	Sidwell @ Zanesville	5747	8 LS	2.636	5000	0.65	0.46	0.69
4414A	Sidwell @ Zanesville	5749	57 LS	2.749	5000	0.66	0.47	0.70
4414	Sidwell @ Zanesville	5764	8 LS	2.610	5000	0.63	0.45	0.67
4413	Shelly @ E. Fultonham	5771	8 GR	2.580	5000	0.73	0.54	0.79
4626	Shelly @ Belle Center	5773	8 GR	2.590	5000	0.69	0.52	0.76
4020	Shelly @ Forest	5776	57 GR	2.686	5000	0.70	0.50	0.75
4624	Barrett @ Sidney (GR)	5777	57 GR	2.688	5000	0.71	0.52	0.77
4205C	Hanson @ Sandusky	5785	57 GR	2.617	5000	0.65	0.49	0.70
5029	Midvale @ Midvale	5792	57 LS	2.718	5000	0.69	0.51	0.75
4624	Barrett @ Sidney (GR)	5811	57 LS	2.628	5000	0.69	0.50	0.74
4730	Moraine Materials @ Germantown	5814	8 LS	2.621	5000	0.67	0.48	0.72
4815	Hanson @ Hillsboro	5817	8 GR	2.616	5000	0.73	0.57	0.80

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
4815	Hanson @ Hillsboro	5819	8 LS	2.681	5000	0.65	0.47	0.69
5064	J.D. Mining @ Magnolia	5820	57 LS	2.702	5000	0.65	0.48	0.70
5115	O-N Minerals @ Cedarville	5838	8 GR	2.671	5000	0.70	0.52	0.76
4788	Evans @ Cincinnati	5840	8 LS	2.700	5000	0.64	0.46	0.68
4003	Shelly @ Kenton	5841	57 LS	2.695	5000	0.64	0.48	0.69
4307	Canton Agg. @ Canton	5856	57 GR	2.520	5000	0.67	0.54	0.74
4811	Hanson @ Sargents	5859	8 LS	2.707	5000	0.68	0.49	0.73
4743	Barrett @ Medway	5865	57 LS	2.684	5000	0.68	0.50	0.73
5115	O-N Minerals @ Cedarville	5865	57 LS	2.684	5000	0.67	0.49	0.72
4015	National @ Delphos	5876	57 GR	2.661	5000	0.73	0.55	0.80
4004	Olen Corporation @ Upper Sandusky	5881	8 CR GR	2.653	5000	0.69	0.51	0.75
4123	Stoneco @ Maumee	5884	57 LS	2.695	5000	0.66	0.48	0.71
4526	Melvin @ Circleville	5896	8 GR	2.524	5000	0.70	0.53	0.77
5068	Kimble @ E. Sparta	5897	8 GR	2.577	5000	0.72	0.55	0.79
4636	National @ Buckland	5898	57 GR	2.533	5000	0.62	0.49	0.67
4005	Meshberger @ Portland	5907	57 GR	2.658	5000	0.68	0.51	0.74
5114	Lafarge @ Manatoulin	5918	57 LS	2.601	5000	0.66	0.48	0.71
4512	National @ Marion	5920	8 LS	2.609	5000	0.63	0.45	0.67
4833	Hanson @ Winchester	5930	8 GR	2.597	5000	0.72	0.54	0.78
4103	Stoneco @ Portage	5951	8 LS	2.715	5000	0.66	0.48	0.71
5027	Oster @ Bolivar #2	5952	8 LS	2.689	5000	0.63	0.47	0.68
4116	Clay Center @ Clay Center	5953	57 LS	2.702	5000	0.65	0.48	0.69
4025	Hanson @ Woodburn	5968	8 GR	2.575	5000	0.70	0.52	0.76
4622	Stoneco @ Celina	5971	8 GR	2.586	5000	0.73	0.56	0.80
4202	National @ Bucyrus	5976	8 GR	2.679	5000	0.71	0.54	0.78
4202	National @ Bucyrus	5977	8 GR	2.652	5000	0.71	0.54	0.77

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
4838	Tow Path Materials @ Lucasville	5978	57 GR	2.683	5000	0.71	0.54	0.78
4838	Tow Path Materials @ Lucasville	5988	57 GR	2.658	5000	0.73	0.56	0.80
4631	Poeppleman @ Bradford	5990	8 GR	2.590	5000	0.68	0.50	0.74
4638	Duff @ Huntsville	5993	8 LS	2.655	5000	0.68	0.49	0.73
4833	Hanson @ Winchester	5998	57 LS	2.636	5000	0.65	0.48	0.70
4413	Shelly @ E. Fultonham	5999	8 LS	2.605	5000	0.64	0.46	0.68
4106	Martin Marietta @ Woodville	6009	57 LS	2.805	5000	0.64	0.48	0.69
5057	Holmes Supply @ Holmesville	6010	57 LS	2.807	5000	0.67	0.50	0.73
4512	National @ Marion	6012	8 LS	2.755	5000	0.66	0.48	0.71
4730	Moraine Materials @ Germantown	6015	57 LS	2.722	5000	0.65	0.47	0.70
4730	Moraine Materials @ Germantown	6016	57 LS	2.659	5000	0.66	0.48	0.71
4839	Ervin Hill @ Hillsboro	6017	57 LS	2.734	5000	0.65	0.47	0.69
4807	Mar-Zane @ Chillicothe	6031	57 LS	2.695	5000	0.67	0.50	0.73
5106	O-N Minerals @ Pt. Inland	6035	8 CR GR	2.513	5000	0.72	0.55	0.79
4118	Stansley @ Genoa	6046	8 SL	2.469	5000	0.65	0.47	0.69
4840	Shelly @ Chillicothe - 2	6049	8 LS	2.663	5000	0.65	0.48	0.70
4509	Olen @ Columbus 100%	6052	8 LS	2.709	5000	0.63	0.46	0.67
4509A	Olen @ Columbus 40%	6058	57 GR	2.679	5000	0.69	0.52	0.75
4206	Erie Materials @ Sandusky	6069	8 GR	2.660	5000	0.72	0.55	0.79
4523	Shelly @ Lockbourne	6073	8 GR	2.592	5000	0.73	0.56	0.79
5020	Newton @ Dover	6076	8 GR	2.602	5000	0.70	0.53	0.77
4519	Shelly @ Ostrander	6099	8 GR	2.642	5000	0.74	0.58	0.81
4611	Enon Sd & Gr @ Enon	6101	8 LS	2.667	5000	0.61	0.45	0.65
4201	Young's @ Loudonville	6120	57 LS	2.713	5000	0.66	0.48	0.70
5111	Drummond @ Drummond	6122	57 LS	2.724	5000	0.65	0.47	0.69
4628	Urbana Materials @ Urbana	6125	8 LS	2.617	5000	0.65	0.47	0.69

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
4403	Shelly @ Coshocton	6133	8 LS	2.687	5000	0.59	0.43	0.61
4837	Hanson @ Grayson	6149	57 LS	2.686	5000	0.66	0.48	0.71
4402	Shelly @ Dresden	6163	8 LS	2.645	5000	0.65	0.47	0.69
4212	Mar-Zane #14 @ Melco	6165	8 LS	2.604	5000	0.63	0.45	0.67
4614	Miller Bros. @ Vandalia	6166	57 LS	2.619	5000	0.66	0.48	0.70
5114	Lafarge @ Manatoulin	6172	8 GR	2.545	5000	0.70	0.53	0.76
4111	Hanson @ Sylvania - 1	6173	57 LS	2.693	5000	0.66	0.49	0.71
4008	National @ Lima	6175	57 GR	2.595	5000	0.71	0.54	0.78
4604	Martin Marietta @ Phillipsburg	6176	8 GR	2.603	5000	0.73	0.57	0.80
4013	Stoneco @ Scott	6212	57 LS	2.647	5000	0.67	0.49	0.72
4844	Three Locks @ Chillicothe	6220	57 LS	2.644	5000	0.68	0.50	0.73
4020	Shelly @ Forest	6236	8 LS	2.679	5000	0.66	0.48	0.71
4804	Shelly @ Chillicothe - 1	6245	8 GR	2.599	5000	0.74	0.56	0.81
4212	Mar-Zane #14 @ Melco	6267	57 LS	2.656	5000	0.67	0.49	0.73
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6270	8 GR	2.617	5000	0.70	0.52	0.76
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6284	57 GR	2.586	5000	0.72	0.54	0.79
4822	Waterloo @ Oak Hill	6310	8 GR	2.590	5000	0.71	0.53	0.77
4206	Erie Materials @ Sandusky	6311	57 GR	2.572	5000	0.71	0.52	0.77
5116	O-N Minerals @ Rogers City	6316	57 LS	2.586	5000	0.66	0.48	0.71
5038	Stocker @ Pt. Washington	6317	8 LS	2.533	5000	0.67	0.48	0.71
4106	Martin Marietta @ Woodville	6331	8 LS	2.662	5000	0.65	0.47	0.69
5052	Anthony @ Wintersville	6340	57 GR	2.656	5000	0.75	0.57	0.82
4114	Hanson @ Bloomville	6348	57 LS	2.658	5000	0.66	0.47	0.70
4205A	Hanson @ Sandusky	6359	57 LS	2.604	5000	0.66	0.48	0.71
4205D	Hanson @ Sandusky	6361	8 LS	2.577	5000	0.65	0.48	0.70
4820	Hanson @ Peebles	6366	8 GR	2.573	5000	0.70	0.54	0.77

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
4820	Hanson @ Peebles	6378	8 LS	2.677	5000	0.65	0.47	0.70
4785	Martin Marietta @ Sabina	6379	8 GR	2.674	5000	0.68	0.51	0.74
4628	Urbana Materials @ Urbana	6380	57 GR	2.697	5000	0.69	0.53	0.76
4110	Hanson @ Waterville	6383	57 GR	2.573	5000	0.72	0.54	0.78
4638	Duff @ Huntsville	6385	8 LS	2.668	5000	0.63	0.44	0.66
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6388	57 LS	2.693	5000	0.65	0.47	0.70
5038	Stocker @ Pt. Washington	6389	8 LS	2.600	5000	0.62	0.45	0.66
4027	National @ Rimer	6392	57 GR	2.594	5000	0.71	0.54	0.77
4215A	Wooster Aggregate @ Wooster	6403	57 LS	2.662	5000	0.66	0.49	0.72
4519	Shelly @ Ostrander	6408	8 LS	2.607	5000	0.62	0.45	0.66
4208	Stein @ Lorain	6409	8 LS	2.630	5000	0.63	0.44	0.67
4002	Hanson @ Paulding	6410	57 LS	2.646	5000	0.65	0.47	0.70
4608	Barrett @ Fairborn	6413	57 LS	2.619	5000	0.65	0.48	0.70
4601	Martin Marietta @ Fairborn 40% CRGR	6431	57 GR	2.688	5000	0.71	0.53	0.77
4738	Carmeuse @ Maysville	6432	8 LS	2.710	5000	0.66	0.48	0.71
4002	Hanson @ Paulding	6434	57 CR GR	2.703	5000	0.68	0.50	0.74
4132	Stoneco @ Ottawa Lake	6436	8 GR	2.624	5000	0.72	0.54	0.78
4030	National @ Carey (W)	6437	57 GR	2.641	5000	0.72	0.55	0.79
4513	Shelly @ York Center	6440	57 LS	2.666	5000	0.65	0.47	0.69
4027	National @ Rimer	6442	8 LS	2.666	5000	0.65	0.47	0.70
4411	Shelly @ Lancaster	6453	57 LS	2.700	5000	0.66	0.50	0.72
5109	Lafarge @ Presque Isle	6464	8 LS	2.794	5000	0.64	0.47	0.68
4105	Lafarge @ Marblehead	6465	57 LS	2.813	5000	0.70	0.53	0.76
5116	O-N Minerals @ Rogers City	6480	8 LS	2.670	5000	0.63	0.45	0.66
4607	Martin Marietta @ Troy	6481	8 LS	2.655	5000	0.60	0.44	0.63
4915	Martin Marietta @ Applegrove	6482	8 GR	2.540	5000	0.71	0.54	0.78

P/S CODE	LOCATION	G#	MATL TYPE	Density (g/cc)	Weight (g)	Wadell	Sneed and Folk	Lees
4205C	Hanson @ Sandusky	6484	57 LS	2.701	5000	0.64	0.46	0.68
4509A	Olen @ Columbus 40%	6485	57 LS	2.693	5000	0.65	0.48	0.69
4416	Mar-Zane #1 @ Zanesville	6489	8 LS	2.640	5000	0.61	0.44	0.64
4132	Stoneco @ Ottawa Lake	6503	57 LS	2.634	5000	0.68	0.50	0.73
4123	Stoneco @ Maumee	6508	57 LS	2.689	5000	0.65	0.47	0.69
4316	Jefferson @ Steetsboro	6511	57 LS	2.577	5000	0.64	0.48	0.69
4842	Mountain @ Greenup, KY	6542	57 GR	2.629	5000	0.70	0.53	0.76
5031	Tube City @ Mingo Jct.	6562	57 LS	2.561	5000	0.68	0.48	0.73
4101	Stoneco @ Lime City	6564	8 LS	2.602	5000	0.68	0.50	0.74
4158	Cardinal @ Perrysburg	6567	8 GR	2.665	5000	0.75	0.58	0.82
4158	Cardinal @ Perrysburg	6578	57 GR	2.680	5000	0.71	0.54	0.78
4637	Mechanicsburg Sd & Gr @ Mechanicsburg	6590	57 LS	2.704	5000	0.64	0.49	0.70
4614	Miller Bros. @ Vandalia	6591	57 GR	2.631	5000	0.71	0.55	0.78
5038	Stocker @ Pt. Washington	6603	8 GR	2.595	5000	0.72	0.54	0.79
4516	Tuffco Sd & Gr @ Plain City	6606	8 LS	2.655	5000	0.64	0.47	0.68
4025	Hanson @ Woodburn	6607	57 LS	2.669	5000	0.68	0.50	0.73
4632	Con-Ag @ St. Mary's	6610	57 LS	2.690	5000	0.64	0.46	0.68
4523	Shelly @ Lockbourne	6634	8 GR	2.603	5000	0.72	0.55	0.79
4523	Shelly @ Lockbourne	6671	57 GR	2.645	5000	0.69	0.52	0.75
4509A	Olen @ Columbus 40%	6674	8 LS	2.634	5000	0.65	0.48	0.70
4005	Meshberger @ Portland	6684	8 GR	2.632	5000	0.74	0.57	0.81
4111	Hanson @ Sylvania - 1	6692	57 LS	2.693	5000	0.64	0.46	0.68
4703	Martin Marietta @ Fairfield	6729	57 LS	2.709	5000	0.62	0.44	0.65
4110	Hanson @ Waterville	6735	57 LS	2.686	5000	0.66	0.48	0.70