Aggregate Shape Characterization Using Digital Image Processing

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AGGREGATE SHAPE CHARACTERIZATION USING DIGITAL IMAGE PROCESSING

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EXECUTIVE SUMMARY

Aggregates must meet certain specifications to be acceptable in asphalt and concrete applications. Among these are specifications that deal with the various aspects of aggregate shape, including flatness and elongation and aggregate angularity. The current practice for ensuring those specifications is the use of manual-mechanical tests. These tests are time consuming, labor intensive and subjective. In addition, tests such as the compacted or uncompacted voids tests (Figure 1), are taken to be a shape (angularity) indicator, even thought the measured quantify is the void ratio.

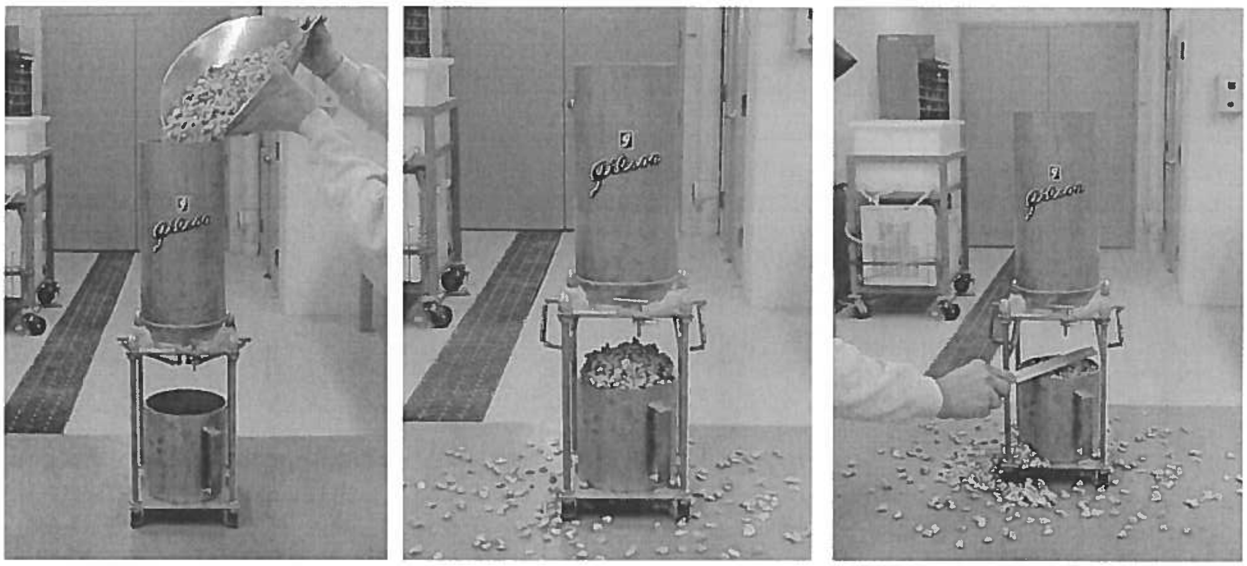


Figure 1: Uncompacted voids test for measuring void ratio/coarse aggregate angularity

This report describes a prototype of an automated digital video image analysis system that measures both the flat and elongation (F&E) ratio, and the angularity of aggregate (Figure 2). This report also compares the results of manual testing with the measurements of the imaging system.

The *concept* is that by using a digital imaging system, quick, inexpensive and objective measurements can be made. Because the measurements are so quick, faster adjustments to manufacturing processes can be made, to decrease the cost of producing off-specification materials. Because the incremental cost of more measurements is negligible, more tests can be performed, improving statistically reliability. Because the measurements are more objective, test results will be less affected by inexperienced or inattentive operators.

The *innovation* is in using state of the art video imaging hardware and software to make a real time measuring system to measure flat and elongation and angularity. New improvements include the use of backlighting to improve the imaging of the aggregate pieces and the measurement of the curve radius of the corners of the aggregate as a measure of angularity. In addition it was demonstrated the there is a potential to use this technology for sand-sized aggregate pieces.

Research results show that image measured F&E ratios are fairly close to matching caliper results, although some differences were found. Repeatability of the imaged measurements was found to be better than with manual tests.

Research results shows that the image measured angularity measurements can correlate well to voids tests. The repeatability of the imaged measurement is not quite as good as that of the voids test.

Analysis of the flat and elongation measurements as a function of crusher type showed that impact type crushers tend to produce more cubical particles, even when rock type is not accounted for.

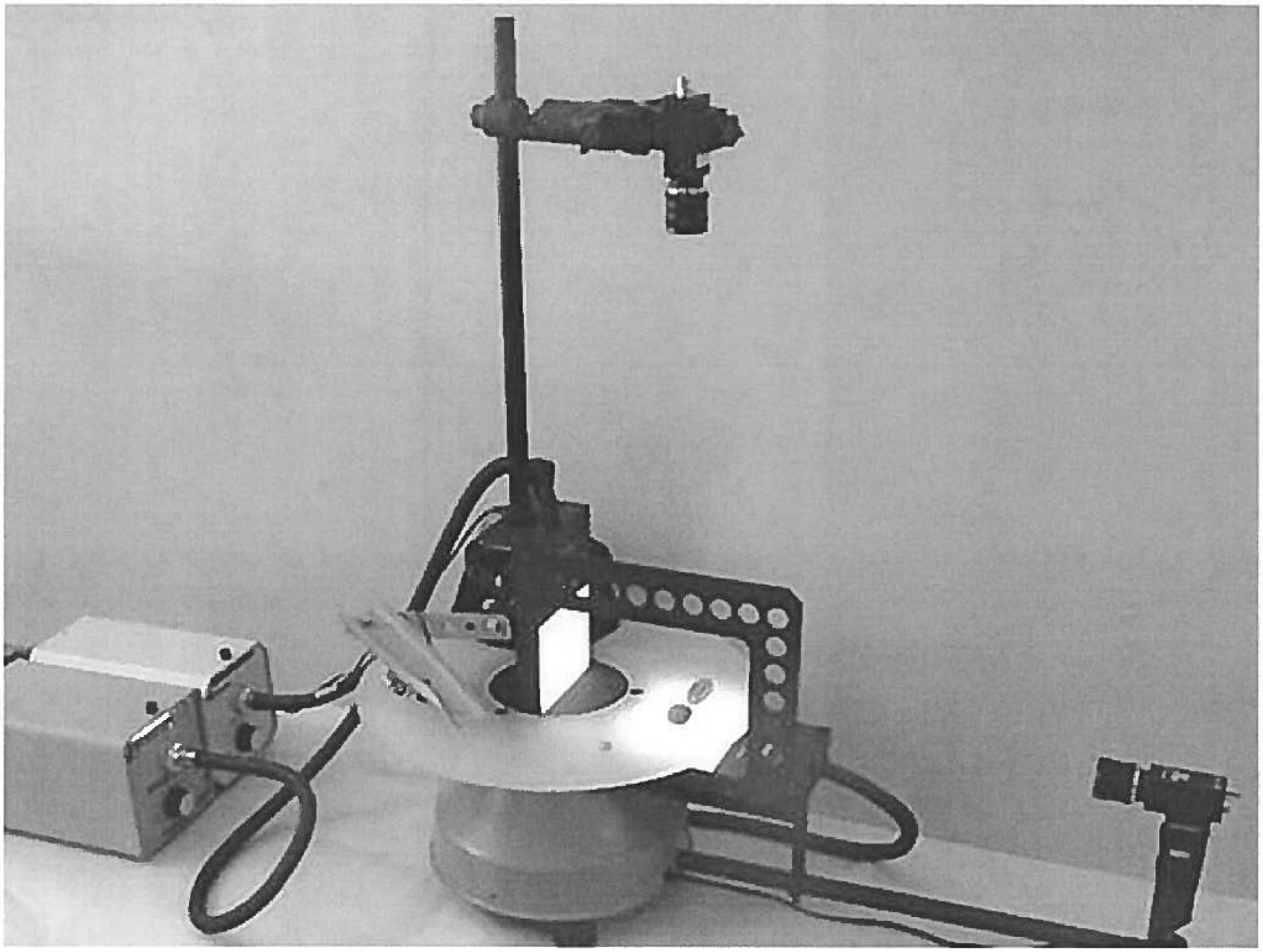


Figure 2: New shape measurement apparatus.

1. IDEA PRODUCT, CONCEPT, AND INNOVATION

1.1 BACKGROUND: THE PURPOSE FOR MEASURING AGGREGATE SHAPE

1.1.1 Introduction

Aggregates in asphalt and concrete applications must pass a stringent series of mechanical, chemical and physical tests in order to demonstrate that they will perform satisfactorily, and meet or exceed specifications. Several physical tests are used to determine the suitability of the aggregate shape in terms of flatness and elongation, or the angularity of the particles. Imaging systems and devices to replace these subjective tedious tests have been and are being developed.

1.1.2 Flat and elongated

1.1.2.1 Reasons to Regulate Amounts of F&E Particles

Flat and elongated aggregate particles are a big concern in the use of hot mix asphalt (HMA) for highway construction. SUPERPAVE, a very recent design in making a more rut resistant and durable asphalt concrete pavement, attempts to control the amount of flat and elongated particles in the asphalt mix by testing for flat and elongated particles under the current standard ASTM test method, ASTM D4791 (1).

The SUPERPAVE aggregate specification requires a limit of 10% of flat and elongated particles for the 5:1 (maximum to minimum particle dimension) ratio (2). There is also some consideration on establishing a new design standard on making the mix design stricter by looking at the 3:1 ratio.

There are two large concerns for regulating the amount of flat and elongated particles in the asphalt concrete mix. The first is that the flat and elongated particles tend to lie flat when placed and compacted. This causes slip planes, which reduces aggregate interlock (3). The other problem that flat and elongated aggregate particles create is they tend to break during the compaction of the asphalt. When these particles break they not only become smaller in size, but also create more fine aggregate particles that are closely regulated in the mix design (3). Buchanan performed an evaluation on flat and elongated particles in asphalt mixtures and how they affected the asphalts' performance (4). He found that when the percent of 3:1 flat and elongated particles was very high, there was a large amount of breakdown in the asphalt. There was also a noticeable influence in the volumetric properties of the HMA mixture when a high percentage of flat and elongated particles are in the mix. There are similar agreements with these conclusions by Benson (5) and Hargett (6). Therefore it is safe to say when there are large quantities of flat and elongated particles in the asphalt mix this can become a serious problem, thus the reason for performing the manual caliper test describe in ASTM D4791, but since the tests are time consuming and tedious the measurements are not done constantly.

1.1.2.2 Shortcomings of Proportional Caliper Measurements of F&E Particles

Besides the ASTM manual caliper test method (Figure 3) being time consuming and tedious, it is also seen to be very subjective. In the ASTM manual method the aggregate samples have to be screened into their separate course particle sizes. Then a uniform sample of approximately 100 pieces of the No. 4 size aggregate particles and larger are run through the caliper set at the specified ratio that is desired. The particles are categorized as either being flat and elongated or not in separate piles and then weighed and tabulated (1). The problem of subjectivity with the caliper test is the test operator having to judge visually what dimension of each aggregate particle is the longest. What the naked human eye may perceive to be the longest dimension may actually be incorrect when the particle is more cubical than the more obvious flat and long particles that are in the same sample. New digital measuring processes hold the promise of eliminating the problems of subjectivity, labor intensiveness, and time consumption.

1.1.2.3 Previous Work with Computer Imaging Measurements

Barksdale et al. (7) researched the possibility of using modern data acquisition procedures to measure aggregate. Although they did not have a definite method or designed apparatus to measure aggregate they concluded that with a relatively low-cost digitizer and microcomputer, it is possible to acquire large quantities of accurate data rapidly.

Kuo et al. (8-10) developed a method to analyze the morphological characteristics of coarse aggregate using a three dimensional image analysis process. They demonstrated that the method could efficiently and accurately measure flatness and elongation of aggregate, with however still some significant amount of manual work that has to be applied because the aggregate in this method is measured on plexiglas holders that have to be reloaded with new aggregate particles each time.

Brzezicki and Kasperkiewicz (11) improved on this concept by measuring the shadows along with the aggregate particle at perpendicular projections, enabling three-dimensional characteristics to be measured.

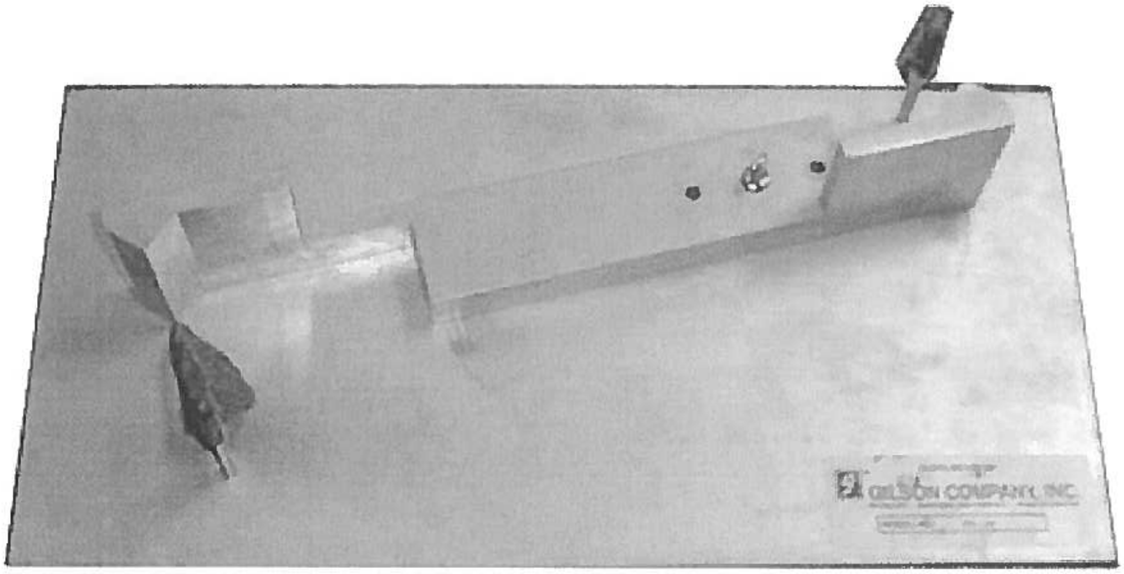


Figure 3. Proportional Caliper for measuring flat and elongated particles

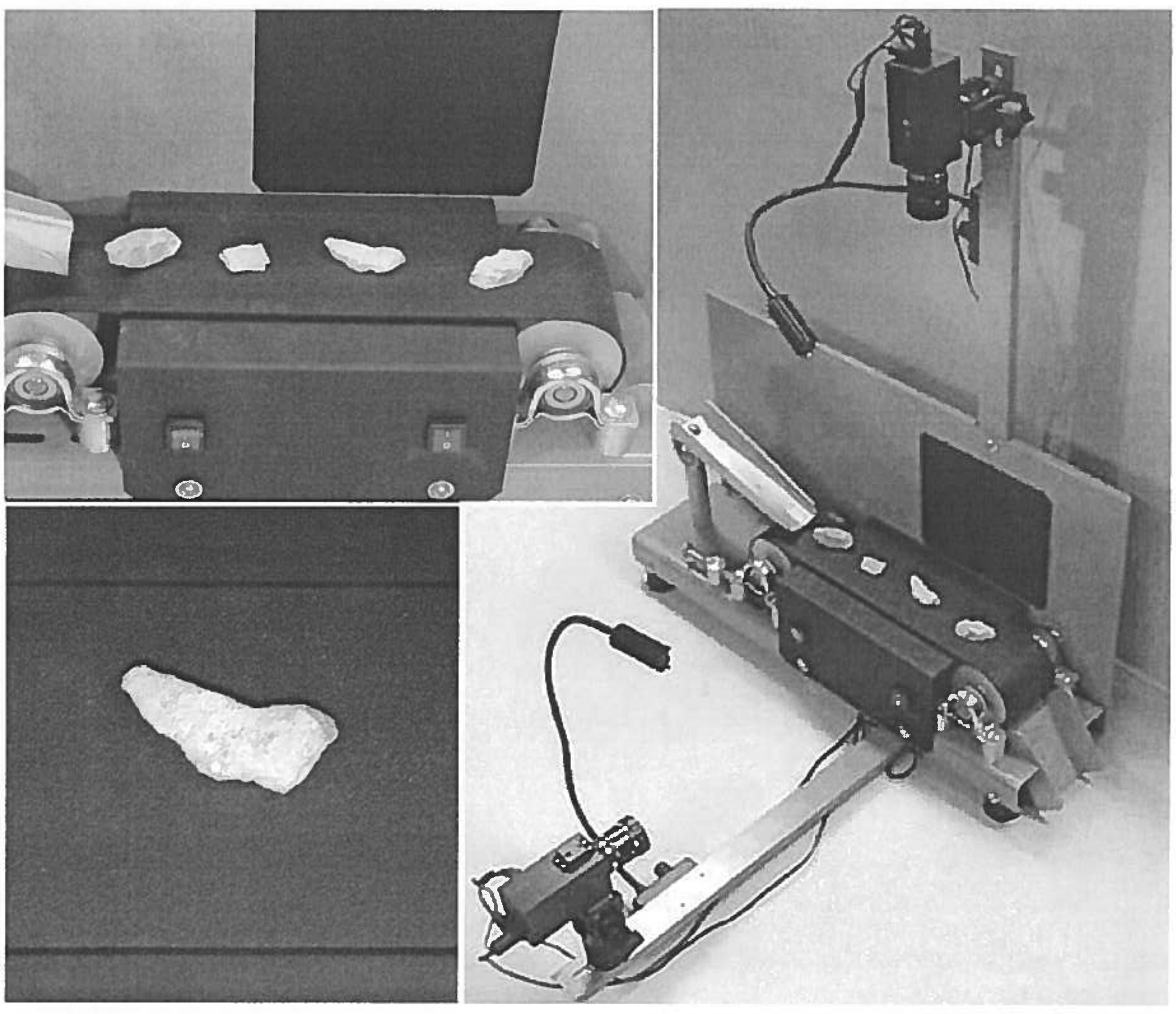


Figure 4. First prototype of the WipShape shape measurement system.

Prowell and Weingart (12-13) evaluated the precision of the VDG-40 in measuring flat and elongated particles. The VDG-40 is argued to have been developed originally for granulometry and not for particle shape measurement (14). In determining the viability of the VDG-40 being able to accurately measure the percent of flat and elongated particles in accordance with ASTM D4791 there was too much variability seen. The most apparent reason that there is a high amount of variability in the analysis is because Weingart and Prowell attempted to correlate the slenderness ratio that was measured by the apparatus and translate the French test method, that was the basis of their test method, to work in accordance with the ASTM D4791 by incorporating a Shape Class Average Ratio (SCAR) formula (15).

A more promising method has been developed at the University of Illinois by Rao and Tutumluer (16) using three cameras at orthogonal views to measure the volume of an aggregate as well as the aspect ratios. A laser based scanning system has been proposed by Kim et al. (17).

A commercially available imaging system name WipShape (Figure 4) has been described by Maerz et al. (14, 18-19).

1.1.3 Angularity

1.1.3.1 Reasons to Regulate Particle Shape

Rounded (as opposed to angular) aggregate particles are also a concern in the use of hot mix asphalt (HMA) for highway construction. Rounded particles are associated with premature rutting (20). Rounded aggregate provides minimal aggregate interlock, and will easily roll over one another allowing movement within the mix, and deep rutting in the long term performance (21). Increasing fine aggregate angularity will increase the VMA (voids in mineral aggregate) thereby reducing durability of the pavement (21).

1.1.3.2 Shortcomings of Shape Measurements

Aggregate shape is nominally defined by the descriptive terms sphericity and roundness (22-24), which are intuitively obvious but difficult to quantify. The test that best quantifies this is the percent crushed particles, or fractured face count, (25). This test can determine whether rounded aggregate pieces have been sufficiently crushed as to present at least two good fractured faces. This test is however completely manual, and very subjective, and does not consider three or four or more crushed faces.

Two more tests attempt to use a presumed correlation between void ratio and shape, uncompacted void test of coarse aggregate, (AASHTO Designation TP56-99), and compacted void test (ASTM D3398-00). In these tests, is assumed that void ratio correlates to aggregate shape.

1.3.3 Previous Work with Computer Imaging Measurements

Digital image analysis systems have been developed and proposed to replace some or all of these tests with imaging devices (20, 26).

1.2 INNOVATION: IMPACT OF IMAGE-BASED MEASUREMENTS

The impacts of a successful image based methodology are numerous:

1. Test results, removed from human subjectivity, will be much more reliable. No longer will the test results vary between operators, or vary based on the disposition of an operator.
2. A greater number of tests will be performed. Faster testing, and the low per unit cost of incremental tests, will result in an increased amount of tests being conducted, allowing better and more statistically valid characterization.
3. Run time adjustments to crushing, screening and other processing equipment will be possible. Because the analysis is quick, a significant reduction of off-specification material can be achieved, and there will be less incentive to pass off-specification material.
4. There will be a lower burden on operators and testing agencies, resulting from lower per sample testing costs.

However there are also difficulties with image based measurement methodologies

1. The capital costs of imaging equipment will be much higher.
2. Inherent small to significant differences in measurement results can be expected, because of the differences between imaging and physical testing techniques.

3. Industry and regulatory resistance can be expected to any new technology that does not give exactly the same results as the "older" manual measurements, even if the "older" measurements are less accurate.

1.3 OBJECTIVES

The project goals, separated in the areas of flat and elongated measurement, and coarse and fine aggregate angularity, are as follow.

1.3.1 Flat and elongated

The objectives of this portion of the research are to verify, and to compare the digital image processor with the standard manual test procedure, ASTM D4791. The scope will include a comparison of several geologically different aggregate types and ranges of particle cubicity.

1. Verification of the accuracy of the system on fragments between 1" to the equivalent of a #4 sieve, with aspect ratios of up to 5:1. Verification will be done manually, using proportional caliper measurements as per ASTM standards as a basis.
2. Fine-tuning and calibrating the system for maximum accuracy and maximum processing speed.
3. Finding difficulties with the system from such causes as excessive dust loading.
4. Writing a standard specification for measurement of flat and elongated using image processing techniques, as a prelude to a possible ASTM or AASHTO standard.

1.3.2 Coarse aggregate angularity

The following are the research goals for measuring coarse aggregate angularity:

1. Develop a method to measure angularity of particles using an image analysis system, and compare to manual measurements such as the percent of fractured faces of natural aggregates (crush counts) and aggregate angularity (compacted and uncompacted voids).
2. Investigate the potential for measuring fine aggregate angularity using imaging methods.

1.4 EXISTING PRODUCT DESCRIPTION

1.4.1 Overview

A commercially available imaging system name WipShape (Figure 4) described by Maerz et al. (14, 18-19) was used for the research.

1.4.2 Hardware

1.4.2.1 Moving belt

The heart of the image analysis system is a black mini-conveyor belt used to present the individual aggregate pieces to be moved into a position to be imaged end then moved out of the way. Pieces must be isolated so that they can be imaged from 2 different directions to get three-dimensional measurements. A vibrating feeder is used to load the belt, while a discharge chute is used to unload the belt.

The black belt and backdrop serve to create a contrast between the sample and the background to aid in the identification of block edges. Small 4 watt lamps on flexible mounts serve to give directed variable angle lighting to increase the contrast between the aggregate piece and the backdrop, and to avoid glare from direct reflections. Cameras are mounted on extension arms, and take plan and profile images (Figure 5).

1.4.2.2 Imaging hardware

Two standard monochrome video cameras were used for imaging, producing standard analog video signals which were digitized by a standard analogy digitizing board. Alternate plan and profile images are taken at about 1/8 second intervals, and digitized to a resolution of 320 by 240 picture elements (pixels).

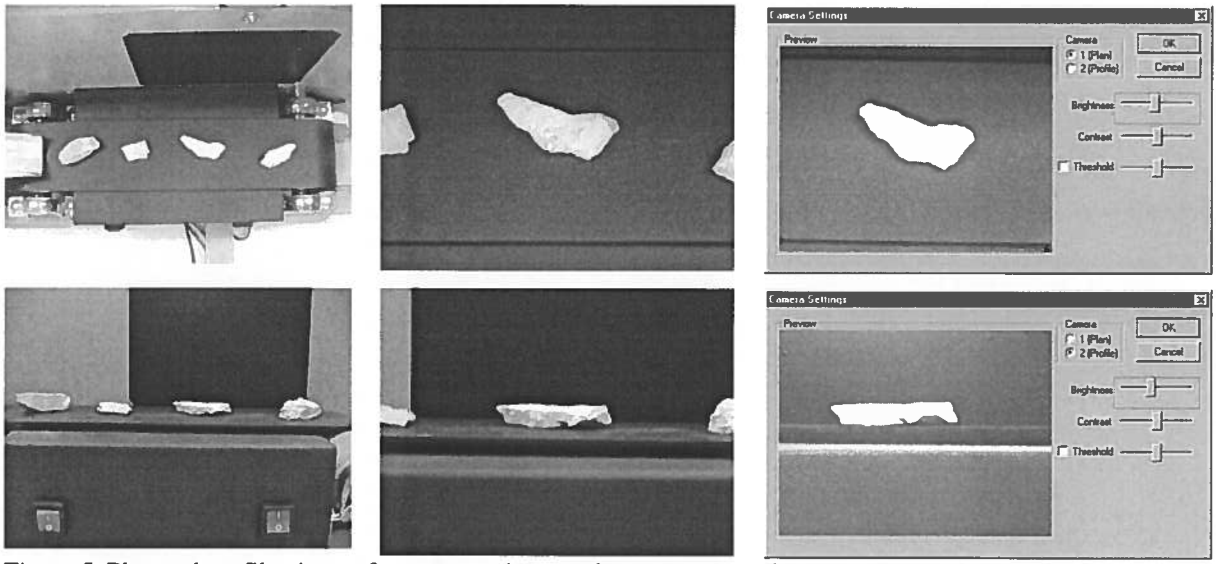


Figure 5. Plan and profile views of aggregate piece on the conveyer on the conveyor.

1.4.3 Software

1.4.3.1 Overview

The software application is developed as a Windows® application under Using Visual c++®, and consists of a software trigger to determine if a block is present in both views, a particle identification routine, and measures on the two views of the particle.

1.4.3.2 Measurements

Working on the binary image (Figure 6), the following operations are done.

1. A perimeter walk creates an array of x-y coordinates defining the outline of each view of the block.
2. A pixel filling (paint) routine calculates the profile surface area of each view of the block.
3. In the plan view, using the perimeter array, the longest dimension (major axis) is identified and measured as the length of the aggregate.
4. In the plan view, the longest half-width on each side of and perpendicular to the major axis is identified and measured. Adding both lengths together gives the width of the aggregate.
5. In the profile view, using the perimeter array, the maximum height of the particle is identified and measured.
6. If the maximum dimension is not greater than the intermediate dimension, or the intermediate dimension is not greater than the minimum dimension, the measurements are re-ordered.

1.4.3.3 Calculations

1. The volume of the piece is calculated by multiplying the length by width by height, by an empirical factor, and multiplying by density to get weight.
2. The size of the aggregate is taken to be the intermediate diameter of the particle. This is to provide compatibility with screening results (It is the intermediate diameter which governs the minimum screen size that a particle can pass through). An empirical calibration factor is used to match screening size measurements.
3. The aspect ratio is determined by dividing the maximum dimension by the minimum dimension. Particles are classified as being greater than 5:1, 4:1, 3:1, 2:1 or 1:1.

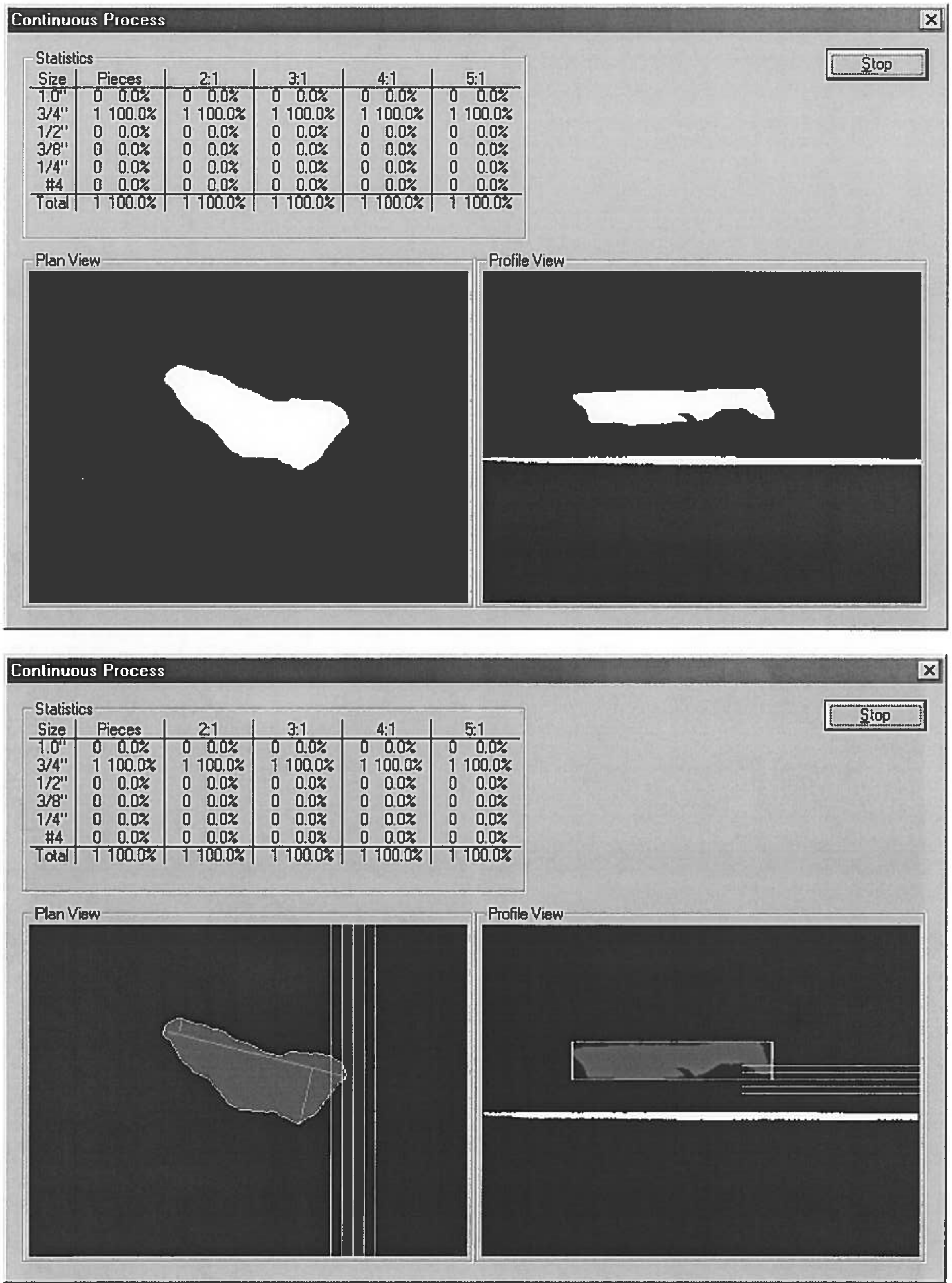


Figure 6. Top: Binarized image of particle from top and from side. Bottom: Processed image, with measurement and blue trigger lines shown.

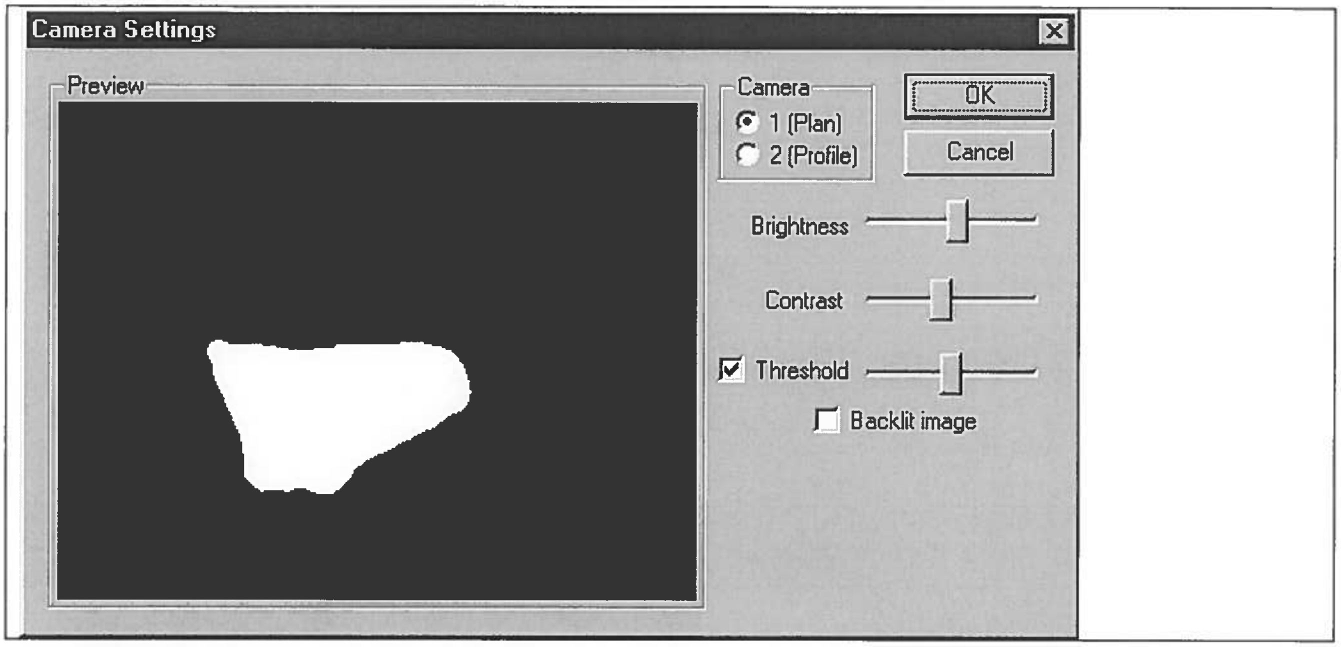


Figure 7. Dialog box to set the brightness, contrast and threshold level:

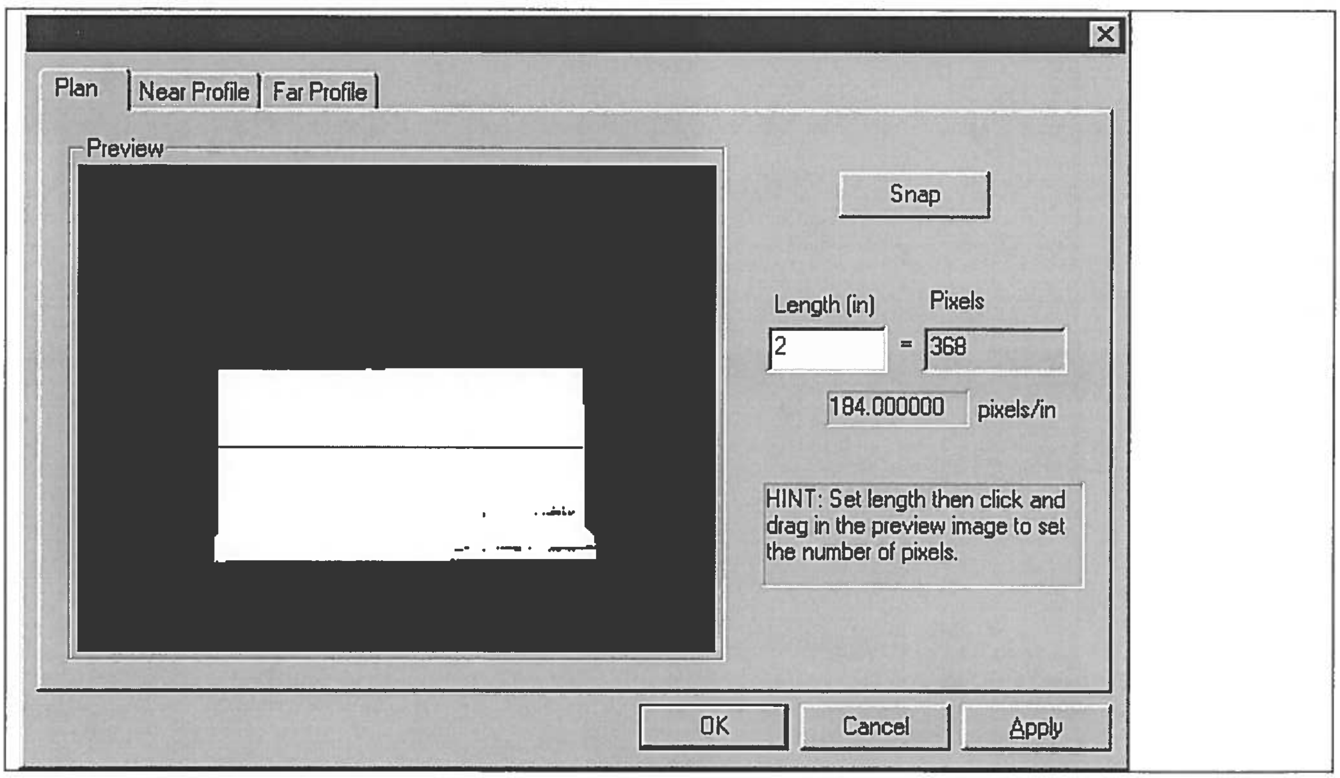


Figure 8. Dialog box to enter the scaling factors.

1.4.3.4 User interface

The user interface consists simply of three modules for: 1) Setting the brightness, contract and threshold levels (Figure 7) as needed for the particular aggregate color/brightness; 2) Setting the scaling factors (Figure 8); and, 3) Running the samples (Figure 6).

1.4.4 Product deficiencies

Several deficiencies with the initial WipShape product were identified:

1. Processing speed was a bit too slow.
2. Image resolution was a bit too low.
3. The setup worked well for light colored aggregates, but it was difficult to maintain the contrast with darker or mottled aggregates.
4. The device lacked a hoper to automatically load the vibrating feeder.
5. The device did not make angularity measurements.

1.5 PRODUCT MODIFICATION

1.5.1 Overview

During the course of the investigation several modifications were made to the system to eliminate perceived deficiencies. These were done by the manufacturer of the product.

1.5.2 Hardware changes – Backlit measurement system

Many of the Missouri aggregate samples that were to be tested are either dark in color or mottled. That makes them difficult to image (Figure 9).

In response, a backlit presentation system was designed (Figure 10). The new apparatus was designed with a fiber optic backlight, through a frosted plexiglas transport turntable. As before, a vibrating feeder is used to load the belt, but a sweeping device is used to unload the belt. Cameras are mounted on extension arms, and take plan and profile images as before.

Because of the backlighting, the fragment color is largely irrelevant, as the image is nominally a black profile on a white background. There are some small issues with very light colored pieces when the ambient lighting is high.

In addition, the maximum potential processing speed was improved because the delivery speed of the turntable is greater than that of the black belt.

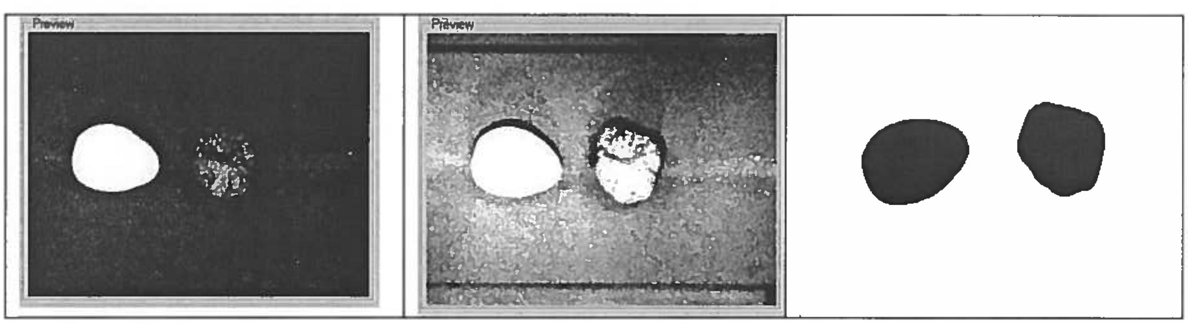


Figure 9: Light and dark particle. Left: Normal lighting hides the dark piece. Middle: increasing the lighting to see the dark piece exposed the belt in the system. Right: Using backlight removes all difficulties from differing colors.

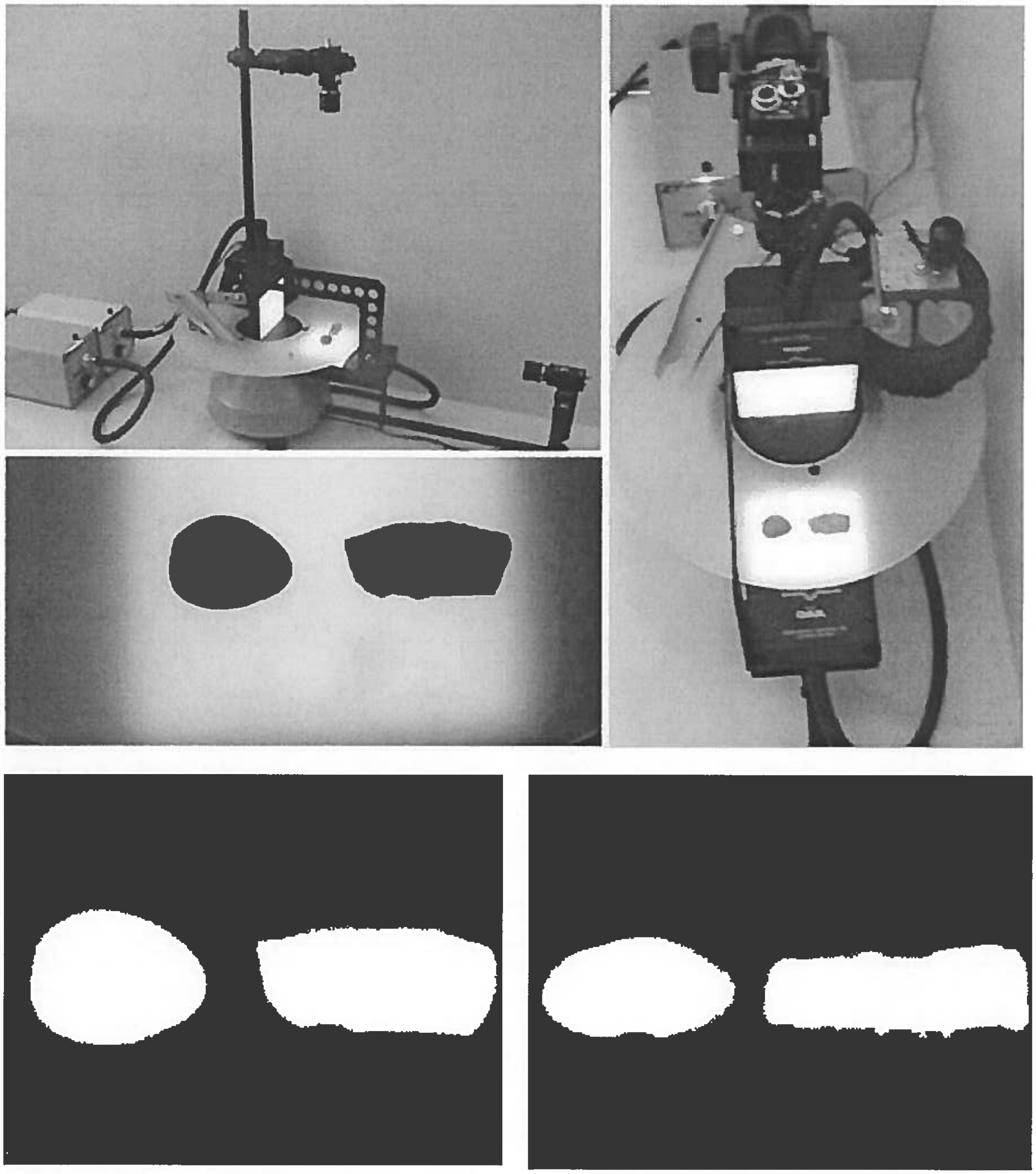


Figure 10. New backlit measuring device (top) and plan (bottom left) and profile (bottom right) view of two pieces of aggregate

1.5.3 Hardware changes – High speed/high resolution image capture

Other hardware modification included the addition of high-speed, progressive scan non-interlaced, double speed synchronized video cameras, which were synchronized to image simultaneously with the help of a digitizing card that supports simultaneous image acquisition from both cameras. (The previous version was limited to alternating frames between cameras.) The resolution of the system was improved from 320 by 240 to 640 by 480, to improve the resolution and measurement accuracy of small particles. On board look up tables (LUT) allow real time thresholding, which produces the binary image required (2 bits per pixel), and reduces the bandwidth required for transferring images. The imaging rate was increased to about 30 frames per second, from an estimated 4-8 frames per second previously.

1.5.4 Software components – Shape measurement

1.5.4.1 Overview

Software modifications have been made to the software to measure the angularity of the aggregate pieces, using the aggregate profile. Many shape measurements abound in the literature such as sphericity, roundness, and Fourier spectra of profiles and fractal dimension of profiles (27). Janoo (28) described several methods of characterizing shape such as degree of angularity, roundness and roughness indexes. These were implemented with no apparent good correlation to actual shape. Next, chord length distributions were measured, without any more success. Finally the Krumbein (29) approach of using inscribed circles in the corners of the aggregate profile, as a measure of radius of curvature was tried. This approach proved more successful.

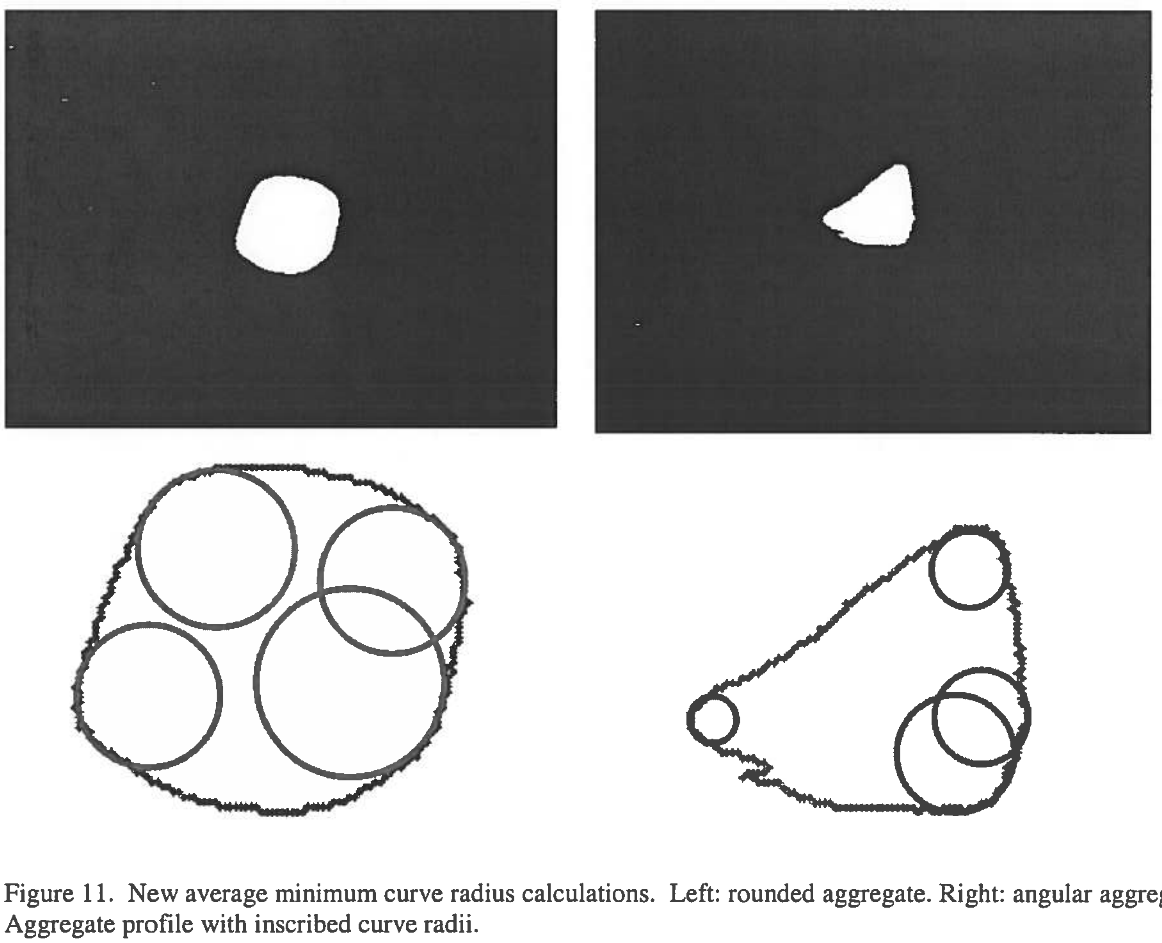


Figure 11. New average minimum curve radius calculations. Left: rounded aggregate. Right: angular aggregate. Bottom: Aggregate profile with inscribed curve radii.

1.5.4.2 Analysis

The best parameter was found to be the "minimum average curve radius". For this method continuous curve radius measurements are taken around the perimeter of the fragment. The measured radii are sorted by size and the four smallest are averaged. Figure 11 shows how the concept of how curve radii are measured.

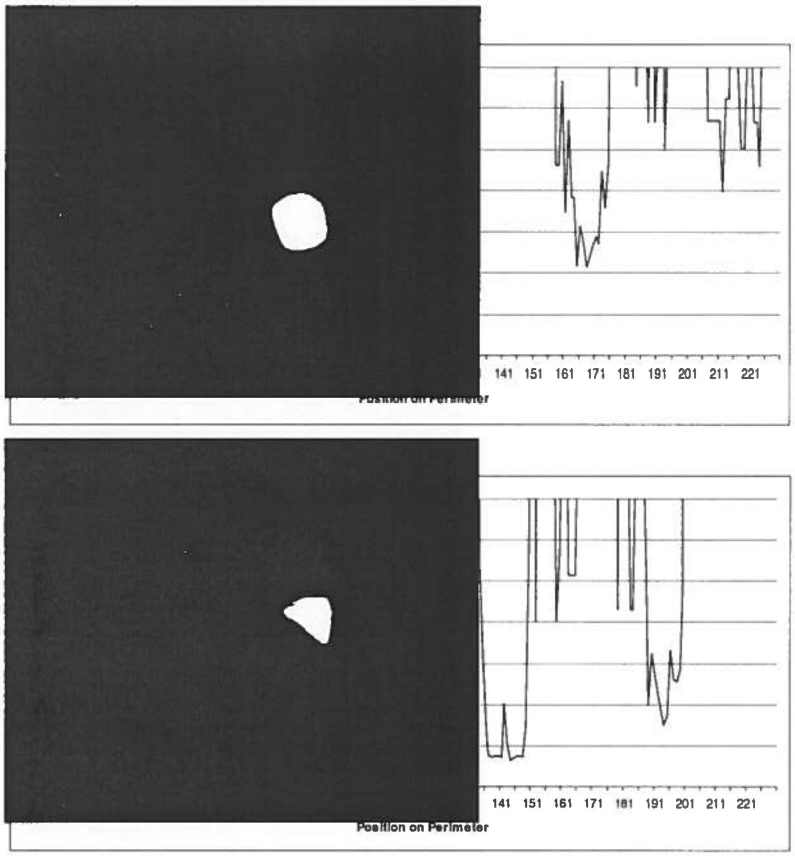


Figure 12. Moving curve radius calculations with the corresponding particle on the right.

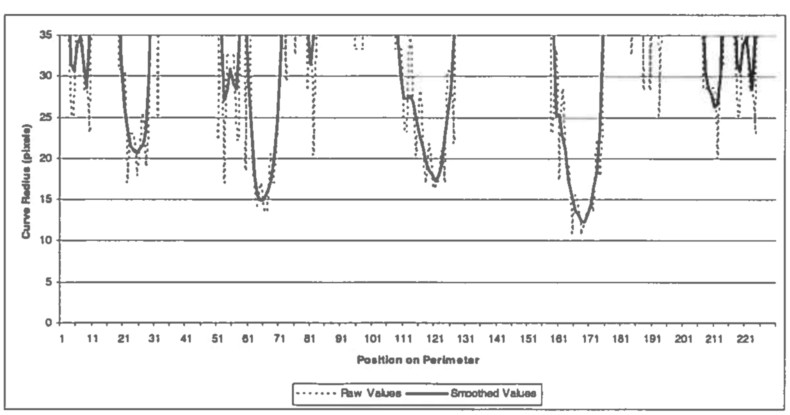


Figure 13. Gaussian smoothed moving curve radius of the particle in figure 12 (top).

Figure 12 shows the moving curve radius calculations, which are calculated along each point on the perimeter of the particle, for an relatively rounded and relatively angular particle. The moving curve radius graph is then smoothed by applying a gaussian low pass filter (Figure 13). Local minima are selected and ordered from smallest to largest. The smallest 4 are then averaged to produce the minimum average curve radius.

The measure of minimum average curve radius is size dependent (large pieces will have larger values). Therefore comparisons of curve radii can be done only on aggregates that are roughly the same size.

1.5.5 User interface

Modifications were made to the user interface to:

1. Report the minimum average curve radius,
2. Fit the larger image into the dialog box,
3. Tighten and lower the search pattern for profile pieces, as not to miss some very flat ones.

The new user interface is shown in figure 14.

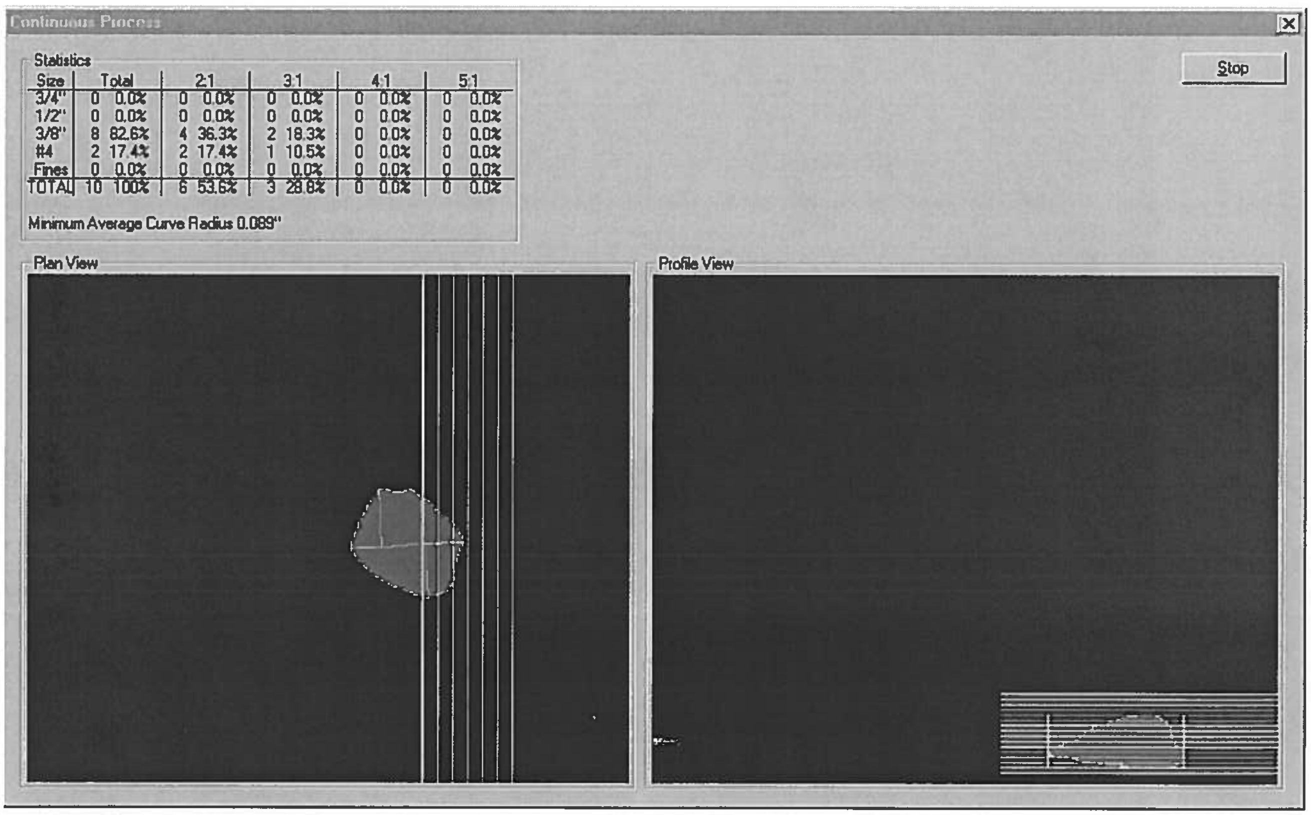


Figure 14. New user interface, showing the particle in red, and search lines in blue.

1.6 POTENTIAL IMPACT

The potential impact of this technology is great. Using the imaging methodology, an analysis will be completely automated, requiring only that the operator load the feed hopper with an aggregate material that has been scalped at the #4 sieve size, start the machine, and read the results a few minutes later. The outcome will be more reliable test results, removed from human subjectivity, an increased amount of testing, in better and more statistically valid characterization, faster results, to make real time adjustments to processing equipment; and, lower unit costs per measurement sample, creating less of a burden on operators. The impacts will be as follow:

1. More reliable test results, removed from human subjectivity. No longer will the test results vary between operators, or be based on the mood or disposition of an operator.
2. Faster testing, and low per unit cost of incremental tests will result in an increased amount of tests being conducted, resulting in better and more statistically valid characterization.
3. The ability to make quick adjustments to crushing, screening and other processing equipment. Because of the quickness of the analysis, a significant reduction of off-specification material will be achieved, and there will be less incentive to pass off-specification material.
4. A lower burden on operators and testing agencies, resulting from lower per sample testing costs.

2. INVESTIGATION AND PLANS FOR IMPLEMENTATION

2.1 OVERVIEW

The investigation consisted of two phases, one for flat and elongated, and the other for shape.

2.2 FLAT AND ELONGATED STUDIES

2.2.1 Previous Studies

A previous study (30) found using six large samples with about 10,000 individual fragments, found excellent agreement between manual caliper measurements made by both the Illinois DOT and the University of Illinois for four of the six samples (#161, #85, #93, and #86) (Figure 15). One sample (#62a) appeared to show progressive deterioration (breakdown) of the sample as it was tested 3 times, and another sample (#52) correlated poorly because the sample contained significant amounts of dark rock that did not image well against the dark belt.

A small reproducibility and repeatability study (31) found that imaging measurements were less variable than manual caliper measurements. Three groups of students, fully trained in the use of proportional calipers, were given an aggregate sample of 310 pieces, and asked to measure flat and elongation using the proportional calipers and using WipShape (No training was required for WipShape). In each case the sample was measured twice. The test results were interpreted in terms of repeatability and reproducibility.

Repeatability, or single-operator precision, can be defined as, "...an estimate of the difference that may be expected between duplicate measurements made on the same material in the same laboratory by the same operator using the same apparatus within a time span of a few days"(32), and can be calculated by (33):

$$r = 1.96\sqrt{2}\sigma_1$$

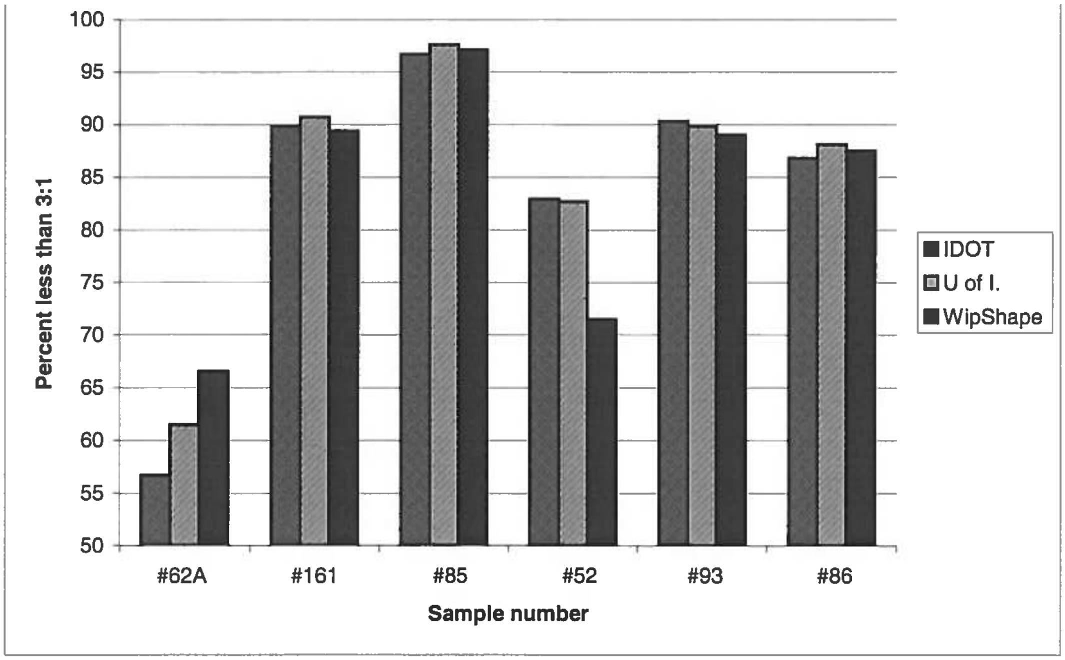
where σ_1 is the is the single operator standard deviation.

Reproducibility, or between-laboratory precision, can be defined as, "...an estimate of the difference that may be expected between measurements made on the same material in two different laboratories" (32), and can be calculated as follows (33):

$$R = 1.96\sqrt{2}\sqrt{\sigma_1^2 + \sigma_2^2}$$

where σ_1 is the is the single operator standard deviation, and σ_2 is the pooled standard deviation for all the measurements.

The results of this study show the repeatability of the imaging method are in general better than that of the proportional caliper device, and the reproducibility is clearly superior (Figure 16).



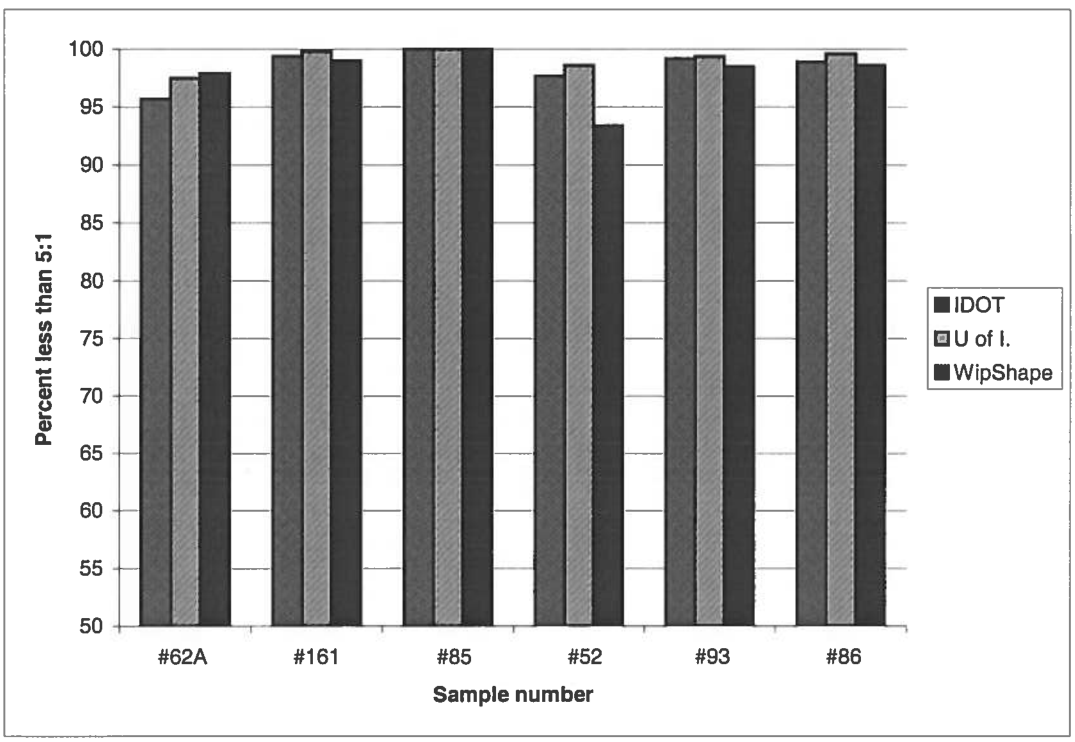


Figure 15. Results of University of Illinois study for 6 aggregate samples, measuring 3:1 ratio (top) and 5:1 ratio (bottom). Measurements were made using proportional caliper first by the Illinois Department of Transport (IDOT), proportional caliper by the University of Illinois (U if I.), and then by University of Illinois using WipShape Imaging.

Sieve Size (passing)	Operator	Proportional Caliper Device			WipShape		
		Trial #1 (%)	Trial #2 (%)	**Repeat. (%)**	Trial #1 (%)	Trial #2 (%)	**Repeat. (%)**
19.0 mm (3/4")	ML	9.2	10.0	**1.64**	12.3	11.5	**1.57**
12.5 mm (1/2")	ML	8.9	9.3	**0.74**	4.7	5.9	**2.35**
19.0 mm (1/2")	YPH	6.1	5.4	**1.39**	9.1	8.9	**0.39**
12.5 mm (3/4")	YPH	5.4	5.7	**0.67**	4.9	5.3	**0.78**
19.0 mm (1/2")	SJ	4.2	3.7	**1.14**	9.7	9.5	**0.39**
12.5 mm (3/4")	SJ	5.1	5.4	**0.74**	4.5	4.3	**0.39**

Sieve Size (passing)	Operator	Proportional Caliper Device			WipShape		
				Reprod. (%)			**Reprod. (%)**
19.0 mm (3/4")	ALL			**8.18**			**4.64**
12.5 mm (1/2")	ALL			**6.01**			**1.30**

Figure 16. Repeatability and reproducibility study results, 3:1 ratio. (Lower repeatability and reproducibility indicates more precise measurements.

2.2.2 Samples

In all, 143 sacks of samples were for potential F&E testing (Appendix 1), along with data on rock type, formation, and crushing method where appropriate. Testing was done first on control samples, and then on larger bulk samples.

2.2.3 Control sample tests

2.2.3.1 Control samples

For the purpose of developing control samples, samples were made from crushed rock sizes #4, 3/8", 1/2", 3/4", and 1", with aspect ratios of 2:1, 3:1, 4:1, 5:1, 18 samples in all (Appendix 2). The sizes were determined by screening and the aspect ratios by proportional calipers.

2.2.3.2 Results

Test results (Figure 17) reveal that there are some differences in the image measured results and those of the proportional caliper. This is not unexpected as differences in the measuring methods would be expected to result in slightly different measurement results.

Overall, on average, by weight, 74% of the sample rocks were classified in the correct shape class. 22% were classified in a shape class that was too low, while 2.9% were classified in a shape class that was too high.

This shows a systematic bias toward under-representation of F&E, and the causes of this bias was removed for the testing of the bulk samples.

Screening and Caliper Measurements		Imaging Measurements			
Size "	Ratio	2:1 %	3:1 %	4:1 %	5:1 %
1	2:1	100.0			
3/4	3:1	25.0	75.0		
3/4	2:1	81.4	18.6		
1/2	5:1		8.1	34.6	57.3
1/2	4:1		40.1	55.6	4.3
1/2	3:1	21.4	78.6	2.7	
1/2	2:1	90.0	10.0		
3/8	4:1		33.4	66.6	
3/8	3:1	27.0	66.4	6.6	
3/8	2:1	89.1	10.9		
#4	5:1			42.4	57.6
#4	4:1	2.4	56.7	40.9	
#4	3:1	13.1	77.7	9.2	
#4	2:1	94.2	5.8		

Figure 17. Flat and elongated testing results. The highlighted numbers represent the (correct) aspect ratios found with the manual caliper.

2.2.4 Bulk sample tests

2.2.4.1 Bulk samples

For the purpose of testing, 20 samples were tested both with proportional caliper (flat and elongation test by ASTM D4791) and using the imaging system. In all, 56,926 pieces were tested, with an average of 2856 pieces per sample. It should be noted that the amount of material tested under the imaging method was considerably more than the manual caliper method. When performing imaging measurements, the entire amount of aggregate retained on each sieve was measured. When performing the manual caliper test, only one hundred particles from each sieve were tested. This is the most likely answer for the differences in percentages between imaging and the manual testing. The purpose of only testing a hundred particles of the entire sample is to save time and money from testing. The amount of time it takes to test at one ratio manually is approximately twenty minutes. This does not include running a gradation on the material to separate the material down to the individual fractions. What this time does include is splitting the size fraction down to a hundred-particle testing sample, and running the sample through the caliper at the desired ratio, then weighing the amounts of flat and elongated particles, and finally calculating the flat and elongation percentages. The amount of time may vary depending on the experience of the operator performing the test, and the type of aggregate being tested. For example it may take less time if testing uncrushed gravel, compared to a crushed stone, because there are noticeably fewer flat and elongated particles without actually running each individual piece through the caliper. WipShape could take the same hundred-particle sample and test each piece in considerably less time and determine the percentages for flat and elongation for all ratios. ASTM recommends reducing each individual sieve fraction of the sample down to approximately 100 particles by rifle splitting to acquire a "representation" of the whole sample when performing the manual caliper tests. While using the imaging system the splitting was not performed, and the whole sample was tested with the video analysis system. Further testing is suggested to show that the splitting down to approximately 100 particles may not result in an adequate representation of the entire sample, thus resulting in the need to test the entire sample. This testing would be highly cumbersome using a manual caliper rather than a video analysis measuring system.

2.2.4.2 Results

Test results are presented in Appendix 3 and Figures 18-22. Test results reveal in general good agreement between proportional caliper results and WipShape results.

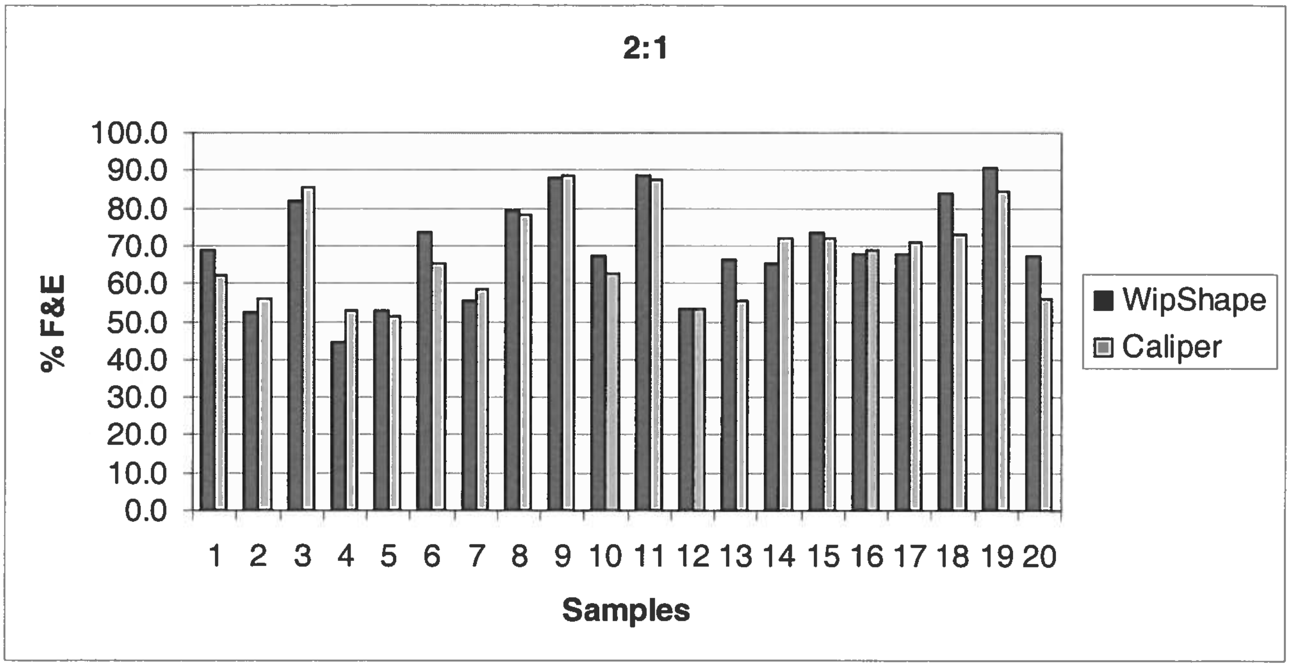


Figure 18. Comparison of WipShape and proportional caliper results, 2:1 aspect ratio, sample numbers correspond to sample numbers in Appendix 3.

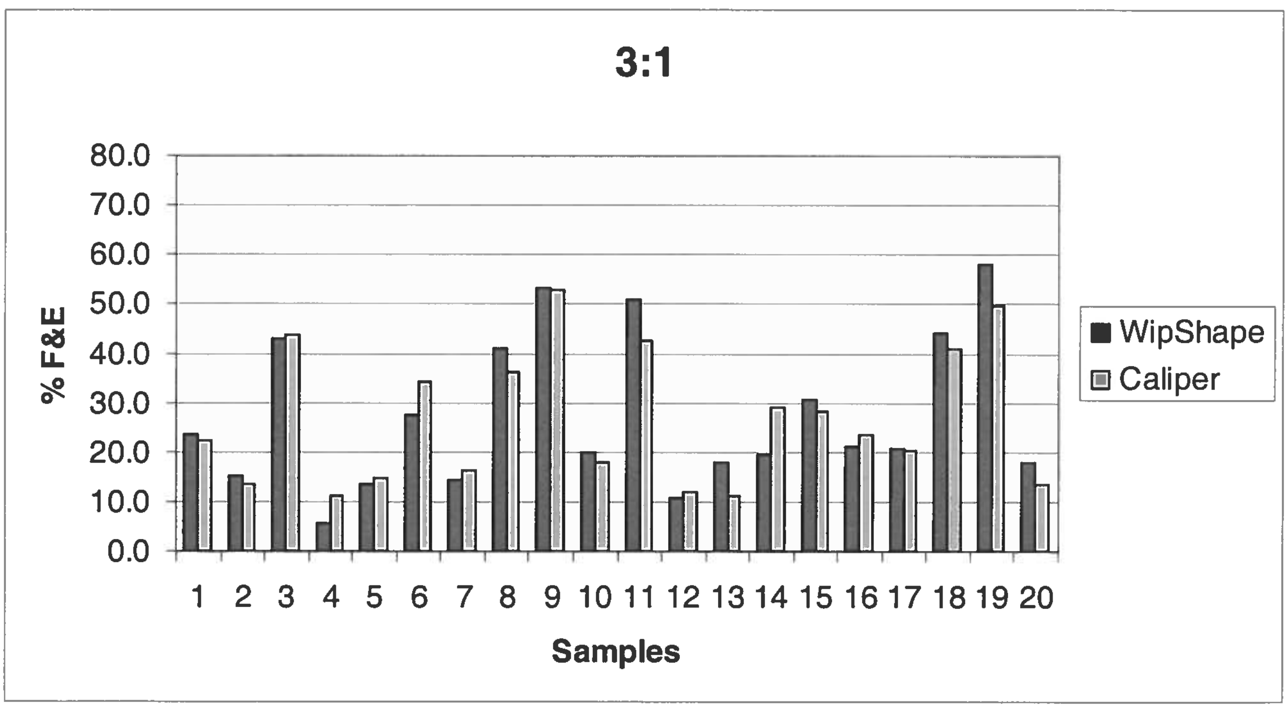


Figure 19. Comparison of WipShape and proportional caliper results, 3:1 aspect ratio, sample numbers correspond to sample numbers in Appendix 3.

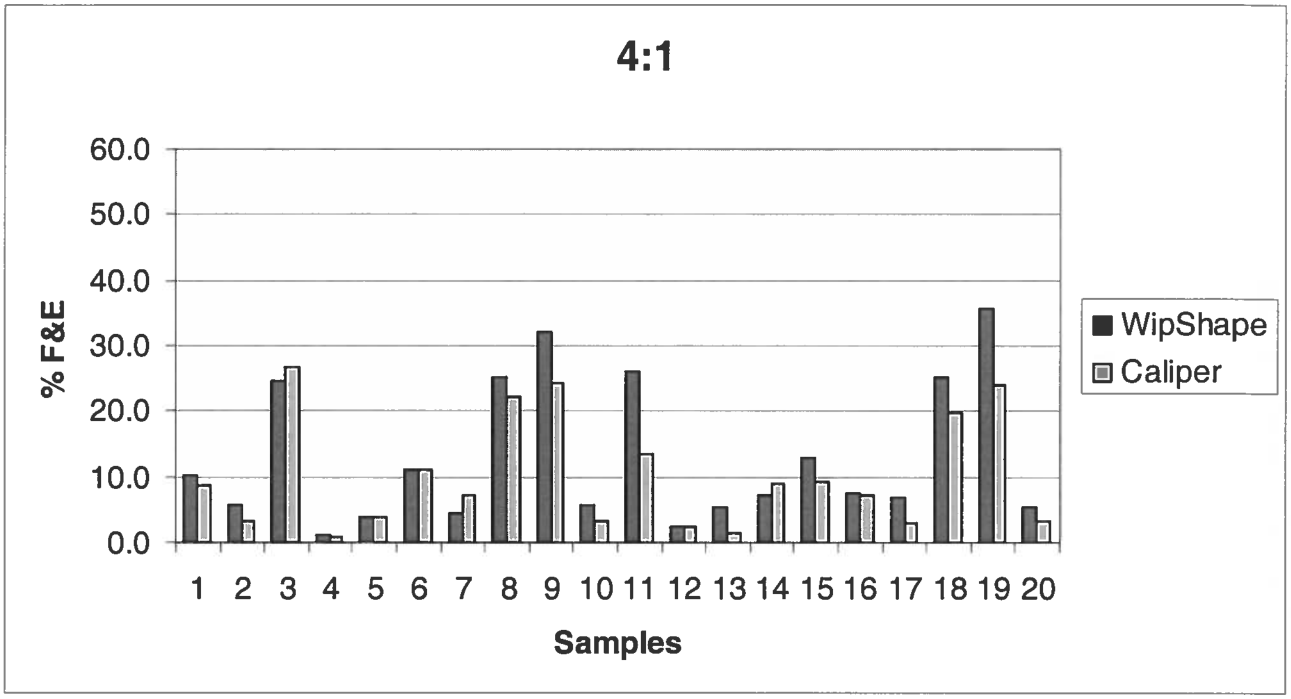


Figure 20. Comparison of WipShape and proportional caliper results, 4:1 aspect ratio, sample numbers correspond to sample numbers in Appendix 3.

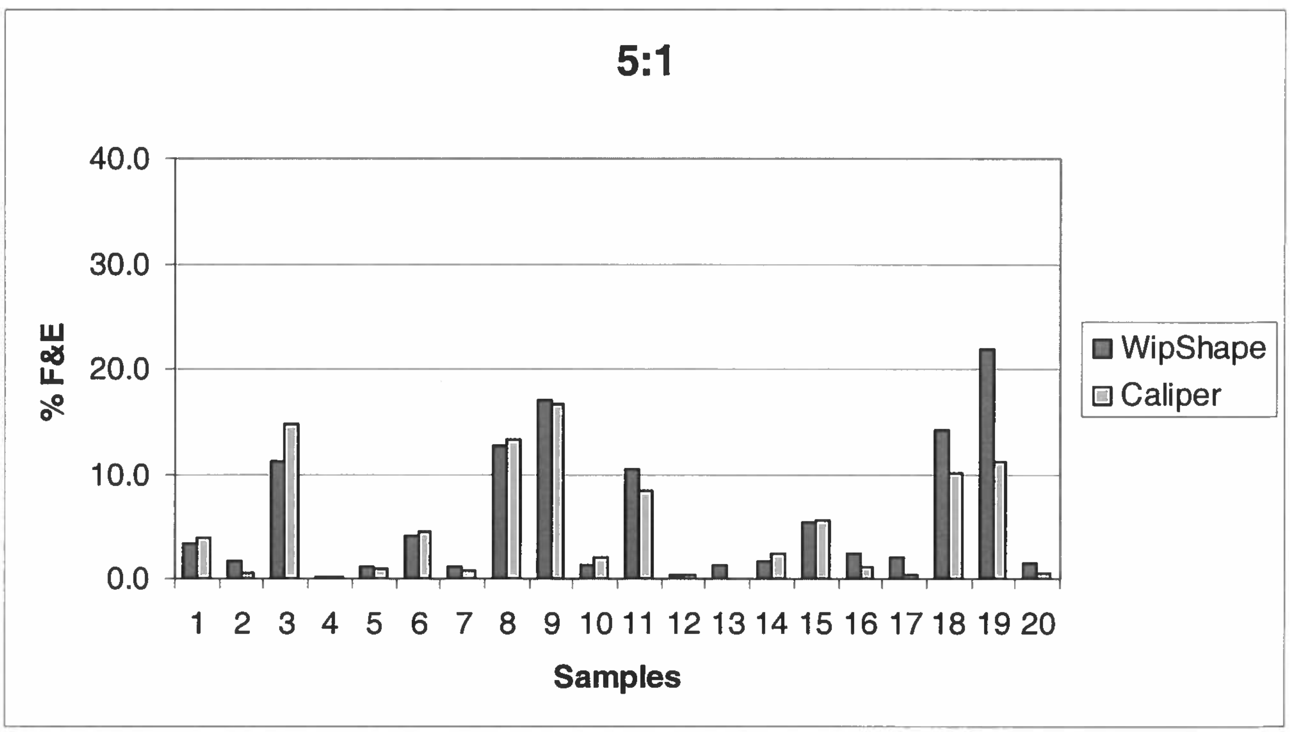


Figure 21. Comparison of WipShape and proportional caliper results, 5:1 aspect ratio, sample numbers correspond to sample numbers in Appendix 3.

The testing was done on individual size fractions, and consequently a %F&E was acquired for each of the 2:1, 3:1, 4:1, and 5:1 ratios. The equation below was used to find the overall % F&E for the entire sample:

$$\% \text{ F\&E, weighted avg.} = \Sigma\ (\% \text{ F\&E}_{sieve\_size})/(\text{Fraction Indiv. Retained \#4 sieve})$$

The results (Figure 22) show that on the 3:1 and 5:1 ration WipShape overestimates and underestimates caliper results almost equally. The average error on the 3:1 is about 0.05%, while on the 5:1 it is about 0.12%. Errors or differences can be expected, because the two measurement techniques are so dissimilar. Figure 23 shows an example where a curved aggregate piece will measure 4:1 with a proportional caliper and 5:1 using optical imaging.

Ratio
# of times WipShape Overestimated:
# of times WipShape Underestimated:
# of times WipShape was exactly the same as manual:

2:1
8
9
0

3:1
9
8
0

4:1
11
4
2

5:1
8
8
1

Ratio
Smallest % difference:
Largest % difference:
Average % difference:

2:1
0.3%
11.0%
0.28%

3:1
0.1%
9.3%
0.05%

4:1

0.0%
12.6%
2.04%

5:1
0.0%
3.5%
0.12%

Figure 22: Analysis of testing results.

Figure 23. This is an example of an aggregate piece (left) which has an intermediate diameter of 1" (as measured by an imaging system) but will pass though a ¾" screen diagonally because it is so thin (center). The aspect ratio as measured by imaging is 4:1, but it will pass through the proportional caliper at a 5:1 setting (right), because it is curved and can be rotated through the opening.

2.2.5 Relationship between crusher type and F&E

2.2.5.1 Effect of crusher type on flat and elongated tendencies

The particle shape of the finished rock product is a function of geologic factors (such as bedding, geologic structure, and grain size), blast patterns, type of crusher, and operational parameters of the crusher. The common wisdom is that a more cubical shape is produced by (in order of merit): impact crushers, roll crushers, and cone crushers (which tend to produce a more flat and elongated shape). Vertical shaft impactors (VSI) seem the best choice to produce a cubical shape. No universal absolute statements can be made because of the interaction of type of rock with crusher characteristics (34- 36).

Additionally, the operational parameters of the crusher can offset the effect of crusher type to a certain extent. For instance, in regard to cone crushers, methods to enhance particle shape include use of choke feeding, higher speed-smaller throw machine, surge bins, automatic feed controls, re-crushing at lower reduction ratios and higher recirculation loads, and a uniform feed material size proportion less than 4:1 (37, 35-26).

Figure 24 shows a summary of the manual flat and elongated (F&E) results as a function of secondary crusher type (cone, impact, hammermill, roll, VSI), geologic type (limestone, dolomite, porphry), formation, quarry, fraction (1, ¾, ½, 3/8 in.), and testing ratio (2:1, 3:1, 4:1, 5:1). F&E results are influenced to a great extent by the size of the aggregate fraction, with F&E increasing as particle size decreases. For each fraction size, Figures 25-29 show the effect of testing ratio, rock characteristics, and crusher type. As can be seen, percent F&E decreases with increasing testing ratio. Beyond that, it becomes more difficult to make comparisons. There were no direct comparisons of a crusher type using aggregate from the same pit, although there was a case of the Plattin limestone (different pits) being crushed by both cone or VSI crushers. In most cases, cone crushers gave higher F&E results than VSI crushers, as expected. The effects of cone vs. hammermill vs. impactor vs. roll were obscured by indeterminate factors such as the interaction of rock source and type with blast and crusher operation. In general, porphry tended to have the greatest F&E results, while limestones and dolomites were similar.

Crusher	Geologic Type	Formation	Quarry	Fraction(in.)	2:1	3:1	4:1	5:1
Cone	Limestone	Burlington	Rocky Fork	1	62.3	9.9	1.2	0.1
		Higginson	Butler	3/4	62.9	18.8	7.6	1.8
				1/2	85.3	43.7	26.7	14.7
		Plattin	Bussen	3/4	51.2	14.7	3.9	1
				3/8	65.4	34.4	11	4.4
		Warsaw	Joplin	1	48.6	9.8	2.5	0.6
				3/8	80.3	40.4	15.3	4.8
		Avg			65.1	24.5	9.7	3.9
Cone	Dolomite		Linn Creek	1/2	62.2	22.1	8.7	4
		Gasconade	Poplar Bluff	3/4	68.4	27.5	12	5
		Avg			65.3	24.8	10.4	4.5
Cone	Porphry		Iron Mtn.	1/2	72.9	40.8	19.8	10.1
			Piedmont	3/4	84.3	49.9	23.9	11.2
		Avg			78.6	45.4	21.9	10.7
Hammermill	Limestone	St. Louis	Weber South	3/4	69.1	23.5	7.2	1.1
				3/8	70.9	20.1	3	0.3
		Avg			70.0	21.8	5.1	0.7
Impactor	Dolomite	Cotter	Baily-Roach	7/8	53.1	11.2	1.0	0.2
Roll	Dolomite	Jefferson City	Couch	3/4	58.6	16.4	7.1	0.8
				3/8	78.2	36.3	22.3	13.2
		Avg			68.4	26.4	14.7	7.0
VSI	Limestone	Plattin	Cape Girardeau	3/4	54.3	10.7	1.5	0.3
				7/16	72.9	20.1	3.0	0.3
	Porphry		Pea Ridge	1/2	56.2	13.5	3.2	0.6

Figure 24. F&E ratios as a function of crusher type and rock type, manual measurements.

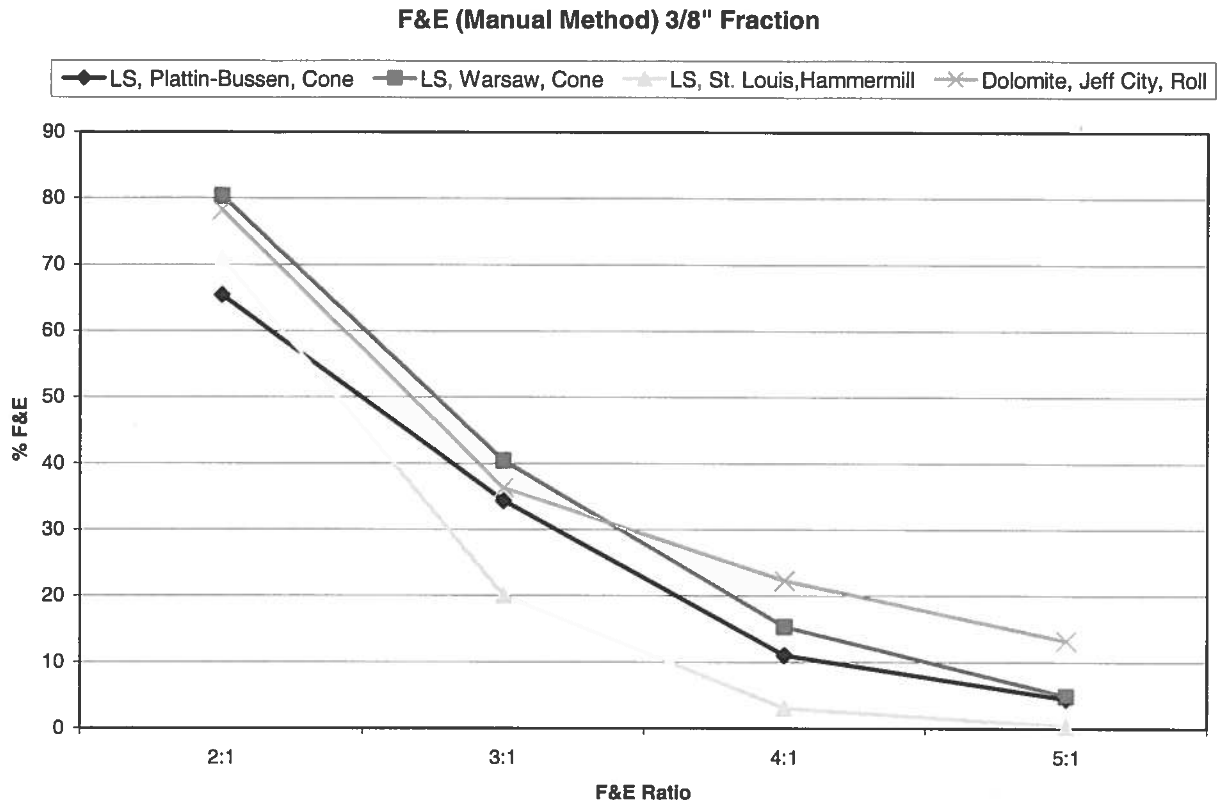


Figure 25. F&E ratios as a function of crusher type and rock type, manual measurements, 3/8" fraction.

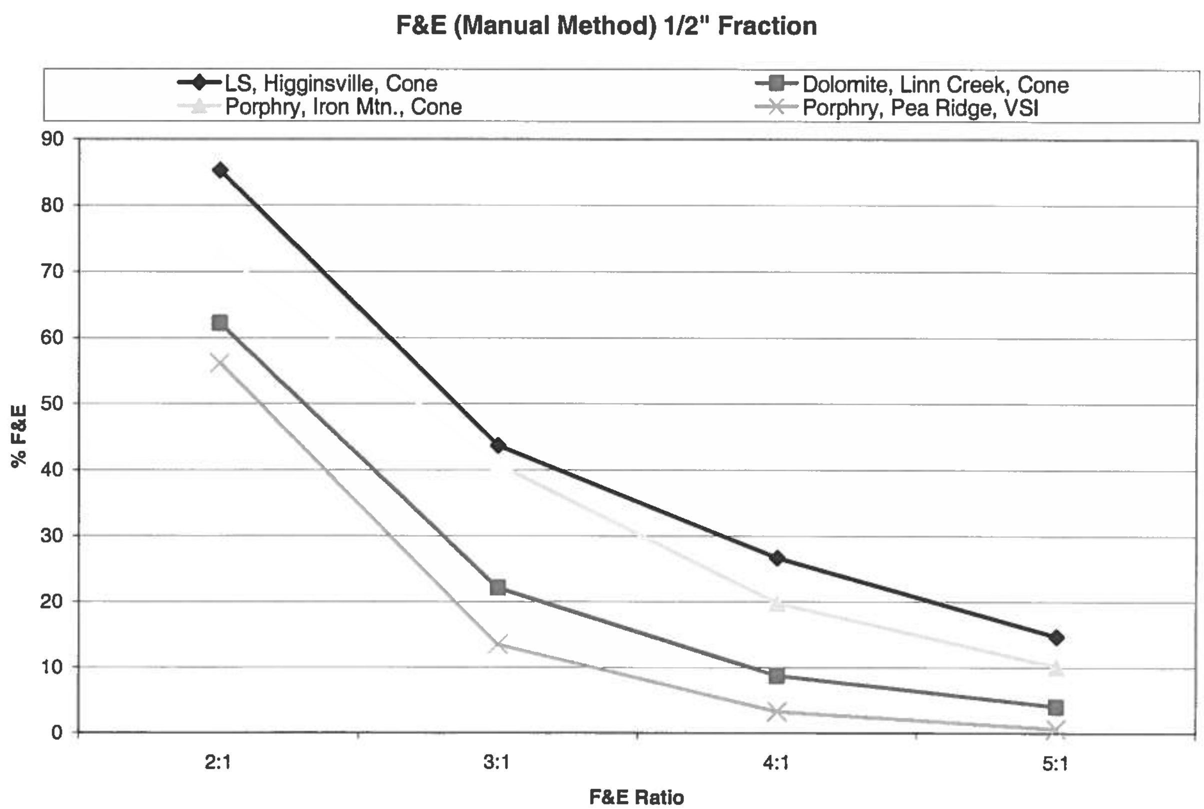


Figure 26. F&E ratios as a function of crusher type and rock type, manual measurements,1/2" fraction.

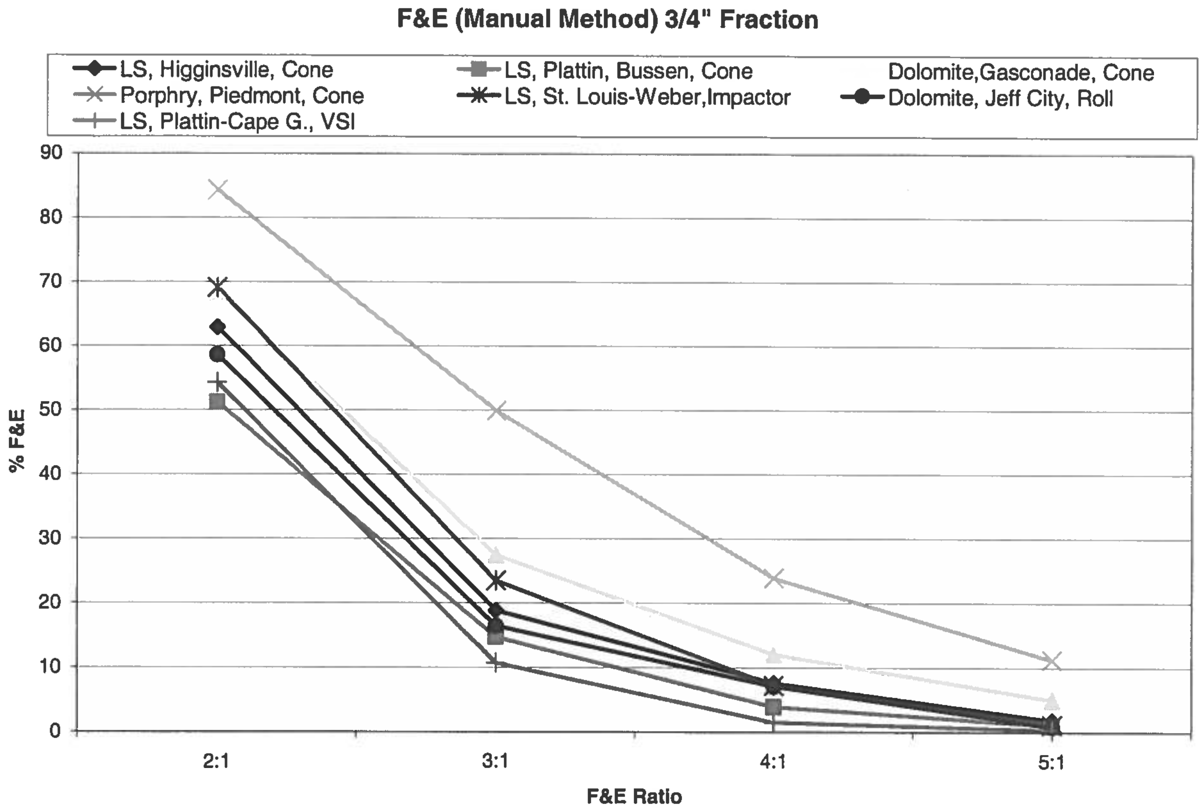


Figure 27. F&E ratios as a function of crusher type and rock type, manual measurements, 3/4" fraction.

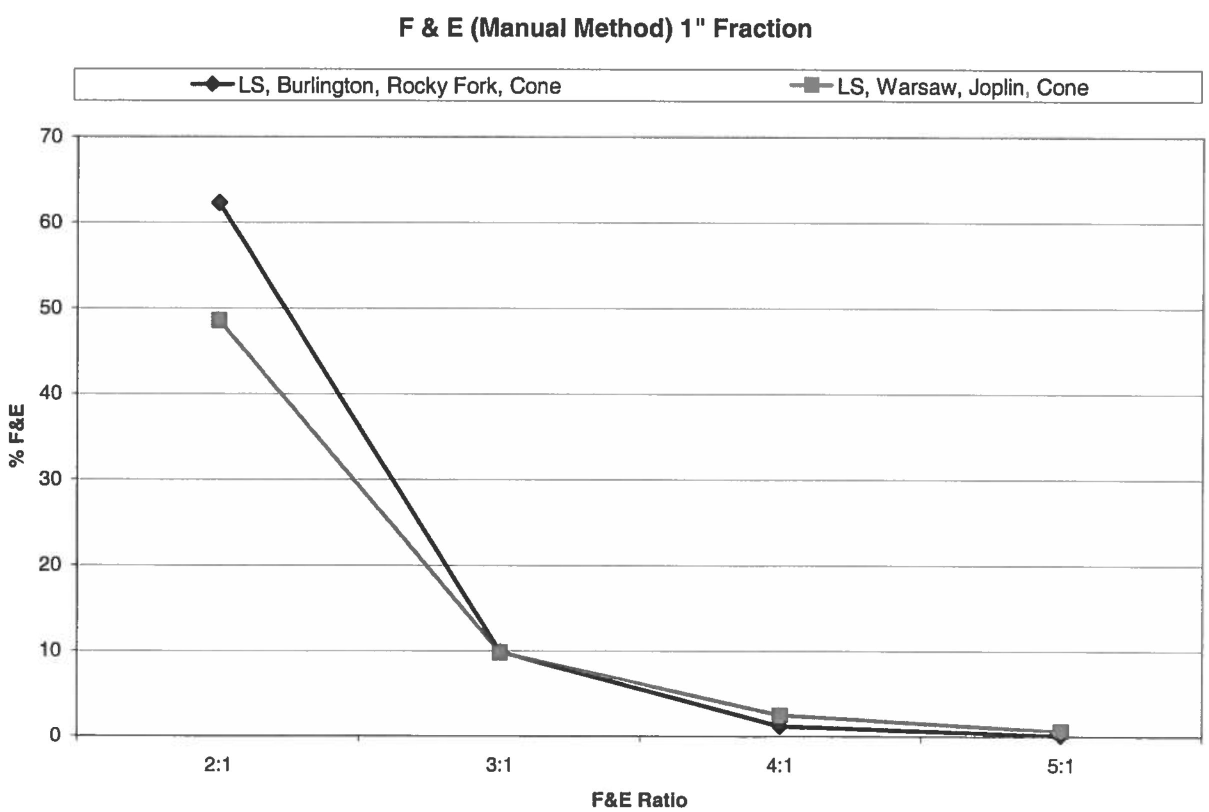


Figure 28. F&E ratios as a function of crusher type and rock type, manual measurements,1" fraction.

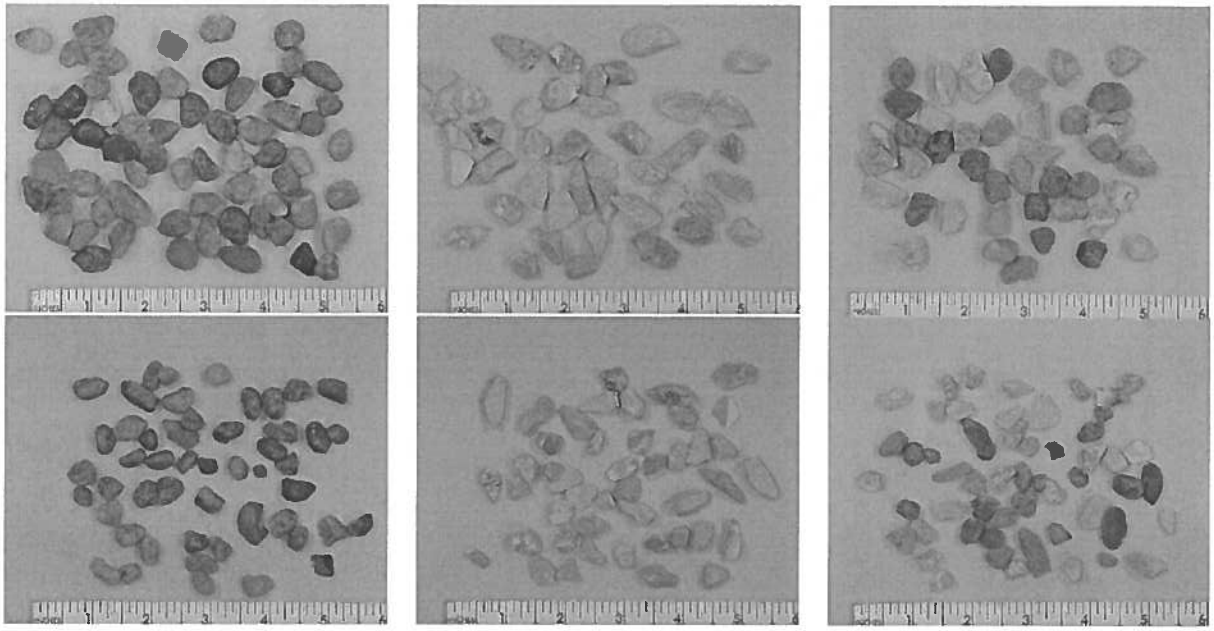


Figure 29. Control samples for shape testing. Top row: 3/8" material. Bottom row: #4 material. Left: semi-rounded river gravel. Center: Angular crushed limestone. Right: 50%/50% mix of river gravel and crushed limestone. Scale in picture is in inches.

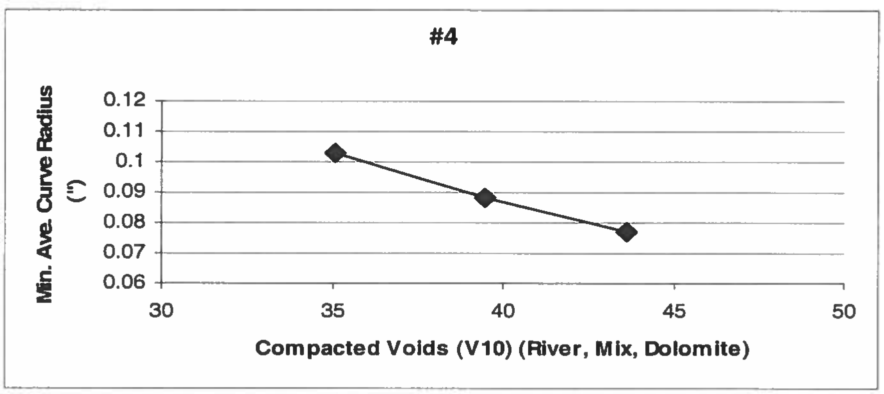


Figure 30. Typical relationship between manual testing (Compacted voids test, 10 blow), and minimum average curve radius as reported by WipShape. Data for #4 control samples, river gravels, mix, and crushed dolomite. Complete results are found in Appendix xxx.

2.3 SHAPE STUDIES

2.3.1 Shape Tests

For the purposes of this investigation, the following tests were conducted on various samples, to be compared with the minimum average curve ratio:

1. Uncompacted voids.
2. Compacted voids.
3. Crush counts

A reasonable correlation between voids tests and angularity as defined by curve radius would verify the assumption that voids and angularity are correlated.

2.2.2 Samples

In addition to the crushed rock samples, obtained for the F&E testing, river gravels were obtained to provide aggregates that would be more rounded (Appendix 1).

2.2.3 Control sample tests

2.3.3.1 Control Samples

For the purpose of testing the algorithms, simple control samples were made (Figure 29). For each of the 3/8" and #4 sieve sizes, samples were obtained for both a river gravel (rounded particles) and a crushed rock (angular). For each, a mixture of 50% river gravel and 50% crushed rock (by weight) was assembled.

2.3.3.2 Testing

Test measurements of minimum average curve radius were conducted and compared to physical laboratory tests of uncompacted voids (AASHTO Designation TP56-99), compacted voids (ASTM D3398-00) and crush counts.

2.3.3.3 Results

The results of the testing show that the imaging measurements of minimum average curve radius appears to be a good predictor of uncompacted voids, compacted voids, and crush counts (Figure 30, Appendix xxx). Further analysis indicates that there may be a very good correlation between uncompacted voids, compacted voids and crush counts (Appendix xxx).

2.3.4 Bulk sample tests

2.3.4.1 Control Samples

For each of the 3/", ½", 3/8" and #4 sizes, samples were obtained and tested three times each with WipShape and two times each with both uncompacted voids (AASHTO Designation TP56-99) and compacted voids tests (ASTM D3398-00) (Appendix xxx).

2.3.4.2 Results

Results of testing the bulk samples reveal in general a linear relationship between the physical tests (uncompacted or compacted voids) and the minimum average curve radius. As before the compacted and uncompacted voids tended to give similar results. The best results were obtained from the #4 and 3/8" material (Appendix xxx). For the 1/2" material, the Missouri River gravel measurement showed an unusually high minimum average curve radius, while the rest of the data was clumped at the other end of the scale. Increased slope indicates that there is perhaps some non-linearity present at the lower void ratios, however there were not enough samples at this end of the scale to get conclusive results. For the 3/4" material, only two samples were tested, and thus the results were inconclusive.

Repeatability

Measuring the repeatability of the various tests (Figure 31) revealed that the best repeatability of all the tests was the compacted voids tests, followed by the uncompacted voids tests, and finally the minimum average curve radius tests. Figure 31 shows a normalized reproducibility, which, for the purpose of comparison, is the calculated reproducibility divided by the mean value of either void ratio or minimum average curve ratio.

In all cases the repeatability is fairly good, although the variability for the imaging measurements were found to be about twice as high as for the uncompacted voids test. The repeatability of the minimum average curve radius was worst for the smallest (#4) fraction. The repeatability of the voids tests was worst for the 3/8" fraction. The repeatability for voids test would be expected to get worse with increasing grainsize, as with larger particles the act of leveling out the final surface would be more difficult with the larger grainsize.

	Min. Ave. Curve Radius	Uncompacted Voids	Compacted Voids (V10)	Compacted Voids (V50)
(#4)				
Canadian Limestone	0.1090	0.0239	0.0044	0.0046
Maramec River	0.0774	0.0128	0.0047	0.0000
Osage River	0.0784	0.0043	0.0048	0.0000
Iron Mt Porphyry	0.0431	0.0074	0.0040	0.0042
Average	*0.3079*	*0.0484*	*0.0180*	*0.0089*
(3/8")				
Canadian Limestone	0.0350	0.0358	0.0341	0.0357
Higginsville Limestone	0.1032	0.0495	0.0408	0.0725
Maramec River	0.0902	0.0344	0.0228	0.0235
Little Piney River	0.0565	0.0199	0.0175	0.0368
Average	*0.2850*	*0.1397*	*0.1151*	*0.1685*
(1/2")				
Canadian Limestone	0.0173	0.0280	0.0043	0.0185
Higginsville Limestone	0.0516	0.0357	0.0044	0.0000
Maramec River	0.0435	0.0509	0.0091	0.0047
Missouri River	0.0327	0.0420	0.0152	0.0106
Little Piney River	0.0636	0.0869	0.0000	0.0000
Average	*0.0418*	*0.0487*	*0.0066*	*0.0068*
(3/4")				
Maramec River	0.0466			
Little Piney River	0.1583			
Average	*0.0776*			
Overall Average	***0.0671***	***0.0332***	***0.0128***	***0.0162***

Figure 31. Ratio of reproducibility to average value of void ratio *or* minimum average curve ratio

2.3.5 Fine aggregate demonstration

As part of this project, a demonstration of measuring fine aggregate was done. No attempt was made to produce a transport and presentation mechanism, rather particles were put on a light table, imaged from two directions, and the images input for analysis into the WipShape software.

For this demonstration, manufactured sand consisting of iron mountain traprock was used. Samples were considered to be "medium sand", retained on a #16 screen. An example is shown if Figure 32 where a piece about 0.14" in length (nominal size of about 0.75") is analyzed.

The analysis is shown in Figure 33, showing it to have an aspect ratio of 2:1, and a minimum average curve radius of 0.0002" (0.005 mm).

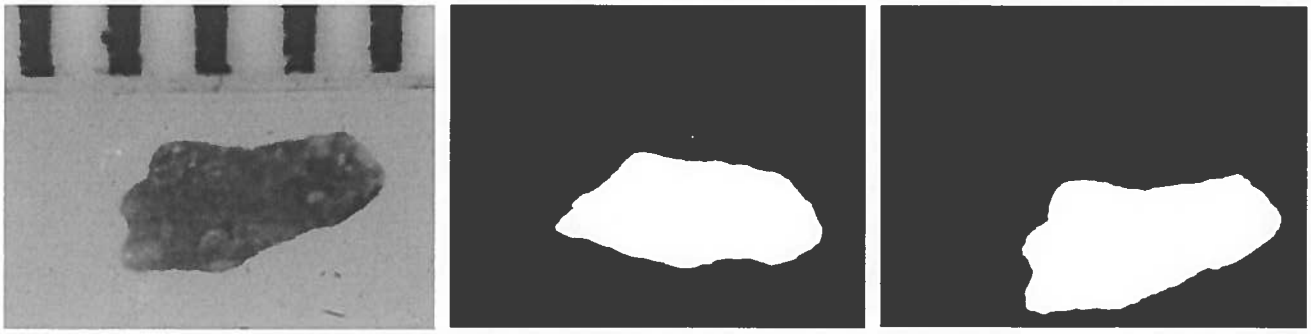


Figure 32. Left: Image of a piece of manufactured medium sand (retained on #16 screen) (Scale of image is in mm). Center: Plan view. Right: Profile view.

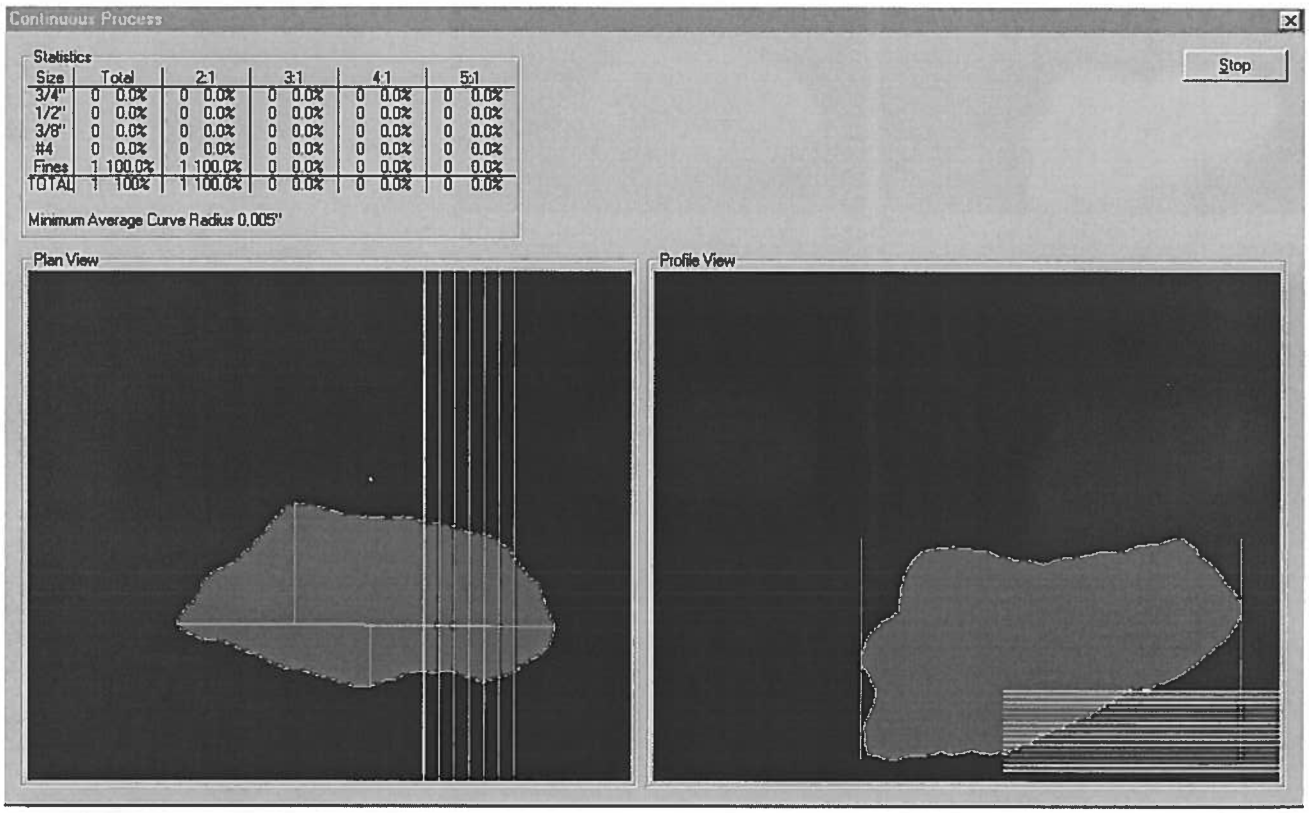


Figure 33. WipShape analysis, revealing an aspect ratio of 2:1 and a minimum curve radius of 0.005".

2.4 Plans For implementation

The results of this investigation are published here and will be as well in journal articles and conference proceedings. The produce, although currently in prototype form is available for marketing.

3. CONCLUSIONS

The results of this investigation have advanced the state of the art in measuring aggregate shape using image analysis. This study resulted in:

1. Finding deficiencies with the existing system, including the need for backlighting, faster speed, higher resolution, and the need for angularity measurements. These deficiencies are corrected by the manufacturer.
2. Demonstrating that the technology could be used for sand-sized aggregates with the proper modifications.
3. Comparison of manual and imaged flat and elongation measurements, demonstrating the efficiency, accuracy, and repeatability of the imaging method.
4. Comparison of manual voids tests (commonly referred to as angularity tests) and the angularity as measured by the imaging method, demonstrating the efficiency, accuracy, and repeatability of the imaging measurement.
5. Analysis of the flat and elongation measurements as a function of crusher type showed that impact type crushers tend to produce more cubical particles, even when rock type is not accounted for.

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APPENDIX 1. SAMPLES OBTAINED

F&E SAMPLES

Source: APAC (Linn Creek, MO)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
1 1/2" Dolomite		Impactor	2
1" Dolomite		Impactor/Cone	2
3/4" Dolomite		Impactor/Cone	2
1/2" Dolomite		Impactor/Cone	2
3/8" Dolomite		Impactor/Cone	2
Manufactured Sand Dolomite		Cone	2
		Total No. of Sacks =	12

Source: APAC (Rocky Fork, Columbia, Till Smith Plant)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
1"	Burlington	Impact/Cone	2
3/4" - 3/8"	Burlington	Impact/Cone	2
1/2"	Burlington	Impact/Cone	2
3/8"	Burlington	Impact/Cone	2
Manufactured Sand	Burlington	Impact/Cone	2
		Total No. of Sacks =	10

Source: Ash Grove Agg. (Butler, MO)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
2" Rock	Higgensville	Primary - Impactor	
	Limestone	Secondary - Cone	2
3/4" Rock	Higgensville	Primary - Impactor	
	Limestone	Secondary - Cone	2
1/2" Seal Coat	Higgensville	Primary - Impactor	
	Limestone	Secondary - Cone	2
		Total No. of Sacks =	6

Source: Ash Grove Agg. (Marshfield)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
3/4" S.P.			2
1/2" S.P.			2
1/2" S.P. Surface level			2
S.P. Manufactured Sand			2
		Total No. of Sacks =	8

Source: Bailey (Roach), Chesepeake, MO

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
7/8" Concrete Rock	Cotter	Primary - Jaw	
	Dolomite	Secondary - Impactor	2
1/2"	Cotter	Primary - Jaw	
	Dolomite	Secondary - Impactor	2
5/16"	Cotter	Primary - Jaw	
	Dolomite	Secondary - Impactor	2
3/16"	Cotter	Primary - Jaw	
	Dolomite	Secondary - Impactor	2
		Total No. of Sacks =	8

Source: Bingham S&G (Picher, Oklahoma)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
Manufactured Sand			2
		Total No. of Sacks =	2

Source: Bussen Antire Quarry (Antire Rd. St. Louis, MO)

Product w/grade & size:	Ledges:	Crusher Type:	#Sacks:
1" Asphalt Stone (Plattin Limestone)	12 - 14	Primary - Impact	
		Secondary - Cone	2
3/4 " Asphalt Stone (Plattin Limestone)	12 - 14	Primary - Impact	
		Secondary - Cone	2
3/8 " Asphalt Stone (Plattin Limestone)	12-14	Primary - Impact	
		Secondary - Cone	2
Screenings (Plattin Limestone)	12 - 14	Primary - Impact	
		Secondary - Cone	1
Screenings (Plattin Limestone)	10 - 12	Impact	
			1
		Total No. of Sacks =	8

Source: Conco Quarry (Willard, MO)

Product w/grade & size:	Ledges:	Crusher Type:	#Sacks:
3/4"			2
1/2"			2
		Total No. of Sacks =	4

Source: Doss & Harper @ Couch

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
#4 Nom. Max. Size	Jeff City Dolomite	Roll Plant	1
3/4" Nom. Max. Size	Jeff City Dolomite	Roll Plant	2
3/8" Nom. Max. Size	Jeff City Dolomite	Roll Plant	2
		Total No. of Sacks =	5

Source: Holt Const. & Rock (Bolivar, MO)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
3/8"			**2**
		Total No. of Sacks =	2

Source: Hunt Midwest @ Randolph

Product w/grade & size:	Ledge:	Crusher Type:	#Sacks:
1 1/2" Superpave	1A-3	Primary - Impactor	
	Bethany Falls	Secondary - 3 Roll & 2 Cone	2
1" Superpave	1A-3	Primary - Impactor	
	Bethany Falls	Secondary - 3 Roll & 2 Cone	2
3/4" Superpave	1A-3	Primary - Impactor	
	Bethany Falls	Secondary - 3 Roll & 2 Cone	2
3/8" Superpave	1A-3	Primary – Impactor	
	Bethany Falls	Secondary - 3 Roll & 2 Cone	2
		Total No. of Sacks =	8

Source: Iron Mt. Trap Rock (Iron Mountain, MO)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
1" Clean Nom. Max. Size	Porphry	Primary- Jaw(3042 Keuken) Secondary - Cone(51" Keuken)	2
1/2" Clean Nom. Max. Size	Porphry	Primary- Jaw(3042 Keuken) Secondary - Cone(51" Keuken)	2
Manufactured Sand	Porphry	Primary- Jaw(3042 Keuken) Secondary - Cone(51" Keuken)	2
		Total No. of Sacks =	6

Source: Joplin Stone (Joplin, MO)

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
1 1/2" Superpave Rock	Warsaw	Primary - Impactor	
		Secondary - Cone	1
1" Concrete Rock	Warsaw	Primary - Impactor	
		Secondary - Cone	2
3/4" Superpave Rock	Warsaw	Primary - Impactor	
		Secondary - Cone	2
1/2" Superpave Rock	Warsaw	Primary - Impactor	
		Secondary - Cone	1
3/8" Superpave Rock	Warsaw	Primary - Impactor	
		Secondary - Cone	2
		Total No. of Sacks =	8

Source: Lafarge @ Pee Ridge

Product w/grade & size:	Formation:	Crusher Type:	#Sacks:
1/2" Nom. Max Size	Porphry	V.S.I	
3/8" Nom. Max Size	Porphry	V.S.I	2
#4 Nom. Max Size	Porphry	V.S.I	2
#8 Nom. Max Size	Porphry	V.S.I	2
		Total No. of Sacks =	8

Source: Lafarge (Warrenton, MO)

Product w/grade & size:	**Formation:**	**Crusher Type:**	**#Sacks:**
1"	Plattin		
I.D. # 13MA0454 & 13MA0491	Limestone		2
3/4" & 1/2"	Plattin		
I.D. # 13MA0454 & 13MA0492	Limestone		2
3/8"	Plattin		
I.D. # 13MA0456	Limestone		2
Manufactured Sand	Plattin		
I.D. # 13MA0457	Limestone		1
Manufactured Sand	Plattin		
I.D. # 13MA0459	Limestone		1
		Total No. of Sacks =	8

Source: Nap #2 Mt. Airy Dist. #2

Product w/grade & size:	**Ledge:**	**Crusher Type:**	**#Sacks:**
1" Fraction	1-4K	Jaw - Primary	
	Burlington/Keokuk	Impact 2 & Cone	2
1/2" Fraction	1-4K	Jaw - Primary	
	Burlington/Keokuk	Impact 2 & Cone	2
3/8" 100204..LD1	1-4K	Jaw - Primary	
	Burlington/Keokuk	Impact 2 & Cone	2
Manufactured Sand	1-4K	Jaw - Primary	
	Burlington/Keokuk	Impact 2 & Cone	2
		Total No. of Sacks =	8

Source: Quality Agg. Quarry @ Piedmont, MO

Product w/grade & size:	**Formation:**	**Crusher Type:**	**#Sacks:**
1" Clean		Primary - Jaw	
	Porphry	Final - Cone	2
3/4" Clean		Primary - Jaw	
	Porphry	Final - Cone	2
Manufactured Sand		Primary - Jaw	
	Porphry	Final - Cone	2
		Total No. of Sacks =	6

Source: SEMO Stone Co. Quarry (Cape Girardeau, MO)

Product w/grade & size:	**Formation:**	**Crusher Type:**	**#Sacks:**
1"	Plattin	Primary - Rotary Impactor	
	Limestone	Secondary - Horiz. Impactor	2
		Final - V.S.I	
3/4"	Plattin	Primary - Rotary Impactor	
	Limestone	Secondary - Horiz. Impactor	2
		Final - V.S.I	
7/16"	Plattin	Primary - Rotary Impactor	
	Limestone	Secondary - Horiz. Impactor	2
		Final - V.S.I	
3/16" (Manufactured Sand)	Plattin	Primary - Rotary Impactor	
	Limestone	Secondary - Horiz. Impactor	2
		Final - V.S.I	
		Total No. of Sacks =	8

Source: Vance Brothers (Joplin, MO)

Product w/grade & size:	**Formation:**	**Crusher Type:**	**#Sacks:**
3/8" Chat for Asphalt	Mining Chat	Screened	2
		Total No. of Sacks =	2

Source: Weber South Quarry (Baumgartner Rd. St. Louis, MO)

Product w/grade & size:	**Ledges:**	**Crusher Type:**	**#Sacks:**
1" Asphalt Stone (St. Louis Limestone)		Primary - Jaw	
	14 - 18	Secondary - Impact	2
		Tertiary - Hammermill	
3/4" Asphalt Stone (St. Louis Lmst.)		Primary - Jaw	
	14 - 18	Secondary - Impact	2
		Tertiary - Hammermill	
3/8" Asphalt Stone (St. Louis Lmst.)		Primary - Jaw	
	14 - 18	Secondary - Impact	2
		Tertiary - Hammermill	
Screenings (St. Louis Lmst.)		Primary - Jaw	
	14 - 18	Secondary - Impact	2
		Tertiary - Hammermill	
		Total No. of Sacks =	8

Source: Williamsville Stone #1 (Poplar Bluff, MO)

Product w/grade & size:	**Formation:**	**Crusher Type:**	**#Sacks:**
1" Nominal Max Size	Gasconade	Primary - Jaw	
	Dolomite	Final - Cone	2
3/4" Nominal Max Size	Gasconade	Primary - Jaw	
	Dolomite	Final - Cone	2
Manufactured Sand	Gasconade	Primary - Cone	
	Dolomite		2
		Total No. of Sacks =	6

Source:	Winter Bros. Gravel (Rte. 30 St. Louis, MO)		
Product w/grade & size:	**Formation:**	**Crusher Type:**	**#Sacks:**
5/8" Chips		Horizontal Impactor	
	--------		2
		Total No. of Sacks =	2

SHAPE SAMPLES

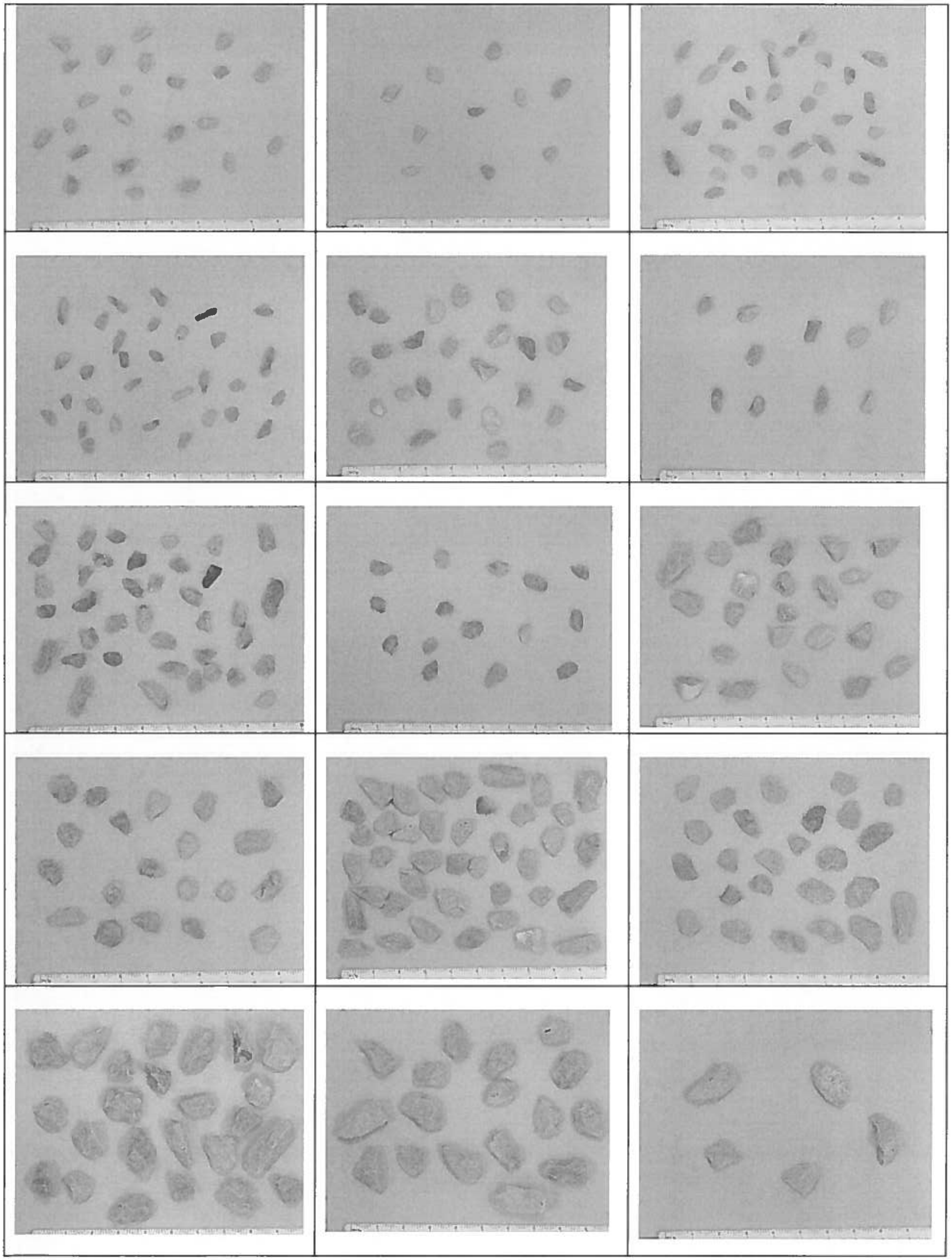
Additional Samples form Capital Quarries, Jefferson City, MO:

1" Missouri river gravel-uncrushed
7/16" Missouri river gravel-uncrushed
11/2" Osage river gravel-uncrushed
1" Osage river gravel-uncrushed
1/2" Osage river gravel-uncrushed
7/16" Osage river gravel-uncrushed
2 bags of crushed Osage river gravel (no size indicated)
7/16" Limestone/Dolomite from Hwy 63 quarry

Additional Samples form Winter Brothers Quarries, St. Louis, MO:

½" Meramec river gravel-uncrushed
1" Meramec river gravel - uncrushed

APPENDIX 2. CONTROL SAMPLES, F&E



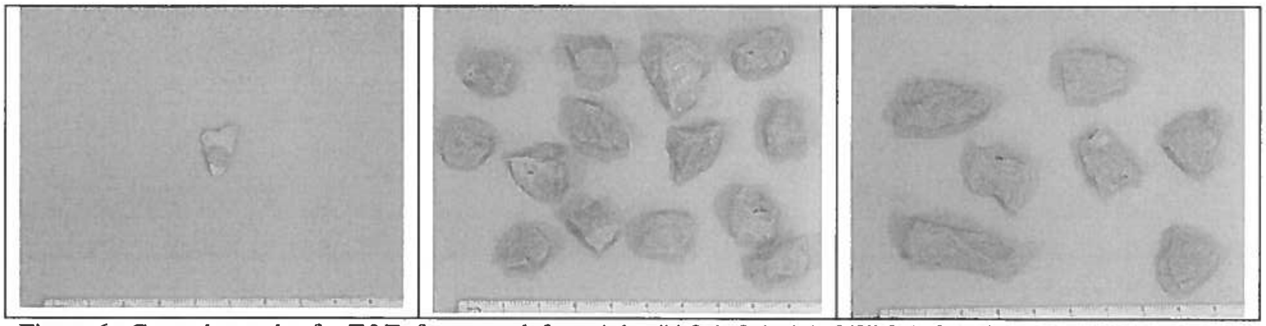


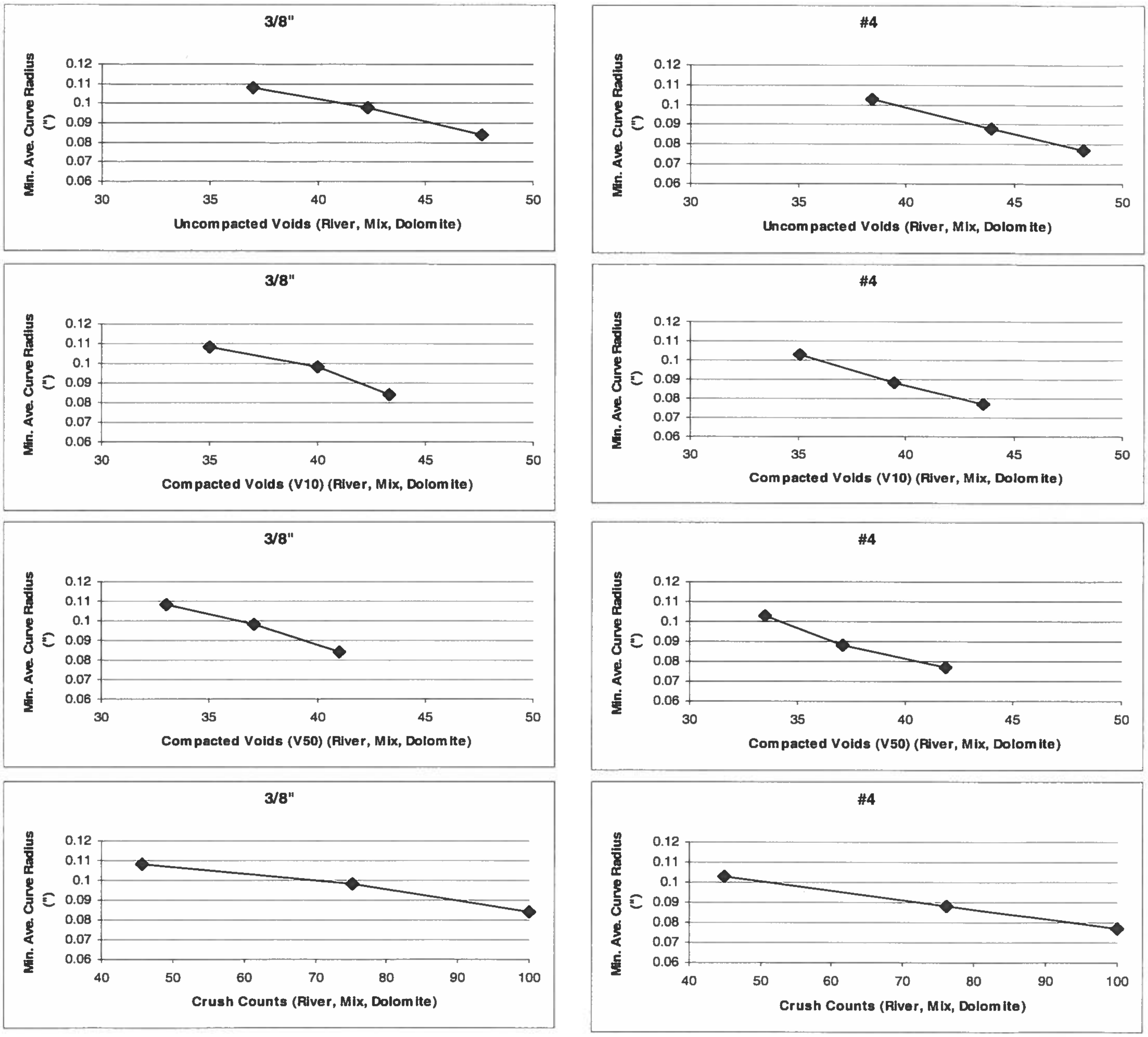
Figure 6: Control samples for F&E, from top, left to right: #4 2:1, 3:1, 4:1, 3/8" 2:1, 3:1, 4:1, 5:1, 1/2" 2:1, 3:1, 4:1, 5: 1, 3/4" 2:1, 3:1, 4:1, 5:1, 1" 2:1, 3:1. Scale in picture is in inches.

APPENDIX 3: FLAT AND ELONGATE SAMPLE MEASUREMENTS

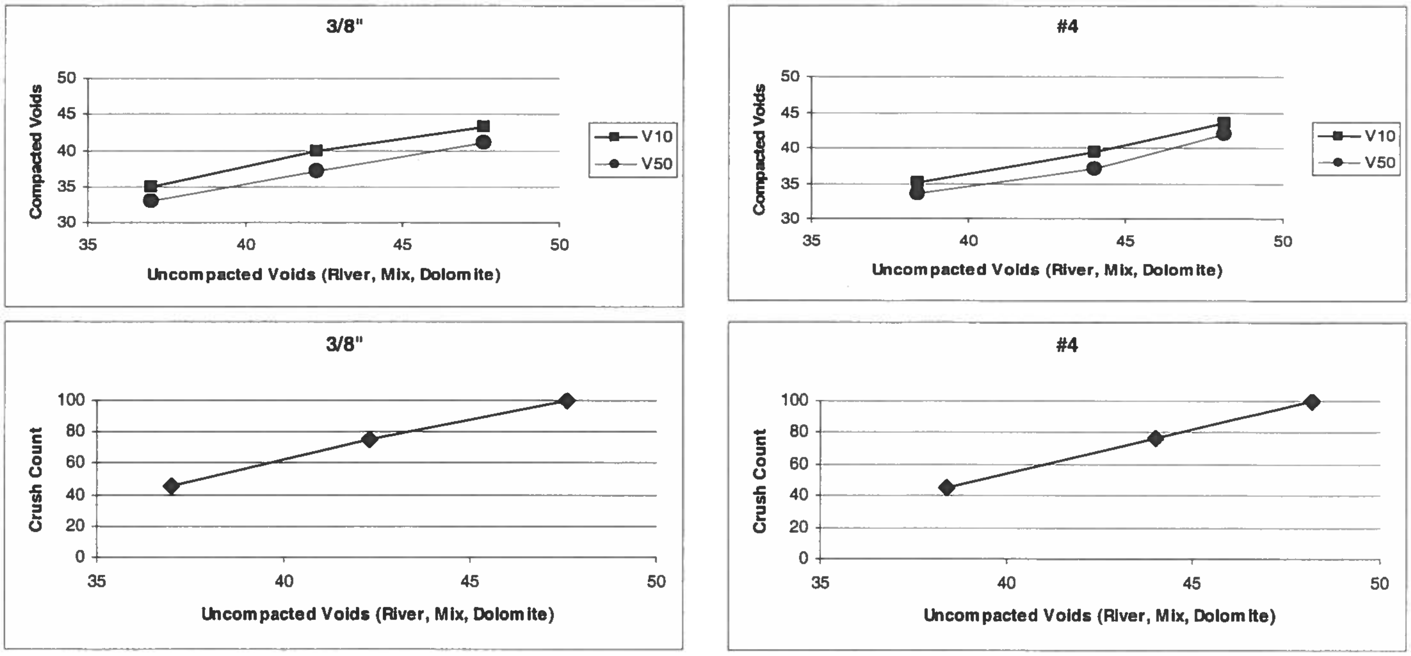
Sample		% F & E weighted average 2:1	3:1	4:1	5:1
APAC Linn Creek, MO 1/2" Dolomite	Caliper	62.2	22.1	8.7	4.0
	WipShape	68.8	23.3	10.1	3.4
2					
Ash Grove Agg., Butler MO 3/4" Rock, Higginsville Limestone	Caliper	56.2	13.5	3.2	0.6
	WipShape	52.6	15.3	5.8	1.7
3					
Ash Grove Agg., Butler MO 1/2" Seal Coat, Higginsville Limestone	Caliper	85.3	43.7	26.7	14.7
	WipShape	81.8	43.1	24.6	11.2
4					
Baily (Roach), Chesapeake MO (Sample #2) 7/8" Concrete Rock, Cotter Dolomite	Caliper	53.1	11.2	1.0	0.2
	WipShape	44.5	5.6	1.3	0.2
5					
Bussen Antire (St. Louis, MO), Plattin Limestone 3/4" Asphalt Stone	Caliper	51.2	14.7	3.9	1.0
	WipShape	52.6	13.6	3.8	1.1
6					
Bussen Antire Quarry, Antire Rd. St. Louis MO 3/8" Asphalt Stone, Plattin Limestone	Caliper	65.4	34.4	11.0	4.4
	WipShape	73.3	27.3	11.0	4.1
7					
Doss & Harper @ Couch 3/4" NMS, Jeff City Dolomite	Caliper	58.6	16.4	7.1	0.8
	WipShape	55.4	14.3	4.4	1.1
8					
Doss & Harper @ Couch 3/8" NMS, Jeff City Dolomite	Caliper	78.2	36.3	22.3	13.2
	WipShape	79.2	41.0	25.1	12.7
9					
Doss & Harper @ Couch # 4 NMS, Jeff City Dolomite	Caliper	88.4	53.1	24.4	16.7
	WipShape	88.0	53.2	32.0	17.1
10					
Hunt Midwest @ Randolph, 1A-3 Bethany Falls ¾" Super Pave	Caliper	62.9	17.8	3.3	2.0
	WipShape	67.3	19.9	5.6	1.3
11					
Hunt Midwest @ Randalph, 1A-3 Bethany Falls 3/8" Super Pave	Caliper	87.8	42.7	13.4	8.5
	WipShape	88.6	51.0	26.0	10.5
12					
Lafarge, Warrenton MO ¾" + 1/2" Plattin Limestone	Caliper	53.5	11.9	2.4	0.4
	WipShape	53.2	10.9	2.4	0.3
13					
Lafarge, Warrenton MO 3/8" Plattin Limestone	Caliper	55.4	11.1	1.6	0.0
	WipShape	66.4	18.1	5.5	1.4
14					
NAP # 2 Mt. Airy Dist. #2 ½" Fraction Ledge # 1-4K Burlington/Keokuk	Caliper	72.0	28.9	8.9	2.4
	WipShape	66.5	19.6	7.3	1.8

NAP # 2 Mt. Airy Dist. #2 3/8" Fraction Ledge # 1-4K Burlington/Keokuk	Caliper WipShape	71.8 73.9	28.4 30.6	9.3 12.3	5.6 5.5
16					
Weber South Quarry, Baumeartner Rd. St.LouisMO ¾" Asphalt Stone, St. Louis Limestone	Caliper WipShape	69.1 68.1	23.5 21.3	7.2 7.6	1.1 2.4
17					
Weber South Quarry, St. Louis MO 3/8" Asphalt Stone, St. Louis Limestone	Caliper WipShape	70.9 67.7	20.1 20.8	3.0 6.8	0.3 2.1
18					
Iron Mountain Trap Rock, Iron Mountain MO ½" Clean Porphry	Caliper WipShape	72.9 83.8	40.8 44.3	19.8 25.2	10.1 14.2
19					
Quality Aggregate, Piedmont MO ¾" Clean Porphry	Caliper WipShape	84.3 90.7	49.9 58.2	23.9 35.8	11.2 21.8
20					
Lafarge @ Pee Ridge ½" NMS Porphry	Caliper WipShape	56.2 67.6	13.5 18.0	3.2 5.5	0.6 0.6

APPENDIX 4: CONTROL SAMPLE ANGULARITY MEASUREMENTS



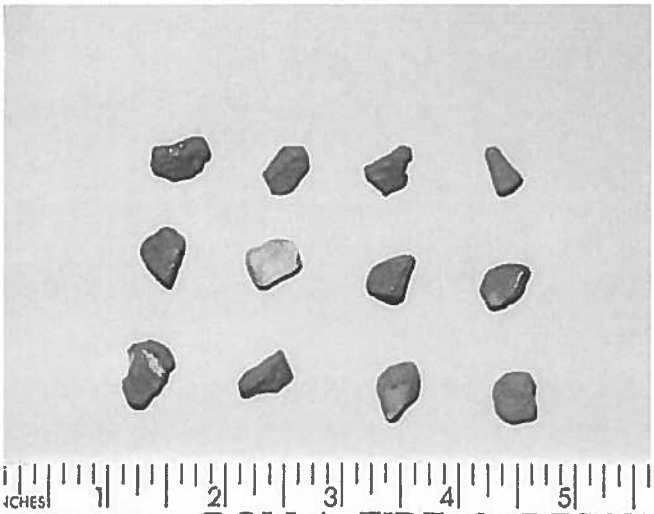
Relationship between Minimum average curve radius in inches (as measured by WipShape) with the manual tests. Left: 3/8" control sample. Right: #4 control sample. Top: Uncompacted voids. Middle: Compacted voids. Bottom: Crush counts.

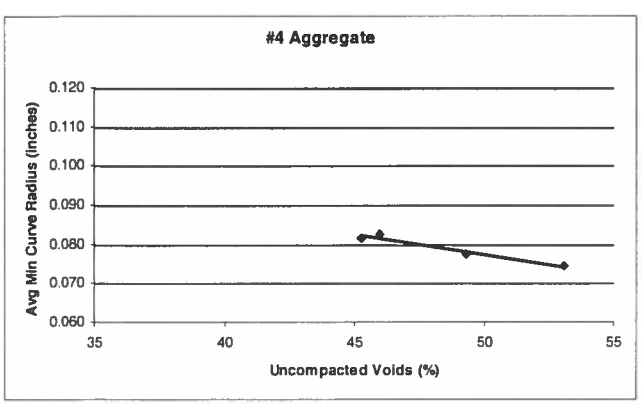


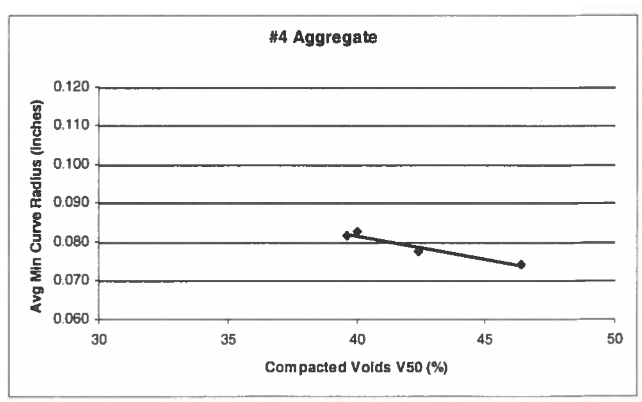
Relationship between the various manual tests. Left: 3/8" control sample. Right: #4 control sample. Top: Compacted vs. uncompacted voids. Bottom: Crush counts vs. uncompacted voids.

APPENDIX 5: BULK SAMPLE ANGULARITY MEASUREMENTS

#4 Retained

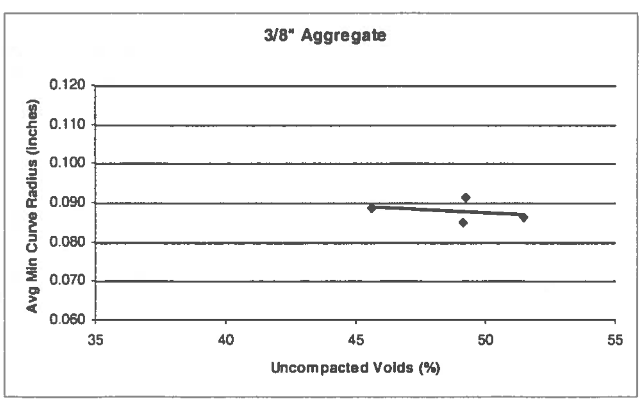


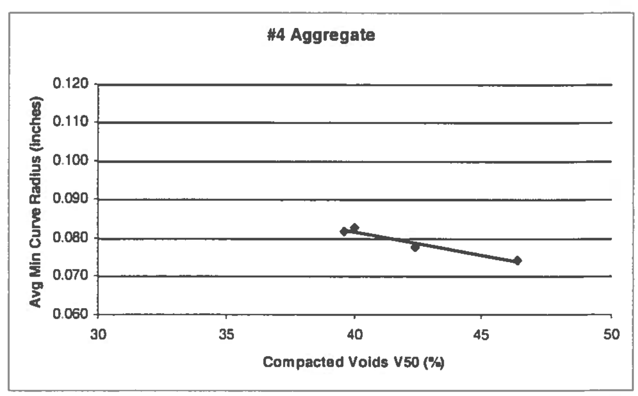




Top left: Osage River gravel. Top right: Maramec River gravel. Center left: Canadian limestone. Center right: Iron Mountain traprock. Bottom left: Uncompacted voids vs. Minimum average curve radius (Osage, Maramec, Canadian, Iron). Bottom right: Compacted voids vs. Minimum average curve radius (Osage, Maramec, Canadian, Iron).

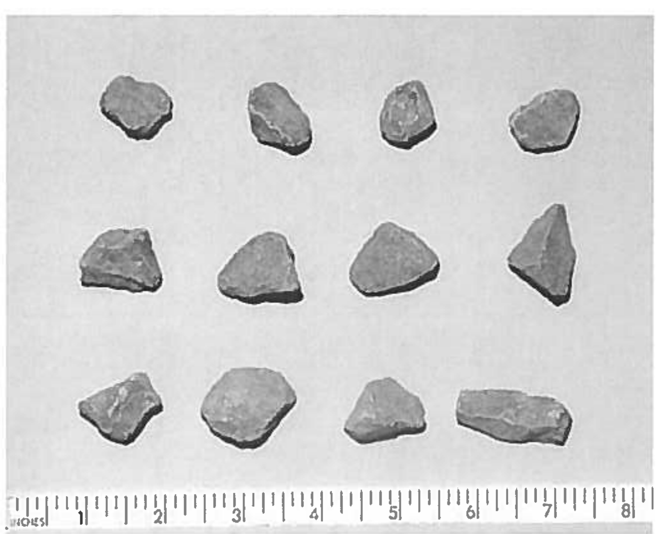
3/8" Retained



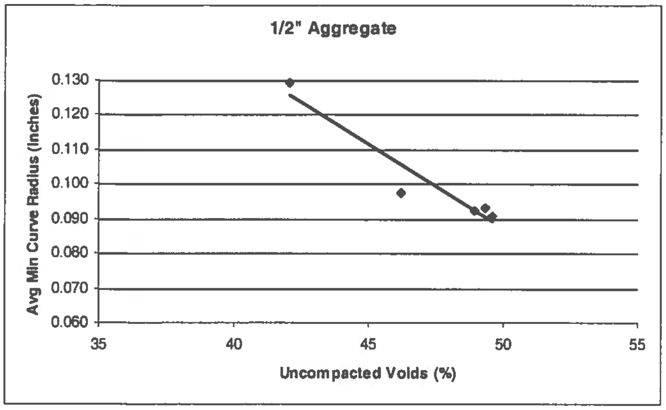


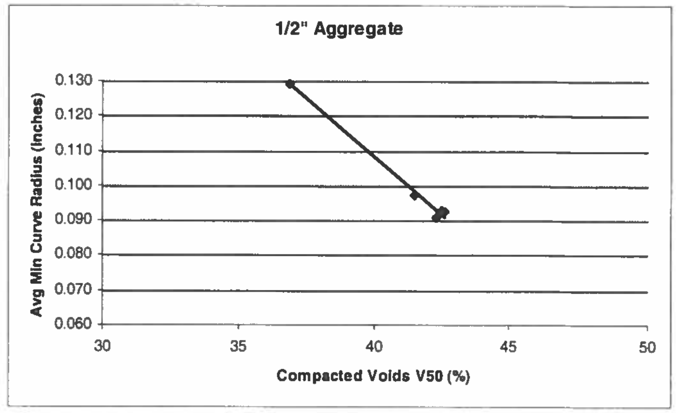
Top left: Meramec River gravel. Top right Little Piney River gravel. Center left: Canadian limestone. Center right:Higginsville Limestone. Bottom left: Uncompacted voids vs. Minimum average curve radius (Maramec, Little Piney, Canadian, Higginsville). Bottom right: Compacted voids vs. Minimum average curve radius (Maramec, Little Piney, Canadian, Higginsville).

1/2" Retained



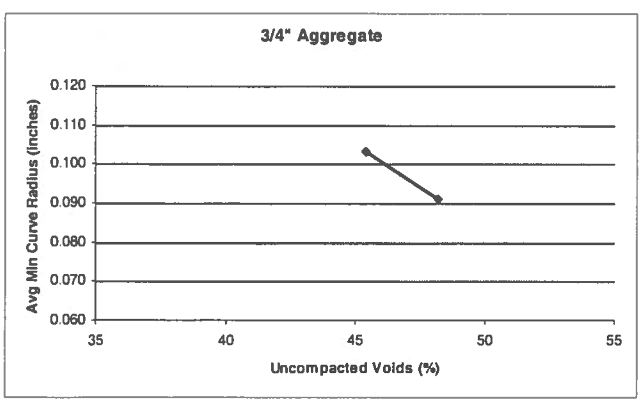
Top left: Missouri River gravel. Top right Maramec River gravel. Center left: Higginsville limestone. Center right: Piney River gravel. Bottom left: Canadian limestone.

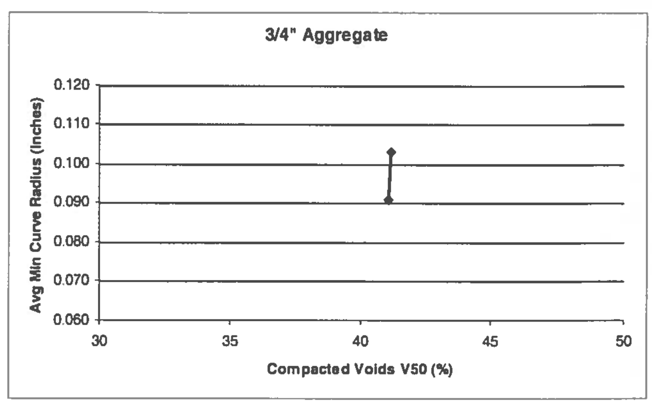




Left: Uncompacted voids vs. Minimum average curve radius (Missouri, Maramec, Higginsville, Little Piney, Canadian). Right: Compacted voids vs. Minimum average curve radius (Missouri, Maramec, Little Piney, Higginsville, Canadian).

3/4" Retained





Top left: Meramec River gravel. Top right Little Piney River gravel. Bottom left: Uncompacted voids vs. Minimum average curve radius (Little Piney, Maramec). Bottom right: Compacted voids vs. Minimum average curve radius (Maramec, Little Piney).