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Comparison of Alternative Devices to Determine Aggregate Shape

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Supplementary Notes

Abstract

This study compared devices (with corresponding procedures) that may be used to classify flat and elongated (F&E) particle content for coarse aggregate sources. The comparison involved the traditional (and manual) proportional caliper and two digital calipers. The material used to conduct these comparisons was from aggregate sources used to produce stone-matrix asphalt during the 2003 and 2004 construction seasons in Virginia. Replicate tests were conducted for each source and each device. The same material was tested by multiple technicians from the Virginia Transportation Research Council's asphalt laboratory and the Virginia Department of Transportation's central materials laboratory.

The central conclusions were: (1) the vertically operated digital caliper is a suitable alternative to the traditional manual proportional caliper; (2) the ROCLOG software facilitates data reduction; and (3) it is important to consider the full gradation analysis when characterizing F&E content of any aggregate source.

This research also documented an estimated time-savings of 45 minutes per aggregate source when performing F&E testing with the vertically operated digital caliper. Given VDOT's standard requirements for aggregate testing, this translates into an annual time-savings of at least 30 hours per laboratory. With an advertised cost of less than $300 per device, the benefit to cost ratio for the vertically operated digital caliper is better than 4 to 1, and the investment is easily justifiable.

FINAL REPORT

COMPARISON OF ALTERNATIVE DEVICES TO DETERMINE AGGREGATE SHAPE

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(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

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ABSTRACT

This study compared devices (with corresponding procedures) that may be used to classify flat and elongated (F&E) particle content for coarse aggregate sources. The comparison involved the traditional (and manual) proportional caliper and two digital calipers. The material used to conduct these comparisons was from aggregate sources used to produce stone-matrix asphalt during the 2003 and 2004 construction seasons in Virginia. Replicate tests were conducted for each source and each device. The same material was tested by multiple technicians from the Virginia Transportation Research Council's asphalt laboratory and the Virginia Department of Transportation's central materials laboratory.

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INTRODUCTION

Flat and elongated (F&E) aggregate particles are widely understood to have an adverse effect on the compaction and overall performance of hot-mix asphalt (Buchanan, 2000; Brown & Cooley, 1999; Aho et al., 2001). F&E particles are simply particles with a ratio of length to thickness that exceeds a specified criterion. Traditionally, the amount of F&E material present in an aggregate source has been determined through a standard test (ASTM D 4791) (ASTM International, 2005) that uses a device known as a proportional caliper (Figure 1). The ASTM standard describes this device as consisting of a "plate with two fixed posts and a swinging arm mounted between them so that the openings between the arms and the posts maintain a constant ratio. The axis position can be adjusted to provide the desired ratio of opening dimensions."

More recently, technologists in the aggregate industry have begun to explore alternatives to the mechanical device. These devices are known generally as digital calipers. They establish the length to thickness ratio by measuring and recording the two relevant dimensions of the aggregate particles. Once this ratio is known, it is a simple matter for integrated software to characterize the degree of flatness or elongation for a given particle.

One version of the digital caliper uses vertically mounted pins (or posts). The length and thickness are established by positioning the aggregate against the stationary pin and sliding the movable pin horizontally until it contacts the particle at a point that is appropriate to represent the relevant dimension (e.g., between the two furthest points on the particle for length, the two narrowest opposing points for thickness). With the horizontally operated device, an operator uses his or her judgment when selecting these locations. The device on the left in Figure 2 is the horizontally operated digital caliper (HDC).

Another version of the digital caliper uses horizontally mounted plates and is oriented vertically (VDC). When establishing the length dimension, the device functions along a vertical axis but otherwise similarly to the HDC. That is, the operator must use his or her judgment when positioning the particle upright in order to represent the length dimension. The thickness

Figure 1. Mechanical Proportional Caliper

dimension however is less subjectively determined. The operator simply places the particle on the bottom plate and lowers the upper plate until it meets the particle. There are certainly instances in which an aggregate particle may rest on the lower plate in multiple orientations. Although there will be some judgment in these cases, this "decision" will be more common with fairly cubicle particles. Theoretically, there are also shape characteristics that would be relevant to F&E particles and would present problems for the VDC plates. The real thickness dimension of a "Pringle-shaped" aggregate, for example, with a distinct concave character would be difficult to capture with plates. The VDC version of the digital caliper is the upright device in Figure 2.

PROBLEM STATEMENT

Although all three devices provide a tool for characterizing aggregate shape, the operation and physical makeup of the various tools will lead to test results that do not agree 100% of the time. The contacts and axis-of-operation for the HDC is most similar to those of the mechanical device. The HDC does offer some degree of automation that should mitigate recording and calculation errors. The difference in the configuration of the VDC will certainly affect test results, although the anticipated reduction in operator influence will likely improve repeatability and reproducibility. Before any device other than the mechanical caliper can be recommended, a rudimentary comparison of the devices was necessary.

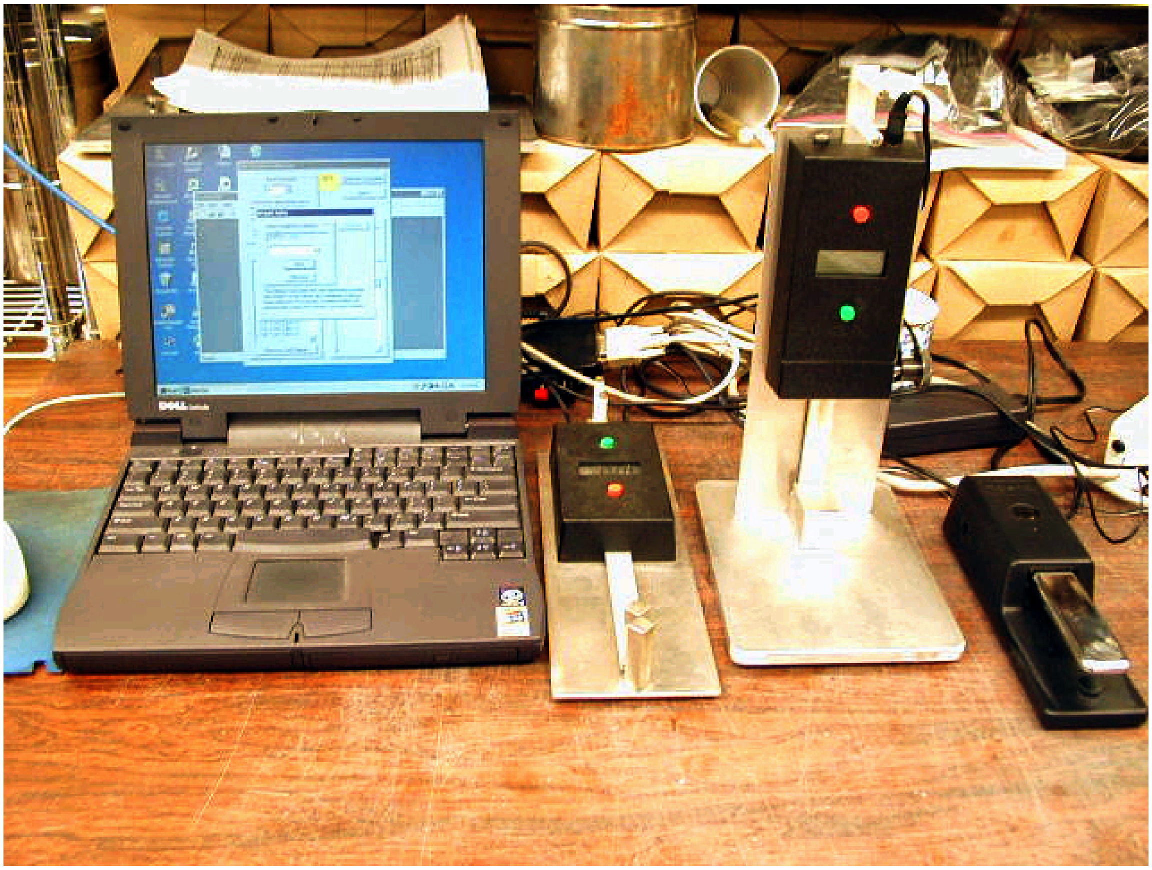

Figure 2. Digital Calipers. The horizontally operated caliper (HDC) with upright pins is in the center. The vertically operated caliper (VDC) with plates is the upright device near the right. The device on the far right is a foot (or elbow) pedal that permits the operator to initiate a reading when both hands are busy.

PURPOSE AND SCOPE

The purpose of this study was to compare devices (with corresponding procedures) that may be used to classify F&E particle content for coarse aggregate sources. The comparison involved the traditional (manual) proportional caliper and two digital calipers. The material used to conduct these comparisons was from aggregate sources used to produce stone-matrix asphalt (SMA) during the 2003 and 2004 construction seasons. Replicate tests were conducted for each source and each device. The same material was tested by multiple technicians from the Virginia Transportation Research Council's (VTRC) asphalt laboratory and the Virginia Department of Transportation's (VDOT) central materials lab. In addition to reviewing and comparing results provided by multiple devices and technicians, the study included an overview (and recommendations) on data recording, reduction, and reporting procedures that may be used.

METHODS

By design, SMA relies heavily on sound and well-shaped (i.e., cubicle) coarse aggregates. For that reason, the F&E particle content of aggregate stock used to produce SMA is closely monitored by producers and VDOT. During the 2003 and 2004 construction seasons, the VTRC asphalt laboratory sampled the coarse aggregate source material from nearly every SMA mixture placed in Virginia (McGhee et al., 2005). From this "population" of stockpile samples, 22 sources were selected and used to evaluate the alternative devices and corresponding procedures for characterizing F&E particle content.

Hardware Evaluation (Device Comparison)

The following laboratory procedures were applied to assess the alternative devices:

1. A gradation analysis of each source material (22 stockpiles) was performed. and coarse aggregate (material larger than the No. 4 sieve) was separated and stored for further testing.

2. Approximately 100 particles (as per ASTM D4791) were selected from each source. Once selected, the identical 100-particle sample was used to represent the original source for all further testing.

3. Each source (represented by the 100-particle sample) was characterized using the standard F&E procedure (with the manual proportional caliper). Each 100-particle sample was tested three times.

4. Each source was characterized using the HDC for three rounds per source.

5. Each source was characterized using the VDC for three rounds per source.

6. F&E test results were summarized by source. The average and standard deviation from three tests of each of the three devices were reported.

7. A subset of the original aggregate matrix (10 stockpiles) was set aside, and a second technician was trained.

8. The second technician (same laboratory) repeated Steps 3 through 6 with a 10-source subset.

9. The summarized test results from two technicians were compared, and the intra-laboratory reproducibility was assessed.

10. The same subset of the original matrix (10 stockpiles) was transported to a third experienced technician in a second laboratory.

11. The third technician (second laboratory) repeated Steps 3 through 6 with the same 10-source subset.

12. The summarized test results from the three technicians and two laboratories supported the final assessment of repeatability and intra- and inter-laboratory reproducibility.

For Steps 3 through 5, one technician completes all testing.

The three hardware options were assessed using VDOT's traditional data reduction procedure for determining F&E particle content, as described later.

Software and Data Reduction

In addition to measurement hardware, it is important to recognize the influence of other important elements of the procedures for characterizing F&E particle content. When digital calipers are used, there are three relevant software components to consider: (1) the ROCLOG Version 1.1 software supplied with the digital calipers, (2) VDOT's standard Excel spreadsheet for calculating F&E particle content (see Appendix B), and (3) an integrated macro developed specifically to move ROCLOG reported data into the VDOT F&E Spreadsheet (contained within spreadsheet). The following describes the three ways that these software elements can be combined, or used alone, to provide an estimate of F&E particle content:

1. *Traditional method.* Particles are measured with a caliper and assigned an F&E classification (i.e., less than 2:1, 2:1 to 3:1, 3:1 to 5:1, 5:1 or greater). A technician places particles in corresponding containers, and the individual containers are weighed. Weights are combined as appropriate to represent entire classifications (e.g., weight of 5:1 material must be accounted for in weight of material exceeding 3:1 criterion). The weights are entered into the standard VDOT F&E Spreadsheet (Appendix B), and the F&E particle content is determined using the full gradation analysis for the source.

2. *ROCLOG with gradation.* Particles are measured with a digital caliper and assigned an F&E classification. A technician places particles in corresponding containers, and the individual containers are weighed. The weights are entered into ROCLOG, which determines F&E particle content for each size fraction (automatically includes all appropriate classifications). Data from a ROCLOG summary report are pasted into the VDOT F&E Spreadsheet (see Appendix B) using the macro, and total weighted F&E particle content is calculated using the full gradation analysis.

3. *ROCLOG without gradation.* Particles are measured with a digital caliper and assigned an F&E classification. A technician places particles in corresponding containers, and the individual containers are weighed. The weights are entered into ROCLOG, which determines F&E particle content for each size fraction (automatically includes all appropriate classifications). There is no mechanism for considering full gradation analysis for source.

The use (or not) of the full gradation results is an important difference among the alternative procedures. The reason involves the way in which the final F&E calculation in the ASTM standard and the VDOT spreadsheet accommodates size fractions that account for less than 10% of the source. For those fractions, the amount of F&E material is not measured but is assumed from the results of the next closest sieve (with more than 10% retained). If the full gradation results are not considered, these smaller fractions will not be accounted for in the final characterization.

Each of these three methods (or software combinations) was applied in accordance with the procedures described per the procedures described under "Hardware Evaluation." The resulting statistics and any observed process efficiencies (or lack thereof) were then used to identify the optimum approach.

FINDINGS

VDOT's Special Provision for SMA (VDOT, 2002a) sets criteria regarding the amount of 5 to 1 and 3 to 1 material (maximum of 5% and 20%, respectively) permitted in a coarse aggregate source. The laboratory testing conducted in support of this research included a shape characterization for each source. Although experience has shown that the 5 to 1 criterion is not an issue, the 3 to 1 limit often proves very difficult to meet (McGhee et al., 2005). To make sure that the most critical (and controversial) of the shape requirements were addressed, the final comparison analysis focused exclusively on the 3 to 1 criterion. A complete source-by-source summary of test results for each technician is included in Appendix A.

Hardware

Single Technician—Large Dataset

The first series of hardware comparison tests involved a single technician, 22 aggregate sources, and the three caliper devices. Table 1 reports the breakdown (by stockpile designation) of the 22 sources. Table 2 summarizes the testing (by device) as conducted by Technician No. 1. The average F&E particle content represents all 22 sources, whereas the standard deviation is the overall average among the three tests for each source.

Figure 3 is another view of the same dataset. In this case, the counts with the digital devices are regressed against those of the manual caliper. This illustration highlights a fairly uniform difference in the respective relationships with the manual caliper. Clearly, the HDC registers a consistently higher total F&E count than the VDC. The average difference for these 22 sources is approximately 6% total F&E material.

Table 1. Breakdown of Aggregate Sources

Number of Sources	VDOT Designation
5	No. 8
7	No. 78
2	No. 68
1	No. 6
1	No. 7
3	No. 57
3	SMA

Table 2. Average and Standard Deviation (Technician No. 1, 3 devices, 22 sources)

Device	3 to 1 Material (%)	SD
MPC	14.9	1.5
HDC	20.7	2.8
VDC	14.6	1.6

MPC = manual proportional caliper, HDC = horizontal digital caliper, VDC = vertical digital caliper.

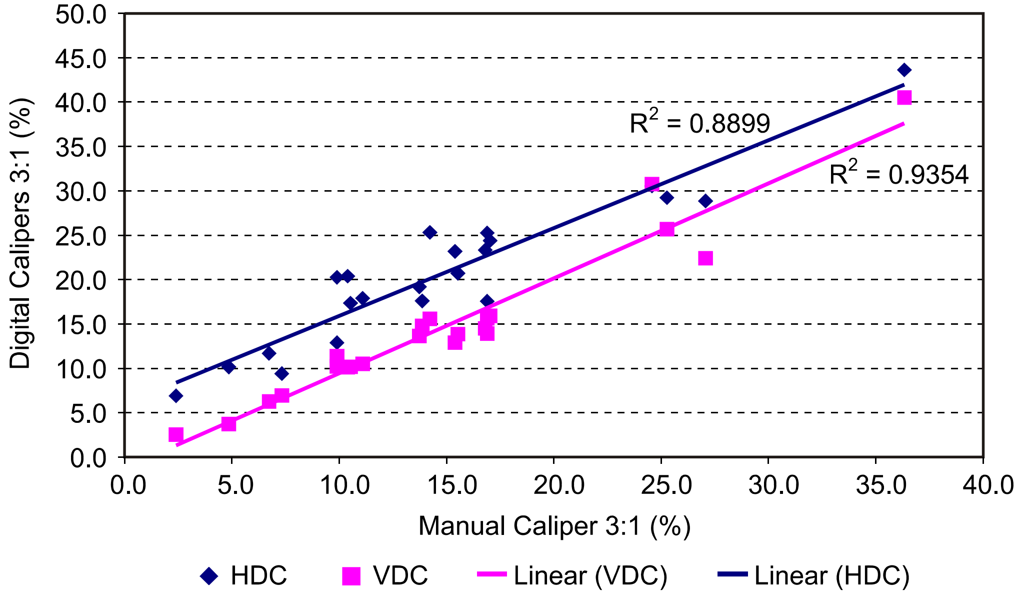

Figure 3. Digital Caliper Results as Function of Manual Caliper (Technician No. 1, 3 devices, 22 sources)

Three Technicians—10 Aggregate Sources

The second series of tests included work from two more technicians and a second laboratory. For this series of tests, 10 sources were arbitrarily selected from the original 22-source dataset. Table 3 describes the makeup of the 10-source dataset.

Figure 4 provides the average F&E particle content for all 10 sources as measured with each instrument and by each technician. The findings of the second technician were similar to those of the first technician. The results from tests performed by the third technician (and second

Table 3. Breakdown of 10-Source Dataset

Number of Sources	VDOT Designation
2	No. 8
3	No. 78
1	No. 68
1	No. 7
2	No. 57
1	SMA

lab) were very different, however. Although the HDC had provided consistently higher F&E values in the first laboratory, the data from the second laboratory associated the HDC with the overall lowest average F&E values.

Figure 5, which depicts the average standard deviations by device, indicates a similar contradiction between laboratories. The findings of the two technicians in the first laboratory were the most repeatable with the manual caliper. In contrast, the findings of the technician in the second laboratory were the most repeatable with the digital devices, especially the HDC.

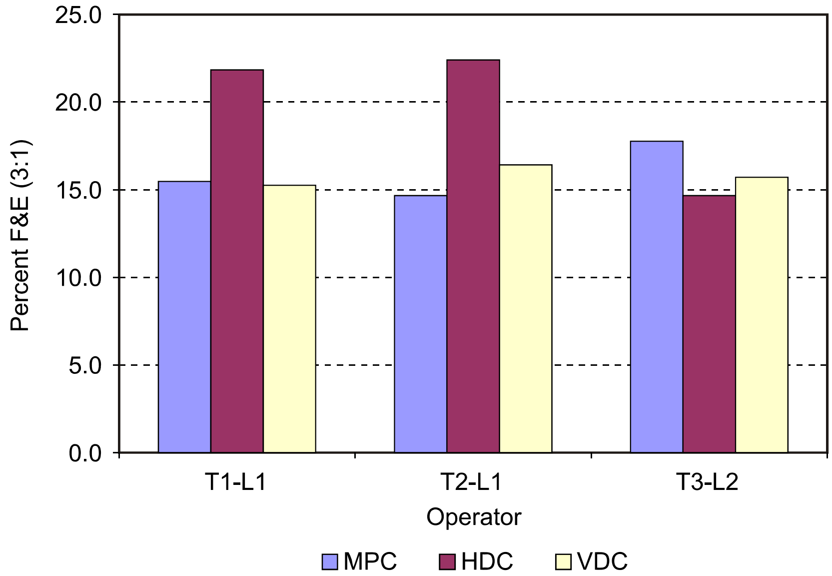

Figure 4. Average F&E Particle Content (3 technicians, 3 devices, 10 sources). MPC = manual proportional caliper; HDC = horizontal digital caliper; VDC = vertical digital caliper; T1-L1 = Technician 1-laboratory 1, etc.

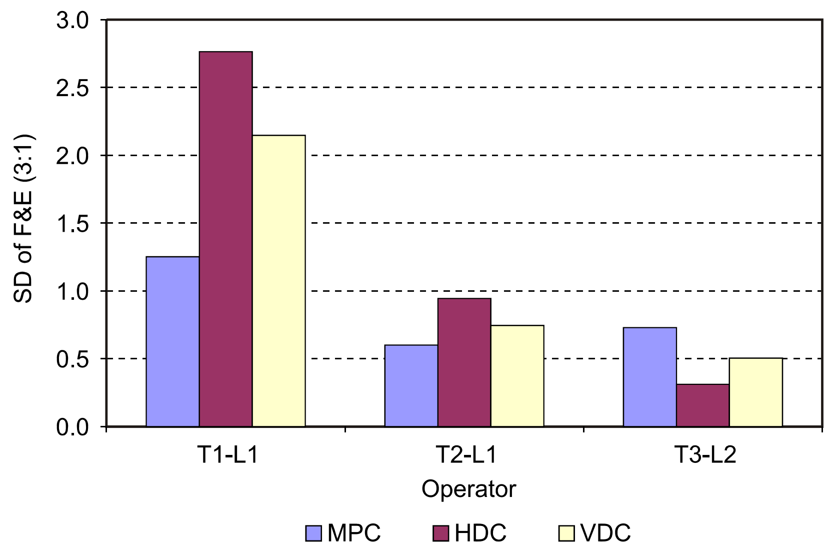

Figure 5. Average Standard Deviation of Measured F&E (3 technicians, 3 devices, 10 sources). MPC = manual proportional caliper; HDC = horizontal digital caliper; VDC = vertical digital caliper; T1-L1 = Technician 1-laboratory 1, etc.

Another point to note from Figure 5 is that the technician who had performed the most tests (Technician No. 1, arguably the most experienced) was having the most difficulty with repeatability. Upon presenting preliminary findings to a group of asphalt experts from VDOT and industry, the researchers learned that this drop in repeatability was not an unusual phenomenon. District laboratory technicians had noted this phenomenon in their test results, especially when subjected to long hours of repeated testing (D. Lee, personal communication, April 2005).

Table 4 summarizes the information presented in Figures 4 and 5. In spite of the differences noted between the two laboratories, the overall trend was for the HDC to report about 6% to 7% more F&E material than did the other two devices. The VDC and MPC appear to supply comparable results for nearly every aggregate source. The laboratory 1 results that related to repeatability (standard deviations) also dominated the overall findings. In summary, the MPC was the most repeatable device, and there was about a 0.5% increase in variability from the MPC to the VDC and yet another 0.5% increase to the HDC.

Table 4. Average and Standard Deviation (All Technicians, 3 devices, 10 sources)

Device	3 to 1 Material (%)	SD
MPC	15.1	0.9
HDC	22.1	1.9
VDC	15.8	1.4

MPC = manual proportional caliper, HDC = horizontal digital caliper, VDC = vertical digital caliper.

General Observations by Technicians

Without exception, the technicians reported a preference for the digital devices. Much of the advantage over the manual caliper appeared to relate to the electronic control and recording systems, which provide some assistance in data reduction (discussed in the next section). Although the pins/posts on the HDC “interacted” similarly to the MPC with the tested particles, the tests went faster. The VDC offered the further advantage of removing subjectivity from at least one measurement dimension (the width or thickness) of each particle.

The technicians further offered a contributor to the marked disagreement (on average) observed between the MPC and the HDC. The similar interaction just mentioned was not without a subtle, but apparently accumulating difference. The posts on the manual device may contact the particle only in the long direction. The narrow dimension is essentially “assumed” when the particle slides through the posts at the other end of the device. With the digital device, both dimensions are measured with no allowance for the particle to slide through anything. Consequently, over the course of a 100-particle test, the slightly larger assumed width from the manual caliper results in less overall F&E material. The reason this effect does not carry over to the VDC suggests some compensating effect from the different shape of the particle/device interface (e.g., flat plates versus narrow posts).

Recommended Hardware

An equipment recommendation was made and accepted (by the Asphalt Research Advisory Committee and VDOT's Materials Division) before the researchers proceeded to the evaluation of software and the data reduction (discussed in the next section). The recommended device for aggregate shape characterization was the VDC, which provides results similar to those of the manual device, demonstrates better overall repeatability than the HDC, and enjoys the unqualified endorsement of the technicians who performed the tests.

Software Assessment and Data Reduction

The assessment of the software and the data reduction options applied test results from the 10-source dataset for all three technicians. Figure 6 presents the average results by technician for each combination (VDC only). Table 5 further reduces the data presented in Figure 6 to reflect averages and repeatability of the three methods. Note that the ROCLOG with gradation results indicate slightly higher F&E particle content with improved repeatability (lower standard deviation). The ROCLOG without gradation averages indicate a noticeable decrease in identified F&E material. The repeatability, however, is nearly equivalent to that of the other semi-automated approach.

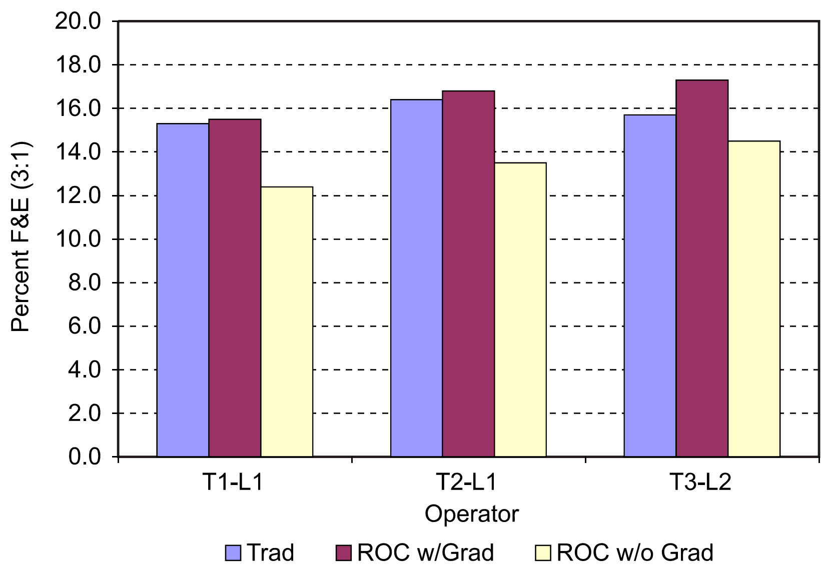

Figure 6. Average F&E Versus Reduction Procedure. Trad. = Traditional method; ROC w/Grad = ROCLOG software using full gradation results for aggregate source; ROC w/o Grad = ROCLOG estimate only.

Table 5. 3 to 1 Content: VDC

Method	Avg.	SD
Traditional	15.8	1.1
ROCLOG with gradation	16.5	0.8
ROCLOG without gradation	13.5	0.7

Table 6 provides additional insight as to how the two semi-automated methods fit the traditional approach. These four linear models pertain to the VDC and findings for the 3 to 1 and 5 to 1 criteria for F&E content. The slope value provides some quantification of how the automated approaches relate to the traditional method, and the y-intercept is offered as a measure of potential built-in bias. Clearly the ROCLOG with gradation provides the superior fit for both criteria.

In addition to the better agreement with the traditional approach, the combination of the ROCLOG software, macro, and F&E spreadsheet (i.e., ROCLOG with gradation) limits the opportunities for data entry error and perhaps even simple misinterpretation of the standard (ASTM D 4791). Given the theoretical similarities between the traditional and ROCLOG with gradation approaches, it is more likely that the lack of perfect agreement is due to data entry errors in the traditional approach.

Table 6. Fit of Automated Techniques to Traditional Method

Average All	VDC 5:1		VDC 3:1	
	ROCLOG w/Gradation	ROCLOG w/o Gradation	ROCLOG w/Gradation	ROCLOG w/o Gradation
Slope	0.79	0.68	0.99	1.05
Y intercept	0.06	-0.02	0.73	-3.45
R^2	0.87	0.76	0.97	0.82

CONCLUSIONS

- The counts with the VDC are in very good agreement with those of the MPC. This good agreement comes with only the slightest decrease in precision.
- The HDC appears to identify approximately 6% to 8% more F&E material than the MPC or the VDC. The higher F&E particle content is accompanied by a noticeable degradation in precision.
- Using the ROCLOG software as part of the system used to reduce F&E data appears to improve the overall repeatability.
- Failure to incorporate the full gradation results for an aggregate source results in a considerable decrease in the amount of F&E material that is typically identified.
- The combination of the ROCLOG software, macro, and F&E spreadsheet (see Appendix B) (i.e., ROCLOG with gradation) limits the opportunities for data entry error and perhaps even simple misinterpretation of the ASTM standard (D 4791).

RECOMMENDATIONS

- VDOT's Materials Division should accept the VDC with horizontal plates as a suitable substitute for the MCD when performing the tests necessary to characterize the flat and elongated content of coarse aggregate sources (ASTM D 4791).

- VDOT's Materials Division and industry laboratories that use the digital calipers should remain cautious when comparing data from other labs. It is essential that the same digital caliper (preferably the VDC) and the same reduction procedures are followed in every instance.

- VDOT's Materials Division should require the combination of the ROCLOG software, the Excel macro, and the VDOT F&E spreadsheet (see Appendix B) for recording, reducing, and reporting F&E particle content for coarse aggregate sources when using digital proportional calipers.

BENEFITS AND COSTS ASSESSMENT

The technicians who conducted the tests necessary to support this research estimated an average time savings of 45 minutes per source. Section 211.05 of VDOT's *Road and Bridge Specifications* (VDOT, 2002b) requires a contractor to test an aggregate source during the mix design phase and then again at the beginning of production. In addition, a contractor is required to run aggregate tests for every 50,000 tons of material used (one test per quarter is a good rule of thumb). In addition to the contractor tests, VDOT technicians will typically verify aggregate test results at the beginning of production and often as a monitoring practice at some point during production.

In 2005, statewide job-mix records indicated that an average of nearly 10 aggregate sources per district were used in the production of SMA. Considering that SMA represented only 14% of the total hot-mix produced in 2005 (McGhee et al., 2005), it is reasonable to expect that district materials technicians test at least 20 sources per year. If these technicians test each source two times with a VDC (rather than a manual caliper), the total annual time savings is 30 hours per laboratory. If the technician and laboratory resources necessary to conduct the tests are valued at $40/hour, the total annual savings will be approximately $1,200. The advertised cost for the vertically operated digital caliper is $285 (HMA Lab Supplies, 2005). Therefore, the benefit/cost ratio for the VDC is better than 4 to 1. For the material producer/supplier who may test many more aggregate sources (many more times), the benefit/cost ratio is likely much higher.

ACKNOWLEDGMENTS

Research staff at the VTRC in cooperation with VDOT's Materials Division conducted this project. The project would not have been possible without the efforts of numerous individuals in the VTRC and VDOT materials laboratories. The authors also acknowledge the assistance and direction from the technical review panel.

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APPENDIX A

SUMMARY OF TEST RESULTS

Tech 1/Lab 1 - Large Dataset

Sample		Average						Standard Deviation					
Log No.	Agg Type	Caliper 5:1	H 5:1	V 5:1	Caliper 3:1	H 3:1	V 3:1	Caliper 5:1	H 5:1	V 5:1	Caliper 3:1	H 3:1	V 3:1
03-1061A	No. 8	1.7	2.9	2.2	11.1	17.9	10.5	0.173	0.265	0.808	3.601	1.700	1.929
03-1050B	No. 8	0.8	3.0	1.1	13.7	19.2	13.7	0.231	0.529	1.250	0.777	3.676	0.603
03-1022A	No. 8	0.3	2.3	0.0	10.4	20.4	10.1	0.520	0.586	0.000	1.311	2.300	1.250
03-1061A	No. 78	2.1	3.3	2.3	9.9	12.9	10.2	0.379	0.709	0.231	1.375	1.652	0.551
03-1044A	No. 8	0.1	1.8	0.1	7.3	9.4	7.0	0.231	0.493	0.173	0.586	2.550	0.473
03-1070A	SMA 7	0.0	0.4	0.2	2.4	6.9	2.5	0.000	0.321	0.289	1.229	4.540	0.945
03-1058A	No. 78F	0.3	3.3	1.9	24.6	30.6	30.8	0.306	2.558	1.779	0.513	8.113	6.005
03-1047A	No. 78	1.6	6.9	1.6	36.3	43.6	40.5	0.666	0.458	0.721	1.553	11.515	2.442
03-1090A	No. 78	0.2	1.8	0.3	16.8	23.3	14.5	0.404	0.321	0.208	0.721	0.971	3.740
03-1065A	No. 8	3.1	5.7	3.0	9.9	20.3	11.4	0.265	1.908	0.115	1.375	0.902	2.022
03-1065A	No. 78	0.2	1.1	0.5	15.5	20.7	13.9	0.346	1.015	0.306	0.950	0.306	0.208
03-1022A	No. 78	0.2	1.2	0.0	10.5	17.4	10.2	0.289	0.709	0.000	0.850	1.106	1.323
03-1058A	No. 78C	0.2	0.2	0.2	6.7	11.7	6.3	0.000	0.000	0.000	0.416	1.572	0.404
03-1044A	No. 68	0.0	0.6	0.0	4.9	10.2	3.7	0.000	0.289	0.000	0.802	2.957	0.153
03-1070A	SMA 6	1.9	7.4	2.0	25.3	29.2	25.7	0.404	1.222	0.058	1.674	2.810	1.808
03-1086B	No. 57F	0.5	2.4	0.3	16.9	17.6	13.9	0.520	1.358	0.289	2.042	3.372	0.709

03-1070A	SMA 5	1.3	3.1	1.5	17.0	24.4	15.9	0.058	0.551	0.173	0.231	0.500	0.321
03-1050B	No. 6	1.9	5.8	2.0	14.2	25.3	15.6	0.265	1.411	0.173	1.097	1.858	1.253
03-1086B	No. 57C	0.6	1.8	0.5	16.9	25.3	15.7	0.153	0.153	0.100	0.436	1.595	2.065
03-1047A	No. 68	1.5	4.1	0.8	27.1	28.9	22.4	0.833	1.039	0.252	8.444	1.193	1.595
03-1050B	No. 7	1.6	7.0	2.5	13.9	17.6	14.8	0.929	1.079	0.231	0.306	3.329	2.606
03-1047A	No. 57	0.3	2.0	0.3	15.4	23.2	12.9	0.115	0.346	0.231	2.207	3.559	1.706
Averages		0.9	3.1	1.1	14.9	20.7	14.6	0.3	0.8	0.3	1.5	2.8	1.6

Tech 2/ Lab 1 - 10-source dataset

Sample		Average						Standard Deviation					
Log No.	Agg Type	Caliper 5:1	H 5:1	V 5:1	Caliper 3:1	H 3:1	V 3:1	Caliper 5:1	H 5:1	V 5:1	Caliper 3:1	H 3:1	V 3:1
03-1022A	No. 8	0.0	0.6	0.1	10.5	18.1	12.4	0.000	0.379	0.115	0.529	0.551	0.794
03-1044A	No. 68	0.0	0.2	0.0	3.0	10.9	4.9	0.000	0.208	0.000	0.231	1.069	0.529
03-1047A	No. 57	0.3	1.8	0.6	13.1	20.9	13.3	0.058	0.289	0.000	0.361	0.208	0.321
03-1050B	No. 7	1.6	4.0	0.9	13.9	18.9	15.9	0.231	0.361	0.624	0.300	0.874	0.200
03-1058A	No. 78F	0.0	3.9	0.0	23.7	34.6	24.0	0.000	0.755	0.000	0.300	1.250	1.706
03-1061A	No. 8	1.9	5.4	1.8	7.8	17.0	13.0	0.153	0.173	0.153	1.039	1.950	1.041
03-1065A	No. 78	0.3	1.8	0.4	14.3	23.7	15.0	0.153	0.306	0.000	0.961	1.457	0.346
03-1070A	SMA 6	2.0	7.5	2.0	26.0	31.2	29.6	0.000	0.987	0.000	0.814	0.757	1.150
03-1086B	No. 57C	0.7	2.8	0.8	17.8	23.8	18.9	0.000	0.493	0.058	0.208	0.379	1.150
03-1090A	No. 78	0.1	1.9	0.3	16.6	25.0	17.2	0.173	0.451	0.000	1.266	0.945	0.208
	Average	0.7	3.0	0.7	14.7	22.4	16.4	0.1	0.4	0.1	0.6	0.9	0.7

Tech 3/Lab 2 - 10-source dataset

Sample		Average						Standard Deviation					
Log No.	Agg Type	Caliper 5:1	H 5:1	V 5:1	Caliper 3:1	H 3:1	V 3:1	Caliper 5:1	H 5:1	V 5:1	Caliper 3:1	H 3:1	V 3:1
03-1022A	No. 8	0.2	0.0	0.0	14.9	12.5	11.9	0.058	0.000	0.000	1.537	0.058	0.404
03-1044A	No. 68	0.4	0.0	0.0	6.4	8.3	3.2	0.000	0.000	0.000	0.100	0.751	0.000
03-1047A	No. 57	1.0	0.6	0.6	15.3	11.1	12.3	0.231	0.000	0.000	1.531	0.058	0.000
03-1050B	No. 7	4.2	2.2	2.4	16.1	16.9	14.7	0.153	0.000	0.081	2.363	0.000	0.289
03-1058A	No. 78F	5.6	0.0	0.0	26.7	25.8	24.4	0.173	0.000	0.000	0.000	2.136	0.404
03-1061A	No. 8	5.1	4.0	2.7	11.9	8.1	12.5	0.000	0.173	1.646	0.231	0.058	1.750
03-1065A	No. 78	1.6	0.5	0.2	16.6	11.9	15.1	0.000	0.000	0.173	0.755	0.000	0.400
03-1070A	SMA 6	4.1	2.4	2.0	29.1	19.2	28.2	0.346	0.115	0.000	0.231	0.058	1.193
03-1086B	No. 57C	2.7	0.8	0.8	20.9	17.1	17.7	0.000	0.000	0.058	0.346	0.000	0.603
03-1090A	No. 78	1.5	0.7	0.3	19.7	15.8	17.1	0.000	0.000	0.000	0.208	0.000	0.000
Averages		2.6	1.1	0.9	17.8	14.7	15.7	0.1	0.0	0.2	0.7	0.3	0.5

APPENDIX B

VDOT F&E SPREADSHEET

Revised 03/14/03

Virginia Department of Transportation
Flat & Elongated Test
Max to Min Dimension
ASTM D4791

Sample ID: ______________________ Project # ______________________ Job Mix #/Material Type ______________________
District: ______________________ Location: ______________________ Producer/Quarry: ______________________
Sample # ______________________ Mix Type: ______________________ Plant: ______________________
Lot # ______________________ Sample Date: ______________________ Technician: ______________________
Date Tested: ______________________

GRADATION						FLAT AND ELONGATED TESTING								
						5:1 Ratio			3:1 Ratio			2:1 Ratio		
			A	B	C, Meas.	D, Meas.	E	F	D, Meas.	E	F	D, Meas.	E	F
U.S. Stand Sieve No.	Weight Retained	Percent Passing	Percent Retained	+ 4 % Retained	Total Weights	Weight	Percent	Weighted Average	Weight	Percent	Weighted Average	Weight	Percent	Weighted Average
37.5mm, 1 1/2 in.										0.0	0.0			
25.0 mm, 1 in.														
19.0 mm, 3/4 in.														
12.5 mm, 1/2 in.														
9.5 mm, 3/8 in.														
4.75 mm, No. 4														
2.36 mm, No. 8					**Totals**									
1.18 mm, No. 16														
600 microns, No. 30														
300 microns, No. 50														
150 microns, No. 100														
75 microns, No. 200														
Pan														
Total														

Weight of original sample. __________ g

Weight after washing. __________ g

1) $\text{Col. B} = \left[\dfrac{\text{Col. A}}{\left(\dfrac{\text{Sum of \% reatained} \geq 4.75 \text{ mm sieve}}{100} \right)} \right]$

2) Col. C is Total Weight of Particles

3) Col. D is Weight th at Failed Analysis

4) $\text{Col. E} = \left[\left(\dfrac{\text{Col. D}}{\text{Col. C}} \right) \times 100 \right]$

5) $\text{Col. F} = \left[\left(\dfrac{\text{Col. B}}{100} \right) \times \text{Col. E} \right]$

6) F & E Value = Sum of Col. Total

Sieve Size	Total No. Particles	No. Particles Failed (5:1)	No. Particles Failed (3:1)

Comments: ____