Precision Estimates of AASHTO T 304, AASHTO T 96, and AASHTO T 11 and Investigation of the Effect of Manual and Mechanical Methods of Washing on Sieve Analysis of Aggregates

DETAILS

0 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-28400-4 | DOI 10.17226/22374

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May 2014

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Research Results Digest 389

CONTENTS

PRECISION ESTIMATES OF AASHTO T 304, AASHTO T 96, AND AASHTO T 11 AND INVESTIGATION OF THE EFFECT OF MANUAL AND MECHANICAL METHODS OF WASHING ON SIEVE ANALYSIS OF AGGREGATES

This digest summarizes key findings of research conducted in Task Order #2 of NCHRP Project 10-87, "Precision Statements for AASHTO Standard Methods of Test," by the AASHTO Materials Reference Laboratory under the direction of the principal investigator, Dr. Haleh Azari.

CHAPTER 1—INTRODUCTION AND RESEARCH APPROACH

1.1 Background

Under NCHRP Project 10-87, the AASHTO Materials Reference Laboratory (AMRL) is conducting a multi-phase research project to improve estimates of precision in AASHTO test methods for a wide range of construction materials. AMRL has an extensive database of test results for the broad range of construction materials collected through its Proficiency Sample Program (PSP) that are used for developing precision estimates (*1*). Laboratories participating in the AMRL PSP receive annual or biannual shipments of paired proficiency samples, which are tested according to specified AASHTO test methods. The results of the testing are returned to AMRL for analysis, summarization, and reporting back to the laboratories. The number of participants in the AMRL PSP program is sufficiently large enough to ensure a statistically sound basis for determination of estimates of precision for standard test methods.

The technique developed by AMRL in NCHRP Project 9-26 is used for analyzing proficiency sample data (*2*). This four-step statistical method removes outlying results and analyzes the core data of a paired data set. The results of the analysis can then be used to obtain reliable single-operator and multilaboratory estimates of precision.

This report includes the results from Task Order #2 of NCHRP Project 10-87 where PSP data from four different PSP testing programs of fine aggregate (AGF) and coarse aggregate (AGC) were used to update precision estimates for AASHTO Standard Test Methods T 96, Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Testing Machine*;* T 304, Uncompacted Void Content of Fine Aggregate; and T 11, Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing (*3–5*).

In the 1996 revisions of AASHTO T 11, the required mass of fine aggregate was changed from 500-g to 300-g. The effect of this change on the variability of the results has not been investigated. As part of updating the precision estimates for AASHTO T 11, the effect of minimum sample size on the results of the test was also investigated.

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Moreover, AASHTO T 11 allows use of mechanical apparatus for the washing operation, provided the results are consistent with those obtained from the manual washing method. The consistency of the results of the two washing methods has not been evaluated. In this study the effect of manual and mechanical methods of washing on the sieve analysis of fine and coarse aggregates was also investigated. For a comprehensive evaluation of the effect of washing method on sieve analysis results, all PSP data pertinent to the manual and mechanical washing methods were analyzed. These are the aggregate gradation data from the Hot Mix Asphalt Extraction Ignition Oven (HMAIO) and Hot Mix Asphalt Solvent Extraction (HMASE), as well as the data from AGF and AGC testing programs. The aggregate gradation data from HMAIO and HMASE have been collected according to AASHTO T 30, Mechanical Analysis of Extracted Aggregate, and the aggregate gradation data from AGF and AGC have been collected according to AASHTO T 27, Sieve Analysis of Fine and Coarse Aggregates (*6*–*7*).

1.2 Problem Statement

AASHTO Standard Test Methods applicable to highway materials require periodic studies to update estimates of precision to account for improvements in the test methods or inclusion of a wider range of materials. For AASHTO T 96, the collection of new data from testing a wide range of materials requires that the precision estimates of the test method be updated. For AASHTO T 304, the current precision statement pertains to void contents determined on "graded standard sand" as described in ASTM C 778 (*8*), which is considered rounded; is graded from 600 µm (No. 30) to 150 µm (No. 100); and may not be typical of other fine aggregates. Additional precision data are needed for void content determination of fine aggregates having different levels of angularity and texture. For AASHTO T 11, the results of the recent modification to the test method on the requirement of minimum sample size of 300-g have not yet compared with the results of the test based on the previous requirement of minimum sample size of 500-g. Moreover, the use of mechanical washing has been allowed as an alternative to manual washing for sieve analysis of aggregates in AASHTO T 11; however, the consistency of the results from mechanical washing with those from manual washing has not been evaluated. The use of mechanical washing has been also allowed in AASHTO T 27 and T 30. Therefore, for a comprehensive comparison of the results from mechanical and manual washing, the PSP sieve analysis data collected according to AASHTO T 27 and T 30 will be included in the analysis.

1.3 Research Objectives

The first objective of this work was to update precision estimates of AASHTO T 96, T 304, and T 11. The second objective was to examine the significance of the difference between variability of percent passing No. 200 sieve of 300-g and 500-g fine aggregate samples measured according to AASHTO T 11. The third objective was to evaluate the effect of manual versus mechanical washing, by comparing the results of sieve analysis of PSP samples, washed manually or mechanically prior to being tested according to AASHTO T 11, T 27, or T 30.

1.4 Scope of Study

The scope of the work involved the following major activities:

1. Update precision estimates of AASHTO T 96, T 304, and T 11.
   a. Organize the most recent sets of PSP data collected according to each test method.
   b. Analyze the data to determine single-operator and multilaboratory estimates of precision.
2. Examine the significance of the difference between the variability of AASHTO T 11 sieve analysis results obtained from 300-g and 500-g sample sizes.
   a. Identify and organize PSP sieve analysis data from 300-g samples and those from 500-g samples of fine aggregates.
   b. Statistically compare the average and pooled variability of the results from testing the 300-g and 500-g samples.
3. Evaluate the effect of manual and mechanical washing on the sieve analysis of PSP aggregates washed prior to being tested according to AASHTO T 11, T 27, or T 30.
   a. Identify and organize the PSP gradation data resulting from manual and mechanical washing.
   b. Perform separate analyses of the precision of aggregate gradation data resulting from manual and mechanical washing.

   c. Statistically compare the average and standard deviation of the percent passing various sieve sizes resulting from manual and mechanical washing.
4. Develop conclusions about the precision estimates prepared in this study, the suitability of a 300-g minimum sample size for AASHTO T 11, and the appropriateness of mechanical washing method for AASHTO T 11, T 27, and T 30 test methods.
5. Prepare proposed precision statements for AASHTO T 96, T 304, and T 11.

CHAPTER 2—DESIGN AND CONDUCT OF THE STUDY

This chapter provides information on the design and conduct of various elements of the study.

2.1 Testing Programs

The data used for the evaluations in this study were collected from laboratories participating in four different PSP testing programs: AGF, AGC, HMAIO, and HMASE.

2.2 Test Methods

The data analyzed for this study are the results of testing aggregates according to five different AASHTO test methods. These are T 96, Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Testing Machine; T 304, Uncompacted Void Content of Fine Aggregate; T 11, Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing; T 27, Sieve Analysis of Fine and Coarse Aggregates; and T 30, Mechanical Analysis of Extracted Aggregate.

2.3 Test Data

For the analyses in this study, only the most recent proficiency sample data (after 1998) were used to account for changes in precision estimates resulting from recent changes in the test methods or from testing a wider range of materials. Another reason for using the data sets collected after 1998 is that the numbers of participating laboratories are considerably larger in comparison to before 1998. Therefore, pooled results from the more recent samples would provide more reliable estimates of precision.

One-hundred and fifty-five sets of data, collected from the laboratories participating in AGC, AGF, HMAIO, and HMASE testing programs of PSP, were used for various evaluations in this study. Table 2-1 through Table 2-5 provide information on the data sets, including the sample pair identification numbers, the testing program, the AASHTO

Table 2-1 PSP data sets used for determining precision estimates of AASHTO T 96.

Test Method	PSP Testing Program	PSP Sample No.
AASHTO T 96	Coarse Aggregate (AGC)	177-178 (Nov. 2012)
		173-174 (Nov. 2011)
		169-170 (Nov.2010)
		165-166 (Nov.2009)
		161-162 (Nov.2008)
		157-158 (Nov.2007)
		153-154 (Nov.2006)
		149-150 (Nov.2005)
		145-146 (Nov.2004)
		141-142 (Nov.2003)
		137-138 (Nov.2002)
		133-134 (Jan.2002)
		129-130 (Dec. 2000)
		125-126 (Jan. 2000)
		121-122 (Dec. 1998)

Table 2-2 PSP data sets used for precision estimates of AASHTO T 304.

Test Method	PSP Testing Program	PSP Sample No.
AASHTO T 304	Fine Aggregate (AGF)	175-176 (March 2012)
		171-172 (March 2011)
		167-168 (March 2010)
		163-164 (March 2009)
		159-160 (March 2008)
		155-156 (March 2007)
		151-152 (April 2006)
		147-148 (May 2005)
		143-144 (May 2004)
		139-140 (May 2003)
		135-136 (May 2002)
		131-132 (May 2001)
		127-128 (June 2000)
		123-124 (June 1999)

Table 2-3 PSP data sets of fine aggregate (AGF) and coarse aggregate (AGC) of PSP data used for determining precision estimates of AASHTO T 11.

Test Method	PSP Testing Program	PSP Sample No.
AASHTO T 11	AGC	177-178 (Nov. 2012)
		173-174 (Nov. 2011)
		169-170 (Nov.2010)
		165-166 (Nov.2009)
		161-162 (Nov.2008)
		157-158 (Nov.2007)
		153-154 (Nov.2006)
		149-150 (Nov.2005)
		145-146 (Nov.2004)
		141-142 (Nov.2003)
		137-138 (Nov.2002)
		133-134 (Jan.2002)
		129-130 (Dec. 2000)
		121-122 (Dec. 1998)
	AGF	175-176 (March 2012)
		171-172 (March 2011)
		167-168 (March 2010)
		163-164 (March 2009)
		159-160 (March 2008)
		155-156 (March 2007)
		151-152 (April 2006)
		147-148 (May 2005)
		143-144 (May 2004)
		139-140 (May 2003)
		135-136 (May 2002)
		131-132 (May 2001)
		127-128 (June 2000)
		123-124 (June 1999)

Table 2-4 PSP data sets used for comparison of percent passing 75-µm (No. 200) sieve by washing of 300-g and 500-g fine aggregate sample sizes following AASHTO T 11.

Test Method	PSP Aggregate Type	Sample Size	PSP Sample No.
AASHTO T 11 Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing	Fine Aggregate	300-g	159-160 (March 2008)
			155-156 (March 2007)
			151-152 (April 2006)
			147-148 (May 2005)
		500-g	175-176 (March 2012)
			171-172 (March 2011)
			167-168 (March 2010)
			163-164 (March 2009)
			143-144 (May 2004)
			139-140 (May 2003)
			135-136 (May 2002)
			131-132 (May 2001)
			127-128 (June 2000)
			123-124 (June 1999)
			119-120 (May 1998)

Table 2-5 PSP data used for comparison of sieve analysis results from manual and mechanical washing.

Test Method and Description	Aggregate Type	Sample No.
AASHTO T 11: Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing and AASHTO T 27: Sieve Analysis of Fine and Coarse Aggregates	Fine Aggregate (AGF)	179-180 (March 2013)
		175-176 (March 2012)
		171-172 (March 2011)
	Coarse Aggregate (AGC)	177-178 (Nov. 2012)
		173-174 (Nov. 2011)
		169-170 (Nov. 2010)
T 30: Mechanical Analysis of Extracted Aggregate	Hot Mix Asphalt Ignition Oven (HMAIO)	25-26 (Feb. 2013)
		23-24 (Feb. 2012)
		21-22 (Feb. 2011)
		19-20 (Feb. 2010)
	Hot Mix Asphalt Solvent Extraction (HMASE)	77-78 (Jan. 2013)
		75-76 (Jan. 2012)
		73-74 (Jan. 2011)

test methods according to which the materials were tested, and the dates the data were collected.

Table 2-1 shows the sample round numbers of the AGC testing program used for preparing precision estimates of AASHTO T 96. The data collected include percent loss of aggregate using the Los Angeles Testing Machine. Fifteen sets of data were available for the precision estimate evaluation of AASHTO T 96.

Table 2-2 shows the sample round numbers of the AGF testing program used for preparing precision estimates of AASHTO T 304. The data collected include the uncompacted void content of fine aggregate. Fourteen sets of data were available for the precision estimate evaluation of AASHTO T 304.

Table 2-3 shows the sample round numbers of the AGF and AGC testing programs used for preparing precision estimates of AASHTO T 11. The data collected according to T 11 include the percent of the material finer than 75-µm (No. 200) sieve by washing. Fourteen sets of data each were available from AGF and AGC for the precision estimate evaluation of AASHTO T 11.

Table 2-4 shows the sample round numbers of the AGF testing program used for evaluating the difference between the precision estimates of results from testing 300-g and 500-g samples according to AASHTO T 11. The data collected include percent of materials finer than 75-µm (No. 200) sieve by washing. Four sets of data were available from testing 300-g samples and 11 sets of data from testing 500-g samples.

Table 2-5 provides the PSP sample round numbers of AGF, AGC, HMAIO, and HMASE used for evaluation of the effect of method of washing (mechanical versus manual) on the sieve analysis results of AASHTO T 11, T 27, and T 30. The information on the method of washing has been collected from the PSP participating laboratories since 2010. There were three sets of data each from testing AGC and AGF samples according to both T 27 and T 11 test methods. There were four sets of data from HMAIO and three sets of data from HMASE samples tested according to T 30.

2.4 Round Robin Study Instructions

Sample instructions and data sheets sent to the laboratories for each of the sample programs are provided in Appendix A, which is not published herein but is available on the TRB website (http://www.trb.org) by searching for NCHRP Project 10-87. The question regarding the method of washing (manual or mechanical) from the participating laboratories have been included in the data sheets of the AGC, AGF, HMAIO, and HMASE testing programs since 2010.

CHAPTER 3—TEST RESULTS AND ANALYSIS

This chapter includes statistical summaries of the data used in this study. The resulting precision estimates for AASHTO T 96, T 304, and T 11 and the outcome of evaluating the effect of minimum sample size on AASHTO T 11 test results are also presented in this chapter. An individual graph for each of the 155 proficiency sample pairs analyzed in this study can be found in Appendixes B through D, which are not published herein but can be found online by searching for NCHRP Project 10-87 on the TRB website (http://www.trb.org).

3.1 Precision Estimates of AASHTO T 96, T 304, and T 11

Using the most recent PSP data sets from testing the AGF and AGC samples (see Tables 2-1 through 2-3), the precision estimates of AASHTO T 96, T 304, and T 11 were updated. For each of the test methods, a summary of statistics of individual data sets as well as the pooled statistics used for the update of repeatability and reproducibility estimates are provided in the following sections. Proposed precision statements that include the precision estimates developed in this chapter are provided in Appendix E.

3.1.1 AASHTO T 96

AASHTO T 96 is identical to ASTM C 131 (*9*) except for several provisions described in AASHTO T 96. The test method covers a procedure for testing coarse aggregates smaller than 37.5 mm (1½ in.) for resistance to degradation using the Los Angeles Testing Machine. A summary of statistics of percent loss of the 15 most recent pairs of PSP coarse aggregate samples tested according to AASHTO T 96 is provided in Table 3-1. The plots of the individual data sets are found in Appendix B.

To decide whether to base the precision estimates on the standard deviation or the coefficient of variation, the relationship between the averages and the variability parameters was examined. Figure 3-1 shows the plots of the averages versus standard deviations and averages versus coefficients of variation.

Table 3-1 Summary of statistics of percent loss of coarse aggregate in Los Angeles Abrasion Testing Machine.

PSP Sample No.	No. of Labs	Average Results		Repeatability			Reproducibility		Reproducibility	
							X Samples		Y Samples	
		X	Y	1s	X Samples CV%	Y Samples CV%	1s	CV%	1s	CV%
177-178	513	24.08	23.90	0.517	2.1	2.2	1.112	4.6	1.075	4.5
173-174	480	13.64	13.77	0.328	2.4	2.4	0.752	5.5	0.735	5.3
169-170	492	26.46	27.34	0.804	3.0	2.9	2.079	7.9	2.098	7.7
165-166	476	21.80	21.75	0.414	1.9	1.9	1.226	5.6	1.242	5.7
161-162	456	56.82	56.73	1.204	2.1	2.1	1.941	3.4	2.007	3.5
157-158	417	13.98	14.18	0.299	2.1	2.1	0.734	5.2	0.740	5.2
153-154	444	36.98	37.20	0.969	2.6	2.6	2.141	5.8	2.102	5.7
149-150	438	42.95	40.22	1.597	3.7	4.0	2.800	6.5	2.400	6.0
145-146	412	27.29	27.48	0.863	3.2	3.1	1.600	5.8	1.500	5.4
141-142	398	13.58	13.72	0.569	4.2	4.1	1.100	7.9	1.100	7.9
137-138	394	16.22	16.02	0.577	3.6	3.6	1.100	6.5	1.100	6.8
133-134	363	21.52	21.35	0.631	2.9	3.0	1.500	6.8	1.500	7.1
129-130	335	20.27	20.30	0.768	3.8	3.8	1.400	7.1	1.500	7.3
125-126	310	41.85	41.83	1.185	2.8	2.8	2.600	6.1	2.600	6.1
121-122	290	13.32	13.19	0.612	4.6	4.6	1.100	8.5	1.200	8.9

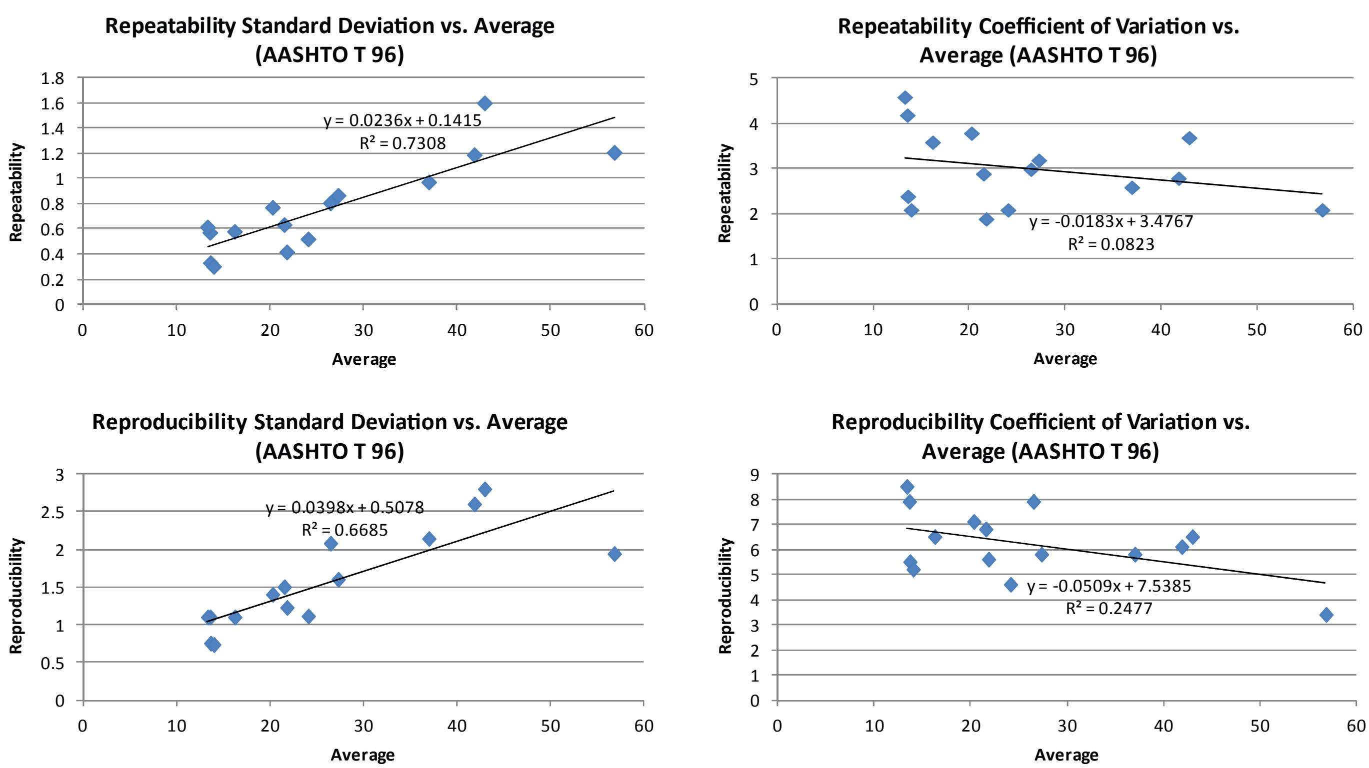

Figure 3-1 Relationship between average and standard deviation and between average and coefficient of variation of the AASHTO T 96 test results.

As indicated from the R^2 values in the plots, there is a strong relationship between averages and both repeatability and reproducibility standard deviations (R^2~ 0.7), while the correlation between averages and both repeatability and reproducibility coefficients of variation is very small (R^2~ 0.07 and 0.27, respectively). Therefore, according to ASTM C 670 (*10*), the form of the precision estimates should be based on the sample coefficient of variation. The repeatability and reproducibility estimates of precision were then computed by averaging the coefficient of variation of the individual samples in Table 3-1. The resulting precision estimates for AASHTO T 96 are provided in Table 3-2. The numbers in the parentheses show the existing precision estimates of ASTM C 131.

3.1.1.1 Comparison of the New and Existing Precision Estimates of AASHTO T 96. The new and existing precision estimates were compared to examine whether or not the precision estimates have changed as a result of inclusion of a wider range of materials. The existing precision estimates are based on average percent loss in a range of 10% to 45%, while the new set of precision estimates is based on average percent loss in a range of 13% to 57%. The comparison of the new precision estimates with the existing precision estimates of ASTM C 131 (Table 3-2) indicates that the 1s% coefficient of variation of 3% computed in this study is 50% higher than the 1s% single-operator coefficient of variation of 2% in ASTM C 131. Similarly, the new 1s% multilaboratory coefficient of variation of 6.2% is 38% higher than the existing 1s% multilaboratory coefficient of variation of 4.5%. The increase in both single-operator and multilaboratory coefficients of variation might be due to inclusion of data from a greater variety of coarse aggregates with a wider range of degradation resistance than those used for developing the precision estimates of ASTM C 131.

3.1.2 AASHTO T 304

AASHTO T 304 describes the determination of the loose uncompacted void content of a sample of fine aggregate. A summary of statistics of uncompacted void content of the 14 most recent pairs of PSP fine aggregate samples tested according to T 304 test method is provided in Table 3-3. The plots of the individual data sets are found in Appendix C.

The plot of the averages versus standard deviations and the averages versus coefficients of variation of the uncompacted void content are shown in Figure 3-2. As indicated from the figure, there are no relationships between the averages and either the standard deviations or the coefficients of variation. Therefore, as specified in ASTM C 670, the form of the precision estimates should be based on the sample standard deviation. The repeatability and reproducibility standard deviations in Table 3-4 were computed by pooling the sample standard deviations shown in Table 3-3 using the following equation (*11*):

$$s_p = \sqrt{\frac{(n_1-1)\,s_1^2+(n_2-1)\,s_2^2+\cdots+(n_k-1)\,s_k^2}{n_1+n_2+\cdots+n_k-k}}$$

(Equation 1)

Where:

s_p = pooled standard deviation
s_k = kth standard deviation
n_k = number of laboratories analyzed resulting in kth standard deviation

3.1.2.1 Comparison of the New and Existing Precision Estimates of T 304. The current precision estimates for AASHTO T 304 are shown in parentheses in Table 3-4. The comparison of the new and existing precision estimates of AASHTO T 304 would indicate if the precision estimates of the test based on actual fine aggregates are different

Table 3-2 Pooled repeatability and reproducibility precisions of T 96 based on the samples' coefficients of variation.

Statistics	1s (%)	d2s (%)
Repeatability	3.0 (2.0)	8.5 (5.7)
Reproducibility	6.2 (4.5)	17.6 (12.7)

Note: The numbers in parentheses represent the existing precision estimates of ASTM C 131.

Table 3-3 Summary of statistics of uncompacted void content of 14 sets of AGF sample pairs.

PSP Sample No.	No. of Labs	Average Results		Repeatability			Reproducibility X Samples		Reproducibility Y Samples	
		X	Y	1s	X Samples CV%	Y Samples CV%	1s	CV%	1s	CV%
175-176	535	44.376	44.433	0.268	0.6	0.6	0.570	1.3	0.570	1.3
171-172	484	42.657	42.609	0.266	0.6	0.6	0.504	1.2	0.524	1.2
167-168	468	43.321	43.018	0.342	0.8	0.8	0.586	1.4	0.568	1.3
163-164	466	43.733	43.842	0.295	0.7	0.7	0.760	1.7	0.763	1.7
159-160	443	41.505	41.555	0.272	0.7	0.7	0.871	2.1	0.863	2.1
155-156	396	43.104	43.125	0.262	0.6	0.6	0.573	1.3	0.560	1.3
151-152	410	43.055	42.940	0.348	0.8	0.8	0.720	1.7	0.670	1.6
147-148	387	42.623	42.631	0.343	0.8	0.8	0.770	1.8	0.780	1.8
143-144	367	43.053	43.085	0.403	0.9	0.9	0.790	1.8	0.790	1.8
139-140	345	43.268	43.393	0.432	1.0	1.0	1.100	2.6	1.200	2.7
135-136	287	42.695	42.749	0.383	0.9	0.9	1.100	2.6	1.100	2.6
131-132	242	43.267	43.183	0.378	0.9	0.9	0.920	2.1	0.860	2.0
127-128	211	42.663	42.682	0.353	0.8	0.8	1.300	3.0	1.300	3.2
123-124	183	42.794	42.806	0.417	1.0	1.0	1.100	2.6	1.100	2.7

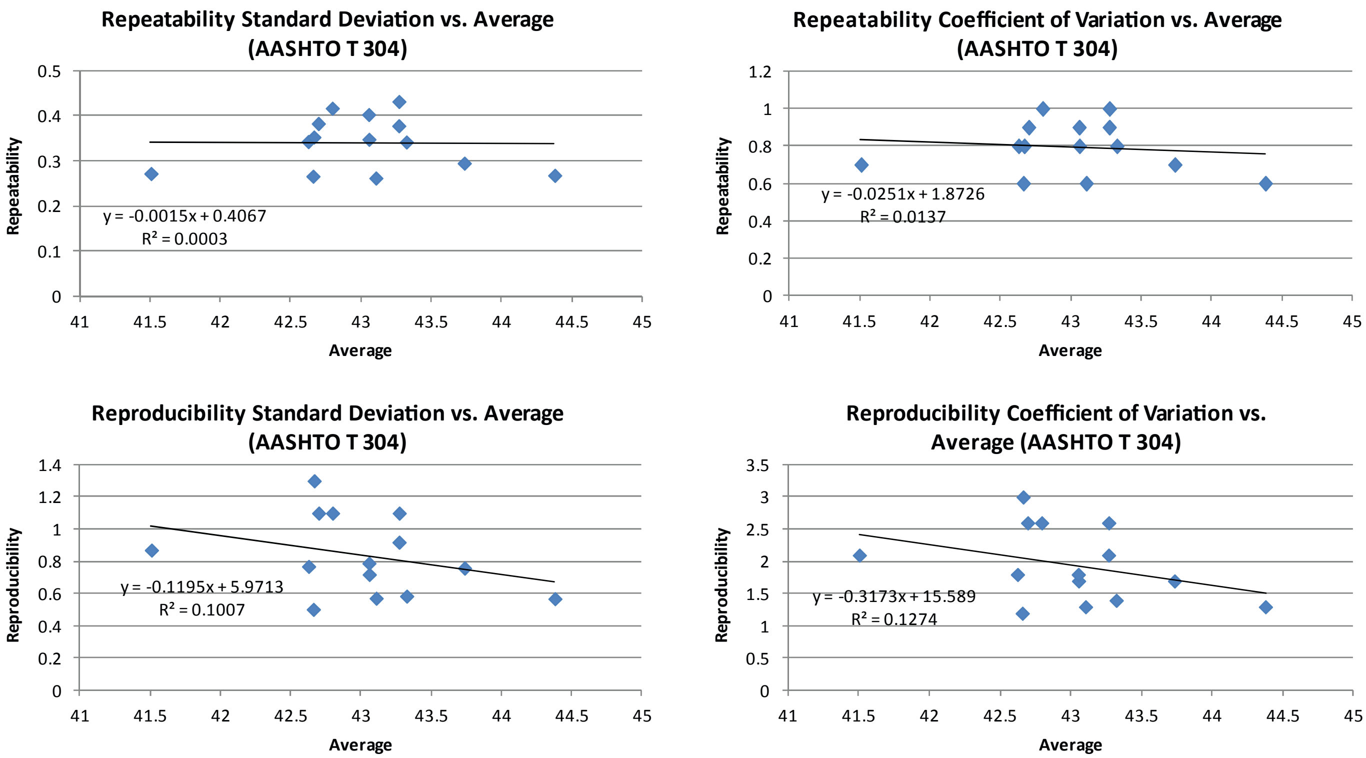

Figure 3-2 Relationship between average and standard deviation and between average and coefficient of variation of the AASHTO T 304 data.

Table 3-4 Pooled repeatability and reproducibility precisions of T 304 based on the samples' standard deviations.

Statistics	1s	d2s
Repeatability	0.33 (0.13)	0.95 (0.37)
Reproducibility	0.81 (0.33)	2.29 (0.93)

Note: The numbers in parentheses represent the existing precision estimates from ASTM C 670.

from the existing precision estimates that were developed based on the graded standard silica sand as described in ASTM C 778. For the new precision estimates, based on the PSP fine aggregates with uncompacted void content in a range of 42% to 45%, the 1s single-operator standard deviation is 0.33% and the 1s multilaboratory standard deviation is 0.81%. These values are significantly larger than the existing single-operator standard deviation of 0.13% and multilaboratory standard deviation of 0.33%, respectively. The larger standard deviations of the PSP data in comparison to the existing standard deviations are expected since the basis of the existing precision estimates is the uncompacted voids of the graded standard silica sand with round particles in a range of 600 µm (No. 30) to 150 µm (No. 100), as described in T 304, which may not be typical of other fine aggregates.

3.1.3 AASHTO T 11

AASHTO T 11 covers determination of the amount of materials finer than a 75-µm (No. 200) sieve by washing. Clay particles and other aggregate particles that are dispersed by the wash water, as well as water-soluble materials, will be removed from the aggregate during the test. A summary of statistics of percent finer than a 75-µm (No. 200) sieve of the 14 most recent pairs each of the AGF and AGC samples of PSP tested according to T 11 test method is provided in Table 3-5 and Table 3-6. The sample size of AGF samples used for this analysis is 500-g, which is the same as the sample size used

Table 3-5 Summary of statistics of percent finer than a 75-µm (No. 200) sieve in coarse aggregates by washing of 14 sets of AGC sample pairs.

PSP Sample No.	No. of Labs	Average Results		Repeatability			Reproducibility		Reproducibility	
							X Samples		Y Samples	
		X	Y	1s	X Samples CV%	Y Samples CV%	1s	CV%	1s	CV%
177-178	1380	0.188	0.189	0.022	12	11.9	0.06	30.106	0.06	29.6
173-174	1371	0.263	0.268	0.041	15.5	15.1	0.12	44.2	0.12	43.8
169-170	1326	1.266	1.121	0.167	13.2	14.9	0.39	30.9	0.38	33.5
165-166	1223	0.298	0.299	0.028	9.5	9.5	0.07	24.9	0.07	24.9
161-162	1240	1.263	1.206	0.14	11.1	11.6	0.38	30.1	0.39	32.1
157-158	1128	0.298	0.278	0.037	12.5	13.4	0.14	45.2	0.13	47.0
153-154	1065	0.891	0.909	0.102	11.4	11.2	0.22	24.5	0.22	24.0
149-150	1111	0.538	0.492	0.091	17	18.6	0.21	39.5	0.2	41.4
145-146	1039	0.382	0.32	0.096	25	29.9	0.16	41.3	0.13	40.9
141-142	964	0.241	0.243	0.133	55.2	54.8	0.14	57.5	0.14	57.9
137-138	876	0.211	0.219	0.06	28.2	27.2	0.11	54	0.12	55.9
133-134	800	0.53	0.518	0.18	34	34.7	0.17	31.6	0.16	30.6
129-130	714	0.276	0.285	0.062	22.4	21.7	0.13	48.2	0.14	48.7
121-122	552	0.453	0.388	0.083	18.3	21.3	0.22	48.7	0.2	51.3

Table 3-6 Summary of statistics of percent finer than a 75-µm (No. 200) sieve in fine aggregates by washing of 14 sets of AGF sample pairs.

PSP Sample No.	No. of Labs	Average Results		Repeatability			Reproducibility		Reproducibility	
							X samples		Y samples	
		X	Y	1s	X samples CV%	Y samples CV%	1s	CV%	1s	CV%
175-176	1354	0.313	0.305	0.042	13.3	13.7	0.13	42.3	0.13	43.7
171-172	1330	1.57	1.409	0.097	6.2	6.9	0.21	13.3	0.26	18.2
167-168	1303	0.786	0.837	0.059	7.5	7.1	0.14	18.3	0.13	16.0
163-164	1287	1.348	1.343	0.075	5.6	5.6	0.18	13.5	0.19	14.0
159-160	1171	1.425	1.419	0.077	5.4	5.5	0.2	14.2	0.2	14.3
155-156	1080	1.825	1.835	0.085	4.7	4.7	0.21	11.5	0.21	11.5
151-152	1125	2.423	2.446	0.144	5.9	5.9	0.34	13.9	0.34	14.1
147-148	1021	1.99	2.028	0.194	9.8	9.6	0.5	25.1	0.5	24.9
143-144	1015	1.277	1.271	0.136	10.7	10.7	0.28	21.8	0.27	20.9
139-140	926	1.988	2.536	0.259	13	10.2	0.46	23.4	0.6	23.6
135-136	810	1.789	1.78	0.145	8.1	8.1	0.41	23.1	0.42	23.5
131-132	698	1.366	1.365	0.147	10.8	10.8	0.34	24.9	0.33	24.5
127-128	625	1.87	1.852	0.209	11.2	11.3	0.41	21.9	0.41	22.1
123-124	587	2.128	2.107	0.145	6.8	6.9	0.5	23.7	0.51	24.2

for developing the existing precision estimates of AASHTO T 11.

Figures 3-3 and 3-4 show the relationships between average percent passing sieve No. 200 and the repeatability/reproducibility standard deviations and the coefficients of variation. A review of the graphs indicates that the correlations between average and standard deviations are stronger than the correlations between average and coefficients of variation. However, to be consistent with the existing precision estimates, the precision estimates should be determined based on standard deviation. The repeatability and reproducibility estimates of precision for coarse and fine aggregates are computed by pooling the standard deviations of the individual samples in Table 3-5 and Table 3-6, respectively, using Equation 1. The computed precision estimate values for coarse and fine aggregates are provided in Table 3-7, with the existing precision estimates of AASHTO T 11 shown in parentheses.

3.1.3.1 Comparison of the New and Existing Precision Estimates of AASHTO T 11. The new and existing precision estimates for AASHTO T 11 in Table 3-7 were compared to determine if the new sets of precision estimates are the same as the existing ones. For the coarse aggregates, with the percent materials finer than a 75-µm (No. 200) sieve by washing in a range of 0.19 % to 1.23%, the new 1s single-operator and multilaboratory standard deviations are 0.10% and 0.21%, respectively. These values are compared with the existing single-operator and multilaboratory standard deviation of 0.10% and 0.22%, respectively, which were prepared from coarse aggregates having less than 1.5% finer than the 75-µm (No. 200) sieve. There is no change in the single-operator standard deviation and a 4.55% decrease in the multilaboratory standard deviation.

For the new precision estimates based on the PSP fine aggregates with materials finer than a 75-µm (No. 200) sieve by washing in a range of 0.31 % to 2.54%, the 1s single-operator and multilaboratory standard deviations are 0.14% and 0.32%, respectively. These values are compared with the existing single-operator and multilaboratory standard deviation of 0.15% and 0.29%, respectively, which were prepared from fine aggregates having 1.0% to 3.0% finer than the 75-µm (No. 200) sieve. There is a 6.7% decrease in the single-operator standard deviation and a 10.3% increase in the multilaboratory standard deviation.

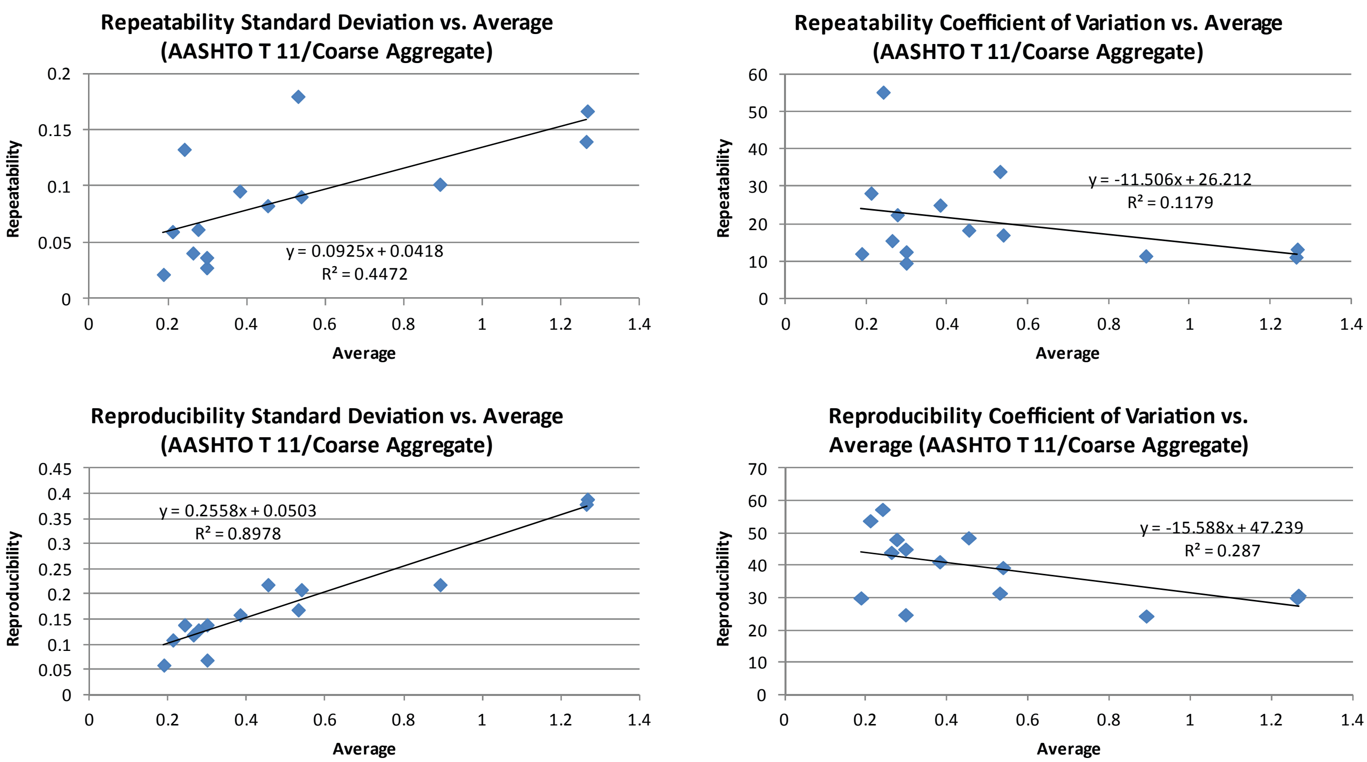

Figure 3-3 Relationship between average and standard deviation and between average and coefficient of variation of percent material finer than a 75-µm (No. 200) sieve by washing of AGC.

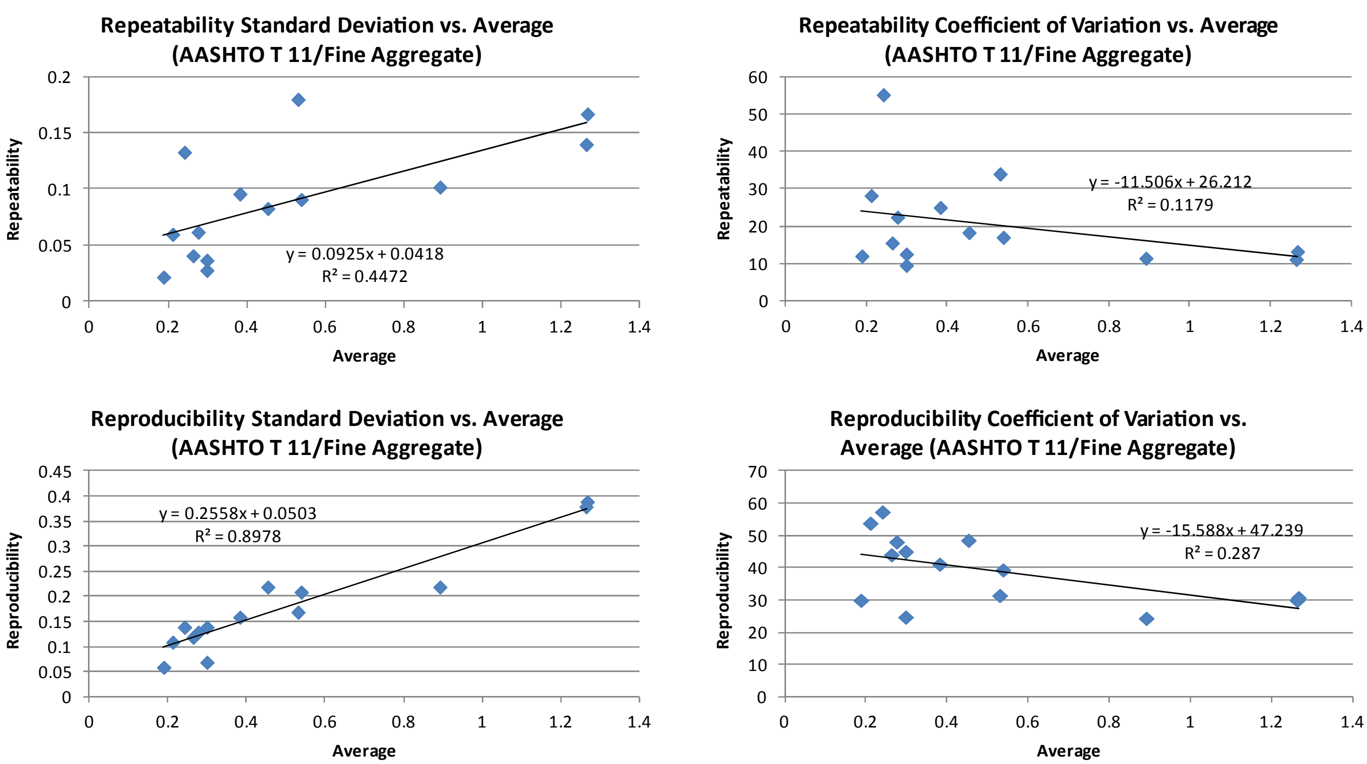

Figure 3-4 Relationship between average and standard deviation and between average and coefficient of variation of percent material finer than a 75-µm (No. 200) sieve by washing of AGF.

Table 3-7 Pooled repeatability and reproducibility precisions of percent material finer than a 75-μm (No. 200) sieve measured according to AASHTO T 11 based on sample standard deviation.

Aggregate Type	Statistics	1s	d2s
Coarse Aggregate	Repeatability	0.10 (0.1)	0.28 (0.28)
	Reproducibility	0.21 (0.22)	0.59 (0.62)
Fine Aggregate	Repeatability	0.14 (0.15)	0.39 (0.43)
	Reproducibility	0.32 (0.29)	0.90 (0.82)

Note: The numbers in parentheses represent the existing precision estimates.

3.2 Evaluation of the Effect of Sample Size on AASHTO T 11 Test Results

The new and existing precision estimates of AASHTO T 11 in Table 3-7 for fine aggregates are based on a nominal sample size of 500 g. A 1996 revision of this test method permits the fine aggregate test sample size to be the minimum of 300 g. Section 12.1.1 of AASHTO T 11 provides the precision estimates based on analysis of the results from testing 300-g and 500-g test samples from Aggregate Proficiency Test Samples 99 and 100, which were essentially identical. As stated in the precision statement of the test method, there are only minor differences between the precision estimates from the two sample sizes. Note 7 of the test method states that the existing precision estimates would be revised to reflect the precision of the test based on 300-g test sample size when a sufficient number of Aggregate Proficiency Tests have been conducted using a sample size of 300 g.

Four sets of PSP percent passing No. 200 sieve data, based on 300-g sample size, have been collected in recent years (see Table 2-4). To examine the reliability of the test results using a 300-g sample size, the precision estimates of the test were determined using the 300-g samples and compared with the precision estimates presented in Section 3.1.3 prepared using 500-g samples.

3.2.1 Results of the Analysis

Table 3-8 provides a summary of statistics of AASHTO T 11 test results based on four 300-g AGF sample sets. The pooled standard deviations and coefficients of variation of the four data sets are provided in Table 3-9 along with the precision estimates determined using 500-g samples (Section 3.1.3). As indicated from Table 3-9, the repeatability standard deviation associated with the 300-g sample size is the same as that associated with the 500-g sample size. However, the reproducibility standard deviation based on the 300-g sample size is 0.01 larger than the reproducibility standard deviation based on the 500-g sample size.

The comparison of the coefficient of variation of the percent passing No. 200 sieve using 300-g and 500-g sample sizes is also shown in Table 3-9. As indicated, both repeatability and reproducibility coefficients of variation corresponding to 300-g samples

Table 3-8 Summary of statistics of percent passing 75-μm sieve by washing for four sets of 300-g PSP fine aggregate sample pairs.

Sample Size	PSP Sample No.	No. of Labs	Average Results		Repeatability			Reproducibility		Reproducibility	
								X Samples		Y Samples	
			X	Y	1s	X Samples CV%	Y Samples CV%	1s	CV%	1s	CV%
300-g	159-160	1139	1.526	1.526	0.100	6.5	6.5	0.213	13.9	0.212	13.9
	155-156	1052	1.962	1.969	0.104	5.3	5.3	0.204	10.4	0.209	10.6
	151-152	1075	2.554	2.571	0.148	5.8	5.7	0.328	12.9	0.329	12.8
	147-148	1020	2.307	2.349	0.200	8.7	8.5	0.470	20.3	0.460	19.7

Table 3-9 1s repeatability and reproducibility standard deviations and coefficients of variation of percent passing 75-µm sieve by washing from 300-g and 500-g samples.

Sample Size	Repeatability		Reproducibility	
	1s	CV %	1s	CV%
300-g	0.14	6.5	0.33	11.7
500-g	0.14	10.1	0.32	20.9

Table 3-10 Results of F-test on variances for comparison of standard deviations of percent passing 75-µm sieve by washing of 300-g and 500-g sample sizes.

Comparison	Computed F		P-Value		Critical F
	Repeatability	Reproducibility	Repeatability	Reproducibility	
300-g vs. 500-g	1.00	1.06	0.023	0.003	1.04

Note: Degrees of freedom for both categories are greater than 1,000.

are noticeably smaller than those corresponding to 500-g samples.

Table 3-10 provides the results of statistical F-test on variance. As shown in the table, the computed F value for reproducibility is slightly greater than the critical F value, meaning that the reproducibility standard deviation of the 300-g samples is statistically larger than that from 500-g samples. However, from a practical standpoint, this is not considered significant since a difference of 0.01% in standard deviation translates into 0.03% percent allowable difference between two results, which is considerably smaller than the multilaboratory d2s of the AASHTO T 11 test method (0.90 %). Based on the analysis of percent passing 75-µm sieve data of PSP samples, there is no need to change the minimum sample size of the fine graded materials (nominal maximum size of 4.75 mm) of 300 g in AASHTO T 11.

CHAPTER 4—EVALUATION OF THE METHOD OF WASHING

Several test methods, including AASHTO T 11, AASHTO T 27, and AASHTO T 30, allow the use of a mechanical apparatus to perform the washing operation providing mechanical washing does not degrade the aggregates. To evaluate the difference between the sieve analysis results from mechanical and manual washing, the PSP gradation data resulting from testing according to these test methods were analyzed. This chapter explores the effect of manual and mechanical washing on sieve analysis results of AASHTO T 11, T 27, and T 30.

4.1 Evaluation of Sieve Analysis Results

The PSP collects sieve analysis data as part of the AGF, AGC, HMAIO, and HMASE testing programs. The data on the method of washing for the HMAIO and AGC samples have been collected since 2010. For the HMASE and AGF samples, the data have been collected since 2011. Using the sieve analysis data collected from samples with a known method of washing, the variability of the data from manual and mechanical washing was separately determined and statistically compared. The following sections provide the results of statistical analysis using the data sets with a known method of washing for the AGC, AGF, HMAIO, and HMASE testing programs. The "p-values" in the table of statistical results indicate the statistical significance. If the p-value is less than 0.05, the difference in average or variability of percent passing resulting from the manual and mechanical washing is significant with 95% probability. If the p-value is smaller than 0.01, the differences are significant with 99% probability. The analyses of individual data sets are provided in Appendixes F through I, which are not published herein, but are available on the TRB website (http://www.trb.org) by searching for NCHRP Project 10-87.

Table 4-1 Results of statistical t-test for comparison of average percent passing various sieve sizes after mechanical and manual washing pooled from AGC 169-170, AGC 173-174, and AGC 177-178 samples.

Sieve Size	Percent Passing, Manual	Percent Passing, Mechanical	Deg. of Freedom	Computed T	P-Value
25.0-mm	99.93	99.93	496	0	1
19.0-mm	85.87	85.93	536	-2.1	0.036
12.5-mm	50.43	50.63	544	-2.7	0.007
9.5-mm	15.20	15.50	558	-7.45	3.625E_13
4.75-mm	1.11	1.31	535	-9.67	1.678E_20
75-µm Washing	0.55	0.69	432	-11	4.286E_25

Note: Critical t for 1% level of significance is 2.58 and for 5% level of significance is 1.96.

4.1.1 Analysis of AGC Data

Table 4-1 through Table 4-3 provide the results of a statistical comparison of the averages and repeatability/reproducibility standard deviations of the percent passing various sieve sizes pooled separately from manual and mechanical washing of AGC169-170, AGC 173-174, and AGC 177-178 samples.

Table 4-1 provides the results of the statistical t-test on average percent passing. As shown in the table, the p-values corresponding to all, except the 25.0-mm sieve, are less than 0.01, indicating that with a probability of 99%, the percent passing all sieve sizes, except the 25.0-mm sieve, of mechanically washed aggregates is significantly larger than those of the manually washed. The significance of the difference increases as the sieve sizes get smaller. The smallest p-value corresponds to the 75-µm sieve size from washing, meaning that with the highest probability, significantly larger amounts of materials finer than 75-µm sieve are washed away from the mechanically washed aggregates than from the manually washed aggregates.

The fact that a higher amount of materials passes through smaller sieve sizes when aggregates are mechanically washed could be the result of two phenomena: (1) dust and fillers attached to the aggregates would be washed away more thoroughly during the mechanical washing and, therefore, particles would become smaller or (2) the aggregates break down

Table 4-2 Results of statistical F-test for comparison of repeatability standard deviations of percent passing various sieve sizes after mechanical and manual washing pooled from AGC 169-170, AGC 173-174, and AGC 177-178 samples.

Sieve Size	Repeatability, Manual	Repeatability, Mechanical	Degrees of Freedom	Computed F	Critical F (α=0.01)	Critical F (α=0.05)	P-Value
25.0-mm	0.118	0.120	387 & 3342	1.04	1.19	1.13	0.31
19.0-mm	0.442	0.413	3518 & 412	1.14	1.19	1.13	0.038
12.5-mm	0.829	0.801	3656 & 430	1.07	1.19	1.13	0.179
9.5-mm	0.539	0.536	3693 & 424	1.01	1.19	1.13	0.463
4.75-mm	0.195	0.170	3684 & 413	1.32	1.19	1.13	2E-04
75-µm Washing	0.095	0.105	369 & 3642	1.24	1.19	1.13	0.002

Table 4-3 Results of statistical F-test for comparison of reproducibility standard deviations of percent passing various sieve sizes after mechanical and manual washing pooled from AGC169-170, AGC 173-174, and AGC 177-178 samples.

Sieve Size	Reproducibility, Manual	Reproducibility, Mechanical	Degrees of Freedom	Computed F	Critical F (α=0.01)	Critical F (α=0.05)	P-Value
25.0-mm	0.159	0.148	3342 & 387	1.15	1.2	1.14	0.04
19.0-mm	0.662	0.603	3518 & 412	1.21	1.19	1.13	0.007
12.5-mm	1.497	1.448	3656 & 430	1.07	1.19	1.13	0.185
9.5-mm	0.882	0.775	3693 & 424	1.3	1.19	1.13	3E-04
4.75-mm	0.432	0.388	3684 & 413	1.24	1.19	1.13	0.002
75-µm Washing	0.222	0.246	369 & 3642	1.23	1.19	1.13	0.003

during the mechanical washing, resulting in an increase of smaller particles. The comparison of the variability of the gradation measurements from manual and mechanical washing might explain which phenomenon is more likely.

The results of the F-test on variance for the statistical comparison of the repeatability standard deviations of percent passing various sieve sizes from manual and mechanical washing of AGC 169-170, AGC 173-174, and AGC 177-178 samples are provided in Table 4-2. It is shown in the table that the variability of percent passing the 19-mm through 4.75-mm sieve sizes from mechanical washing is smaller than the variability of percent passing from manual washing; the results of the 19.0-mm and 4.75-mm sieves are statistically significant. However, the variability of percent passing 75-µm sieve from mechanical washing is significantly larger than that from manual washing. The graphical comparison of the mechanical and manual repeatability standard deviations is shown in Figure 4-1.

The results of the F-test on variance for the statistical comparison of the reproducibility standard deviations of percent passing various sieve sizes from manual and mechanical washing are provided in Table 4-3. It is shown in the tables that for all except the 75-µm sieve, the variability of percent passing from mechanical washing is lower than the variability of percent passing from manual washing

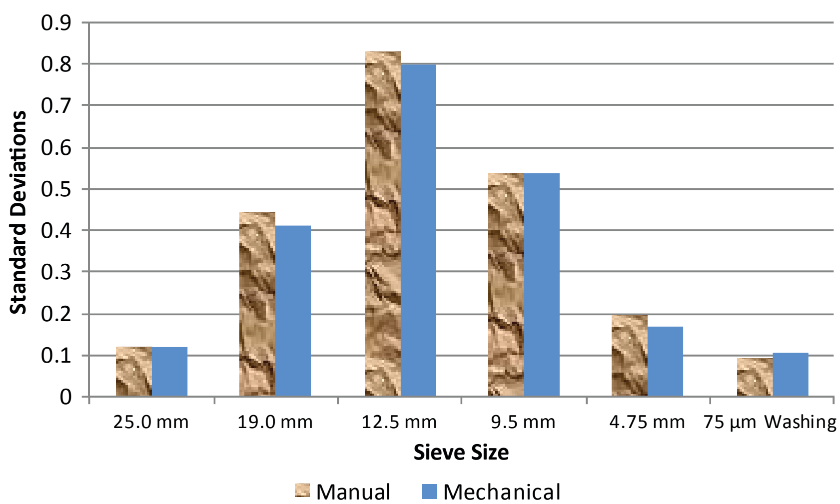

Figure 4-1 Repeatability standard deviations of percent passing various sieve sizes after manual and mechanical washing pooled from AGC 169-170, AGC 173-174, and AGC 177-178 samples.

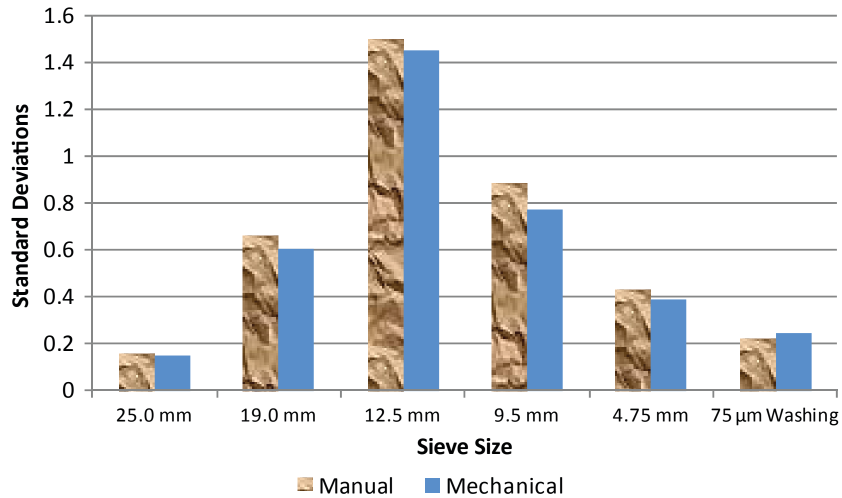

Figure 4-2 Reproducibility standard deviations of percent passing various sieve sizes after manual and mechanical washing pooled from AGC 169-170, AGC 173-174, and AGC 177-178 samples.

and the variability associated with 19.0-mm, 9.5-mm, and 4.75-mm sieve sizes is statistically significant. The variability of percent passing the 75-µm sieve for mechanical washing is significantly larger than that for manual washing at both the 1% and 5% levels of significance. The graphical comparison of the mechanical and manual reproducibility standard deviations is shown in Figure 4-2.

From the above, it is observed that with the exception of percent passing the 75-µm sieve, the mechanical washing method has resulted in lower repeatability and reproducibility standard deviations of the percent passing of various sieve sizes. Therefore, it might be concluded that mechanical washing would improve removal of the filler and dust from coarse aggregates over manual washing. The results of the statistical test of significance for individual sample pairs of AGC 169-170, AGC 173-174, and AGC 177-178 can be found in Appendix F.

4.1.2 Analysis of AGF Data

Table 4-4 through Table 4-6 provide the results of statistical comparison of the pooled averages and repeatability/reproducibility standard deviations of percent passing various sieve sizes from manual and

Table 4-4 Results of the statistical t-test for comparison of average percent passing various sieve sizes from mechanical and manual washing pooled from AGF 171-172, AGF 175-176, and AGF 179-180 samples.

Sieve Size	Percent Passing, Manual	Percent Passing, Mechanical	Degrees of Freedom	Computed t	P-Value
4.75-mm	99.93	99.97	389	-9.08	5.7E-18
2.36-mm	85.77	85.97	377	-5.75	1.8E-08
1.18-mm	71.04	71.15	378	-4.64	4.9E-06
600-µm	52.17	52.28	379	-2.39	1.7E-02
300-µm	19.61	19.81	378	-5.03	7.7E-07
150-µm	3.59	3.69	391	-6.82	3.5E-11
75-µm	1.09	1.15	404	-5.53	5.8E-08
75-µm Washing	0.95	1.03	423	-8.35	9.8E-16

Note: Critical t for 1% level of significance is 2.59 and for 5% level of significance is 1.96.

Table 4-5 Results of the statistical F-test for comparison of repeatability standard deviations of percent passing various sieve sizes after mechanical and manual washing, pooled from AGF 171-172, AGF 175-176, and AGF 179-180 samples.

Sieve Size	1s Repeatability, Manual	1s Repeatability, Mechanical	Degrees of Freedom	Computed F	Critical F (α=0.01)	Critical F (α=0.05)	P-Value
4.75-mm	0.056	0.065	335 & 3898	1.35	1.2	1.14	5.09E-05
2.36-mm	0.371	0.380	313 & 3873	1.05	1.2	1.14	0.262
1.18-mm	0.311	0.293	3900 & 317	1.12	1.22	1.15	0.089
600-µm	0.310	0.295	3882 & 323	1.1	1.22	1.15	0.128
300-µm	0.230	0.211	3871 & 321	1.19	1.22	1.15	0.022
150-µm	0.117	0.117	318 & 3809	1.01	1.2	1.14	0.461
75-µm	0.089	0.089	317 & 3816	1.01	1.2	1.14	0.42
75-µm Washing	0.080	0.074	3998 & 326	1.18	1.22	1.15	0.026

mechanical washing of AGF 171-172, AGF 175-176, and AGF 179-180 fine aggregates.

Table 4-4 provides the results of the statistical t-test on average percent passing from manual and mechanical washing of AGF 171-172, AGF 175-176, and AGF 179-180 samples. As shown from the p-values in the table, the percent passing all sieve sizes from mechanical washing are significantly larger than those from manual washing.

The results of the statistical F-test on variance for comparison of the repeatability standard deviations of percent passing various sieve sizes from manual and mechanical washing, pooled from AGF 171-172, AGF 175-176, and AGF 179-180 samples, are provided in Table 4-5. From the p-values, it is indicated that the repeatability standard deviation of percent passing of three sieve sizes, 4.75-mm, 300-µm, and 75-µm, are significantly different; the mechanical washing resulted in significantly lower standard deviation of percent passing 300-µm and 75-µm sieves, while manual washing resulted in significantly lower standard deviation of percent passing of 4.75-mm particles. The differences between all other sieve sizes are not significant. The graphical

Table 4-6 Results of statistical F-test for comparison of reproducibility standard deviations of percent passing various sieve sizes after mechanical and manual washing pooled from AGF 171-172, AGF 175-176, and AGF 179-180 samples.

Sieve Size	1s Reproducibility, Manual	1s Reproducibility, Mechanical	Degrees of Freedom	Computed F	Critical F (α=0.01)	Critical F (α=0.05)	P-Value
4.75-mm	0.061	0.065	335 & 3898	1.11	1.2	1.14	0.084
2.36-mm	0.667	0.607	3873 & 313	1.21	1.22	1.15	0.015
1.18-mm	0.432	0.405	3900 & 317	1.14	1.22	1.15	0.064
600-µm	0.793	0.794	323 & 3882	1	1.2	1.14	0.479
300-µm	0.706	0.697	3871 & 321	1.03	1.22	1.15	0.387
150-µm	0.294	0.257	3809 & 318	1.31	1.22	1.15	0.001
75-µm	0.215	0.172	3816 & 317	1.56	1.22	1.15	2.05E-07
75-µm Washing	0.221	0.169	3998 & 326	1.71	1.22	1.15	5.57E-10

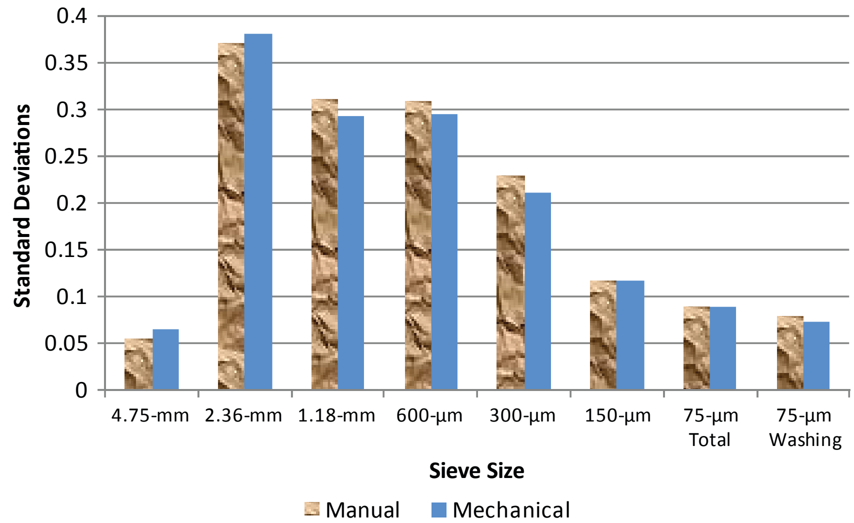

Figure 4-3 Repeatability standard deviations of percent passing various sieve sizes after manual and mechanical washing pooled from AGF 171-172, AGF 175-176, and AGF 179-180 samples.

comparison of the mechanical and manual repeatability standard deviations is shown in Figure 4-3.

The results of the statistical F-test on variance for comparison of the reproducibility standard deviations of percent passing various sieve sizes from manual and mechanical washing, pooled from AGF 171-172, AGF 175-176, and AGF 179-180 samples, are provided in Table 4-6. It is indicated from the table that the reproducibility standard deviation of the majority of sieve sizes is smaller from mechanical washing than from manual washing. The p-values in Table 4-6 show that the reproducibility standard deviation of percent passing of four sieve sizes including 75-µm by sieving and by mechanical washing are significantly lower than those from manual washing. The differences between all other sieve sizes are not statistically significant. The graphical comparison of the mechanical and manual repeatability standard deviations is shown in Figure 4-4. The results of statistical test of significance for individual sample pairs of AGF 171-172, AGF 175-176, and AGF 179-180 samples can be found in Appendix G.

From the above, it is observed that the mechanical washing method has resulted in lower repeatability

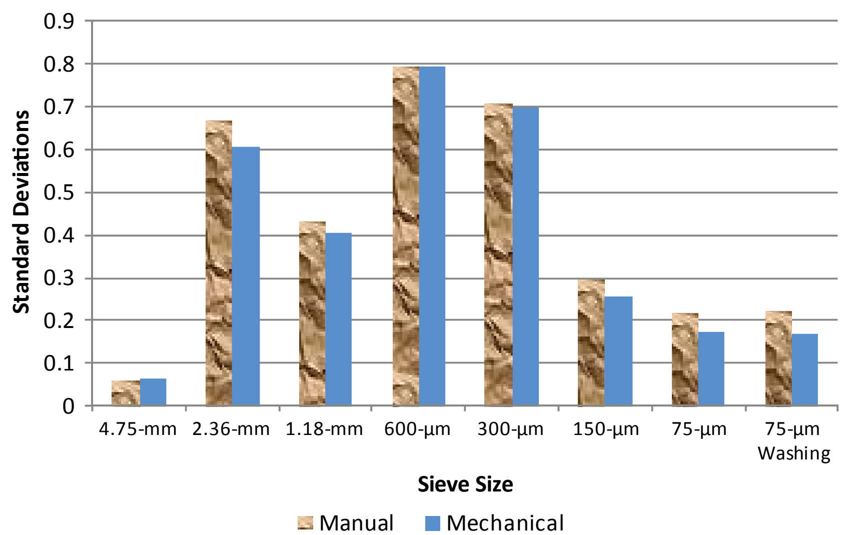

Figure 4-4 Reproducibility standard deviations of percent passing various sieve sizes from manual and mechanical washing pooled from AGF 171-172, AGF 175-176, and AGF 179-180 samples.

Table 4-7 Results of the statistical t-test for comparison of average percent passing various sieve sizes for mechanical and manual washing pooled from HMAIO 19-20, 21-22, 23-24, and 25-26 samples.

Sieve Size	Average Percent Passing, Manual	Average Percent Passing, Mechanical	Deg. of Freedom	Computed t	P-Value
12.5-mm	94.68	94.68	755	0	1
9.5-mm	86.23	86.28	770	-2.55	0.011
4.75-mm	60.98	61.08	712	-3.81	0.000
2.36-mm	39.28	39.53	752	-5.64	2.37E-08
1.18-mm	25.60	25.83	748	-8.82	7.967E-18
600-µm	17.30	17.58	730	-10.60	1.554E-24
300-µm	12.40	12.75	716	-12.83	4.717E-34
150-µm	9.79	10.18	693	-13.93	4.817E-39
75 µm, Total	8.31	8.66	708	-11.97	3.501E-30

Note: Critical t for 1% level of significance is 2.58 and for 5% level of significance is 1.97.

and reproducibility standard deviations of the percent passing of a majority of sieve sizes. Therefore, it might be concluded that mechanical washing would improve removal of the filler and dust from fine aggregates, compared with the manual washing.

4.1.3 Analysis of HMAIO Data

Table 4-7 through Table 4-9 provide the results of the statistical comparison of the pooled averages and repeatability/reproducibility standard deviations of the percent passing various sieve sizes from manual and mechanical washing of HMAIO 19-20, 21-22, 23-24 and 25-26 samples.

Table 4-7 provides the results of the statistical t-test on average percent passing from manual and mechanical washing of HMAIO 19-20, 21-22, 23-24 and 25-26 samples. As shown in the table, with the exception of the percent passing the 12.5-mm sieve

Table 4-8 Results of statistical F-test for comparison of repeatability standard deviations of percent passing various sieve sizes from mechanical and manual washing pooled from HMAIO 19-20, 21-22, 23-24, and 25-26 samples.

Sieve Size	1s Repeatability, Manual	1s Repeatability, Mechanical	Deg. of Freedom	Computed F	Critical F(α=.01)	Critical F(α=.05)	P-Value
12.5-mm	0.387	0.394	506 & 2321	1.04	1.17	1.12	0.297
9.5-mm	0.329	0.329	2273 & 500	1	1.18	1.12	0.497
4.75-mm	0.392	0.445	493 & 2212	1.29	1.17	1.12	8E-05
2.36-mm	0.732	0.756	507 & 2275	1.07	1.17	1.12	0.175
1.18-mm	0.324	0.329	495 & 2208	1.03	1.17	1.12	0.349
600-µm	0.322	0.333	491 & 2199	1.07	1.17	1.12	0.164
300-µm	0.306	0.316	489 & 2218	1.07	1.17	1.12	0.164
150-µm	0.305	0.308	478 & 2219	1.02	1.18	1.12	0.388
75 µm, Total	0.287	0.3	487 & 2211	1.1	1.17	1.12	0.094

Table 4-9 Results of the statistical F-test for comparison of reproducibility standard deviations of percent passing various sieve sizes after mechanical and manual washing pooled from HMAIO 19-20, 21-22, 23-24, and 25-26 samples.

Sieve Size	Reproducibility, Manual	Reproducibility, Mechanical	Deg. of Freedom	Computed F	Critical F(α=.01)	Critical F(α=.05)	P-Value
12.5-mm	0.482	0.471	2321 & 506	1.05	1.18	1.12	0.26
9.5-mm	0.418	0.393	2273 & 500	1.13	1.18	1.12	0.04
4.75-mm	0.512	0.531	493 & 2212	1.08	1.17	1.12	0.147
2.36-mm	0.905	0.902	2275 & 507	1.01	1.18	1.12	0.469
1.8-mm	0.525	0.511	2208 & 495	1.06	1.18	1.13	0.223
600-µm	0.523	0.519	2199 & 491	1.01	1.18	1.13	0.433
300-µm	0.542	0.548	489 & 2218	1.02	1.17	1.12	0.377
150-µm	0.557	0.564	478 & 2219	1.03	1.18	1.12	0.351
75 µm, Total	0.562	0.575	487 & 2211	1.04	1.17	1.12	0.265

size, the percent passing all sieve sizes from mechanical washing is significantly larger than the percent passing manual washing.

The results of the statistical F-test on variance for comparison of the repeatability standard deviations of manual and mechanical washing pooled from HMAIO 19-20, 21-22, 23-24, and 25-26 samples are provided in Table 4-8. The table shows that the repeatability standard deviations of the percent passing all sieve sizes are larger from mechanical washing than those from manual washing; however, only the repeatability standard deviation of the percent passing the 4.75-mm sieve from mechanical washing is significantly larger than that from the manual washing (p-value of 8×10^{-5}). The graphical comparison of the mechanical and manual repeatability standard deviations is shown in Figure 4-5.

The results of the statistical F-test on variance for comparison of the reproducibility standard deviations of the percent passing various sieve sizes

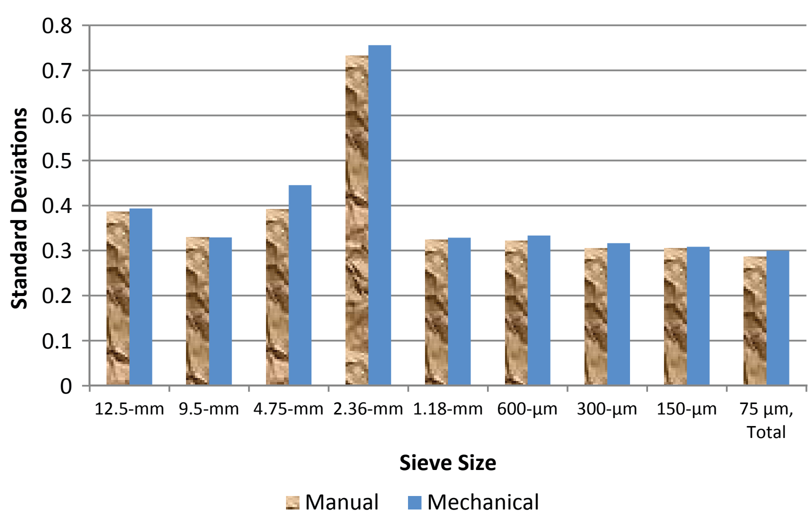

Figure 4-5 Repeatability standard deviations of percent passing various sieve sizes from manual and mechanical washing pooled from HMAIO 19-20, 21-22, 23-24, and 25-26 samples.

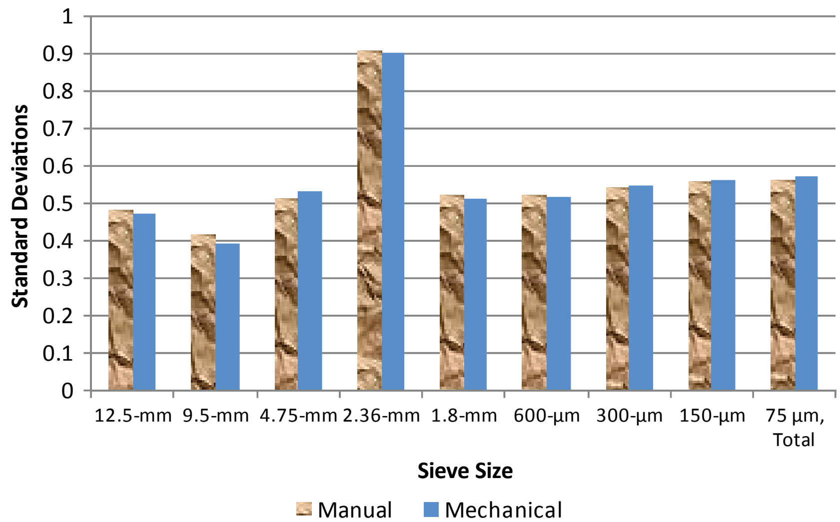

Figure 4-6 Reproducibility standard deviations of percent passing various sieve sizes from manual and mechanical washing pooled from HMAIO 19-20, 21-22, 23-24, and 25-26 samples.

from manual and mechanical washing, pooled from HMAIO 19-20, 21-22, 23-24, and 25-26 samples, are provided in Table 4-9. It is indicated from the table that mechanical washing provided improved reproducibility precision of percent passing of six out of nine sieve sizes. The p-values in the table indicate that the only case of statistical significance corresponds to the percent passing the 9.5-mm sieve, where mechanical washing has significantly improved the variability of measurements. The graphical comparison of the mechanical and manual reproducibility standard deviations is demonstrated in Figure 4-6.

From the above, it is observed that the mechanical washing method has resulted in improved reproducibility standard deviations of the percent passing of the majority of sieve sizes. Therefore, it might be concluded that mechanical washing could help in more consistent removal of the filler and dust from the extracted aggregates over the manual washing. The results of the statistical tests of HMAIO 19-20, 21-22, 23-24, and 25-26 samples can be found in Appendix H.

4.1.4 Analysis of HMASE Data

Table 4-10 through Table 4-12 provide the results of the statistical comparison of the pooled averages and repeatability/reproducibility standard deviations of the percent passing various sieve sizes from manual and mechanical washing of HMASE 73-74, 75-76, and 77-78 samples.

Table 4-10 provides the results of the statistical t-test on average percent passing values corresponding to manual and mechanical washing of HMASE 73-74, 75-76, and 77-78 samples. As shown in the table, for a majority of sieve sizes, the mechanical washing has resulted in a larger percent passing than the manual washing. The p-values in Table 4-10 indicate that for 4.75-mm, 300-µm, 150-µm, and 75-µm sieve sizes, mechanical washing resulted in a significantly larger percent passing than manual washing.

The results of the statistical F-test on variance for comparison of the repeatability standard deviations of manual and mechanical washing, pooled from HMASE 73-74, 75-76, and 77-78 samples, are provided in Table 4-11. As indicated from the table, mechanical washing resulted in a larger repeatability standard deviation than manual washing for eight out of nine sieve sizes. However, the p-values indicate that none of the differences in percent passing values are statistically significant. The graphical comparison of the mechanical and manual repeatability standard deviations is demonstrated in Figure 4-7.

The statistical F-test on variance for comparison of the reproducibility standard deviations of percent passing various sieve sizes from manual and mechanical washing, pooled from HMASE 73-74, 75-76, and 77-78 samples, is provided in Table 4-12.

Table 4-10 Results of the statistical t-test for comparison of average percent passing various sieve sizes for mechanical and manual washing pooled from HMASE 73-74, 75-76, and 77-78 samples.

Sieve Size	Average Percent Passing, Manual	Average Percent Passing, Mechanical	Deg. of Freedom	Computed t	P-Value
12.5-mm	94.90	94.90	211	0	1
9.5-mm	86.70	86.73	205	-0.87	0.383
4.75-mm	60.30	60.37	194	-2.03	0.044
2.36-mm	38.20	38.20	233	0	1
1.18-mm	24.67	24.73	228	-1.25	0.214
600-µm	17.17	17.23	231	-1.21	0.228
300-µm	12.83	13.07	218	-4.11	5.625E-05
150-µm	10.50	10.77	213	-4.56	8.765E-06
75 µm, Total	9.07	9.23	213	-2.9	0.004

Note: Critical t for 1% level of significance is 2.59 and for 5% level of significance is 1.97.

This table shows that for five out of nine sieve sizes, mechanical washing resulted in larger reproducibility standard deviations than manual washing. However, the p-values indicate that the differences in reproducibility standard deviations of percent passing from manual and mechanical washing are not statistically significant. The graphical comparison of the mechanical and manual reproducibility standard deviations is presented in Figure 4-8.

From the above, it is observed that the mechanical washing of HMASE has resulted in variability that is not significantly different from that of manual washing. This and the fact that mechanical washing resulted in significantly more materials passing through

Table 4-11 Results of the statistical F-test for comparison of repeatability standard deviations of percent passing various sieve sizes after mechanical and manual washing pooled from HMASE 73-74, 75-76, and 77-78 samples.

Sieve Size	1s Repeatability, Manual	1s Repeatability, Mechanical	Deg. of Freedom	Computed F	Critical F(α=.01)	Critical F(α=.05)	P-Value
12.5-mm	0.3	0.315	144 & 654	1.11	1.34	1.23	0.209
9.5-mm	0.292	0.305	146 & 645	1.09	1.34	1.23	0.241
4.75-mm	0.223	0.244	132 & 600	1.2	1.35	1.24	0.079
2.36-mm	0.777	0.807	151 & 693	1.08	1.33	1.22	0.265
1.18-mm	0.396	0.396	658 & 146	1	1.37	1.25	0.509
600-µm	0.399	0.401	146 & 664	1.01	1.33	1.23	0.446
300-µm	0.391	0.398	149 & 664	1.04	1.33	1.23	0.374
150-µm	0.378	0.368	672 & 146	1.05	1.37	1.25	0.357
75 µm, Total	0.36	0.371	143 & 659	1.06	1.34	1.23	0.314

Table 4-12 Results of the statistical F-test for comparison of reproducibility standard deviations of percent passing various sieve sizes after mechanical and manual washing pooled from HMASE 73-74, 75-76, and 77-78 samples.

Sieve Size	Reproducibility, Manual	Reproducibility, Mechanical	Deg. of Freedom	Computed F	Critical F(α=.01)	Critical F(α=.05)	P-Value
12.5-mm	0.391	0.395	144 & 654	1.02	1.34	1.23	0.417
9.5-mm	0.388	0.424	146 & 645	1.2	1.34	1.23	0.076
4.75-mm	0.342	0.344	132 & 600	1.01	1.35	1.24	0.457
2.36-mm	0.994	0.927	693 & 151	1.15	1.36	1.24	0.146
1.18-mm	0.622	0.578	658 & 146	1.16	1.37	1.25	0.136
600-µm	0.653	0.594	664 & 146	1.21	1.37	1.25	0.08
300-µm	0.616	0.631	149 & 664	1.05	1.33	1.23	0.342
150-µm	0.636	0.644	146 & 672	1.03	1.33	1.23	0.409
75 µm, Total	0.635	0.623	659 & 143	1.04	1.37	1.25	0.395

the 300-µm sieve and smaller suggests that better washing of aggregates would occur from mechanical washing. The results of the statistical test of significance for individual sample pairs of HMASE 73-74, 75-76, and 77-78 samples can be found in Appendix I.

4.2 Evaluation of Degradation from Mechanical Washing

In previous sections, the comparison of the average percent material passing various sieve sizes from mechanical and manual washing indicated that with mechanical washing a significantly larger percent of material passes through various sieve sizes. This might indicate that in addition to separation of filler from coarser aggregates, some degradation of the coarser aggregates is taking place. To explore the possibility of degrading of the mechanically washed aggregates, the percent loss or gain was computed for each sieve size. Tables 4-13 through 4-16 show the calculations for determining the amount of degradation of the aggregates in each of the AGF, AGC,

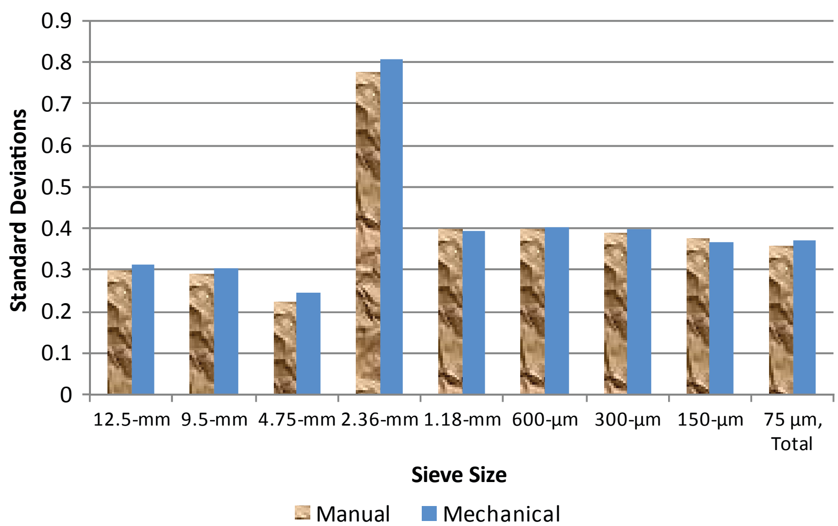

Figure 4-7 Repeatability standard deviations of percent passing various sieve sizes after manual and mechanical washing pooled from HMASE 73-74, 75-76, and 77-78 samples.

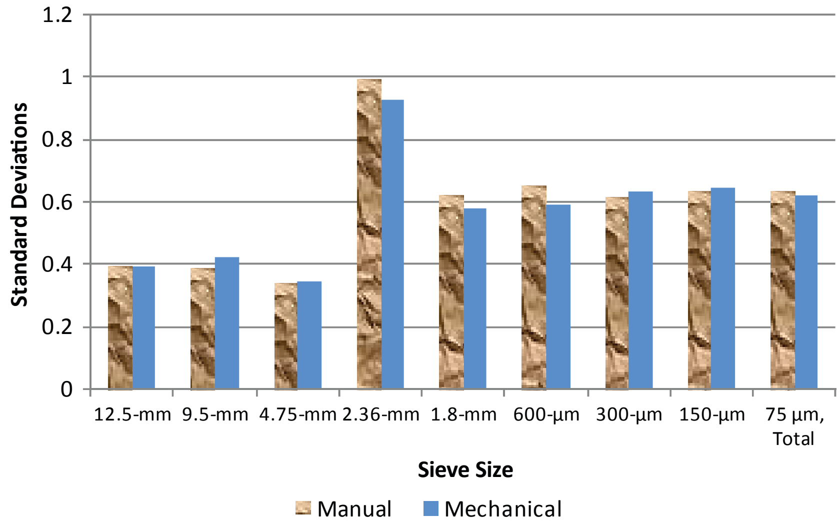

Figure 4-8 Reproducibility standard deviations of percent passing various sieve sizes after manual and mechanical washing, pooled from HMASE 73-74, 75-76, and 77-78 samples.

Table 4-13 Percent degradation of fine aggregates from mechanical washing.

Sample ID	Sieve Sizes	% Retained-Manual	% Retained-Mechanical	%Loss/ %Gain	%Degradation
AGF 171-172	4.75 mm	0.2	0.1	-0.1	0.30
	2.36 mm	14.3	14.3	0	
	1.18 mm	14.3	14.3	0	
	600 µm	18.4	18.5	0.1	
	300 µm	34.4	34.2	-0.2	
	150 µm	13.6	13.7	0.1	
	75 µm total	3.1	3.2	0.1	
	Pan	1.7	1.7	0	
AGF 175-176	4.75 mm	14.1	13.8	-0.3	0.40
	2.36 mm	15.2	15.4	0.2	
	1.18 mm	18.6	18.6	0	
	600 µm	31.9	31.8	-0.1	
	300 µm	18.62	18.75	0.13	
	150 µm	1.2	1.2	0	
	75 µm total	0.08	0.08	0	
	Pan	0.3	0.37	0.07	
AGF 179-180	4.75 mm	14.1	13.88	-0.22	0.32
	2.36 mm	14.69	14.78	0.09	
	1.18 mm	19.6	19.5	-0.1	
	600 µm	31.39	31.41	0.02	
	300 µm	15.84	15.91	0.07	
	150 µm	3.19	3.23	0.04	
	75 µm total	0.14	0.16	0.02	
	Pan	1.05	1.13	0.08	

Table 4-14 Percent degradation of coarse aggregates from mechanical washing.

Sample ID	Sieve Sizes	% Retained-Manual	% Retained-Mechanical	%Loss/ %Gain	%Degradation
AGC 169-170	25.0 mm	0.2	0.2	0	0.6
	19.0 mm	13.8	13.7	-0.1	
	12.5 mm	33.6	33.5	-0.1	
	9.5 mm	37.9	37.5	-0.4	
	4.75 mm	12.1	12.3	0.2	
	75 µm washing	1.2	1.3	0.1	
	Pan	1.2	1.5	0.3	
AGC 173-174	19.0 mm	13.6	13.5	-0.1	0.3
	12.5 mm	35	34.8	-0.2	
	9.5 mm	34.4	34.5	0.1	
	4.75 mm	16.5	16.61	0.11	
	75 µm washing	0.24	0.25	0.01	
	Pan	0.26	0.34	0.08	
AGC 177-178	19.0 mm	14.8	14.8	0	0.1
	12.5 mm	37.7	37.6	-0.1	
	9.5 mm	33.4	33.4	0	
	4.75 mm	13.66	13.66	0	
	75 µm washing	0.26	0.3	0.04	
	Pan	0.18	0.24	0.06	

HMAIO, and HMASE samples. The details of the calculation are explained as follows:

1. For each sieve size, the percent retained is computed using the percent passing corresponding to both manual and mechanical washing.
2. Assuming that no degradation is taking place from manual washing for each sieve, subtracting the percent retained corresponding to the manual washing from that of the mechanical washing would provide the percent change in a particular sieve, either from loss or gain.
3. For each sieve, a negative value indicates loss of aggregates and a positive value indicates gain of aggregates for that sieve size, which have resulted from loss of aggregates in upper sieve sizes.
4. Since the loss of aggregates in upper sieves would result in the gain of aggregates in the lower sieves, summation of all the positive values should always be equal to the summation of all the negative values. The absolute value of the percent loss is the measure of degradation.

The following observations are made from evaluation of the degradation values in Tables 4-13 through 4-16:

1. As indicated from the tables, the largest and smallest degradation corresponds to coarse aggregates (AGC169-170 and AGC 177-178) with the total degradation values of 0.6% and 0.1%, respectively.
2. On average, the degradation of fine aggregate and coarse aggregate is about 0.33% compared with degradation of aggregates from ignition oven or solvent extraction of about 0.45%. This difference suggests that extracted aggregates degrade more than the virgin aggregates.
3. The maximum percent loss that has been observed for any sieve size corresponding to AGF, AGC, HMAIO, and HMASE aggregates is 0.4%. This value is considerably smaller

Table 4-15 Percent degradation of ignition oven aggregates from mechanical washing.

Sample ID	Sieve Sizes	% Retained-Manual	% Retained-Mechanical	%Loss/ %Gain	%Degradation
HMAIO 19-20	12.5 mm	5.8	5.8	0	0.4
	9.5 mm	9.2	9.2	0	
	4.75 mm	22.3	22.2	-0.1	
	2.36 mm	19.1	19	-0.1	
	1.18 mm	16	16	0	
	600 µm	11	10.9	-0.1	
	300 µm	6.2	6.1	-0.1	
	150 µm	2.75	2.77	0.02	
	75 µm, Total	1	1.01	0.01	
	Pan	6.65	7.02	0.37	
HMAIO 21-22	12.5 mm	4.4	4.5	0.1	0.5
	9.5 mm	6.6	6.5	-0.1	
	4.75 mm	27.4	27.3	-0.1	
	2.36 mm	22	21.9	-0.1	
	1.18 mm	12.6	12.6	0	
	600 µm	7.6	7.6	0	
	300 µm	4.9	4.8	-0.1	
	150 µm	2.9	2.8	-0.1	
	75 µm, Total	1.9	2	0.1	
	Pan	9.7	10	0.3	
HMAIO 23-24	12.5 mm	5.6	5.6	0	0.5
	9.5 mm	10.2	10.1	-0.1	
	4.75 mm	24.5	24.5	0	
	2.36 mm	25	24.8	-0.2	
	1.18 mm	13.2	13.2	0	
	600 µm	6.2	6.3	0.1	
	300 µm	3.7	3.6	-0.1	
	150 µm	2.1	2	-0.1	
	75 µm, Total	1.3	1.4	0.1	
	Pan	8.2	8.5	0.3	
HMAIO 25-26	12.5 mm	5.5	5.4	-0.1	0.5
	9.5 mm	7.8	7.8	0	
	4.75 mm	26.8	26.8	0	
	2.36 mm	20.7	20.5	-0.2	
	1.18 mm	12.9	13	0.1	
	600 µm	8.4	8.2	-0.2	
	300 µm	4.8	4.8	0	
	150 µm	2.7	2.7	0	
	75 µm, Total	1.7	1.7	0	
	Pan	8.7	9.1	0.4	

Table 4-16 Percent degradation of solvent extraction aggregates from mechanical washing.

Sample ID	Sieve Sizes	% Retained-Manual	% Retained-Mechanical	%Loss/ %Gain	%Degradation
HMASE 73-74	12.5 mm	4	4	0	0.4
	9.5 mm	6.7	6.7	0	
	4.75 mm	27.4	27.3	-0.1	
	2.36 mm	22.7	22.7	0	
	1.18 mm	13.5	13.5	0	
	600 µm	8	7.9	-0.1	
	300 µm	4.5	4.4	-0.1	
	150 µm	2.4	2.3	-0.1	
	75 µm, Total	1.5	1.7	0.2	
	Pan	9.3	9.5	0.2	
HMASE 75-76	12.5 mm	5.7	5.7	0	0.4
	9.5 mm	10	10	0	
	4.75 mm	24.6	24.5	-0.1	
	2.36 mm	23.9	24	0.1	
	1.18 mm	13.5	13.4	-0.1	
	600 µm	6.2	6.3	0.1	
	300 µm	3.7	3.5	-0.2	
	150 µm	2.1	2.1	0	
	75 µm, Total	1.3	1.3	0	
	Pan	9	9.2	0.2	
HMASE 77-78	12.5 mm	5.6	5.6	0	0.4
	9.5 mm	7.9	7.8	-0.1	
	4.75 mm	27.2	27.3	0.1	
	2.36 mm	19.7	19.8	0.1	
	1.18 mm	13.6	13.5	-0.1	
	600 µm	8.3	8.3	0	
	300 µm	4.8	4.6	-0.2	
	150 µm	2.5	2.5	0	
	75 µm, Total	1.5	1.6	0.1	
	Pan	8.9	9	0.1	

than the multilaboratory d2s for percent passing various sieve sizes provided in AASHTO T 27 or AASHTO T 30. Therefore, from a practical point of view, the amount of degradation of these aggregates resulting from mechanical washing is not significant.

Based on the findings above, use of mechanical washing can be allowed in place of the manual washing without any significant change in percent passing each sieve size. However, since the amount of degradation greatly depends on the type of aggregate used, it is recommended that a comparison of sieve analysis results from manual and mechanical washing of a laboratory-prepared aggregate blend of known gradation be made for each aggregate type. If the difference between percent passing each sieve size from manual and mechanical washing is smaller than the multilaboratory d2s values specified in T 11, T 27, or T 30, then mechanical washing could be used for evaluation of other samples of the same aggregate type.

4.3 Effect of Mechanical Washing Duration on Degradation

The degradation values computed in the previous section were the average values resulting from various mechanical washing durations. The laboratories have been conducting mechanical washing for different durations, which could have significant effect on the degradation of aggregate. In fact, part of the between-laboratory variability could be caused by the different durations of the mechanical washing practiced by different laboratories. AMRL, in addition to the data on the method of washing, has been collecting data on the duration of the mechanical washing, which can be used for evaluating the effect of washing duration on aggregate degradation.

For this evaluation, the information on the duration of mechanical washing was used to group the gradation data. Depending on the information received, the data were grouped in three or four categories. For the coarse aggregate, the sieve analysis data were grouped into three categories of 1-5 min, 6-10 min, and more than 11 min. For the AGF, HMAIO, and HMASE aggregates, data were grouped into four categories of 1-5 min, 6-10 min, 11-15 min and more than 16 min. Using the procedure explained in the previous section, the amount of degradation was computed for each washing duration group.

Figures 4-9 through 4-12 show the effect of mechanical washing duration on the amount of aggregate degradation. As indicated from the figures, for each of the aggregate types (AGF, AGC, HMAIO, HMASE), there is an increase in the amount of degradation with the increase in washing time. The deviation between gradations from the manual and mechanical seems to be considerable after 10 minutes of agitation.

To determine an appropriate washing duration range, the percent degradation for each washing period is compared with the acceptable range of two results (multilaboratory d2s) of the total percentage passing different sieve sizes specified in AASHTO T 27 and AASHTO T 30. For both original and extracted aggregates, the comparisons of the degradation levels in Figures 4-9 through 4-12 with the multilaboratory d2s values in AASHTO T 27 and AASHTO T 30 indicate that washing duration should be limited to 10 minutes to ensure that percent degradation is smaller than the largest acceptable difference between results of two laboratories, which is 0.6%. This limitation would improve the between-laboratory variability from mechanical washing as well as reducing the degradation of aggregates. The washing process can be ended earlier if water becomes clear before the end of the 10-minute period. On the other hand, lack of clarity in water at the end of the 10-minute period would indicate that mechanical washing produces considerable amount of filler by degrading the aggregates and, therefore, a manual wash should be used.

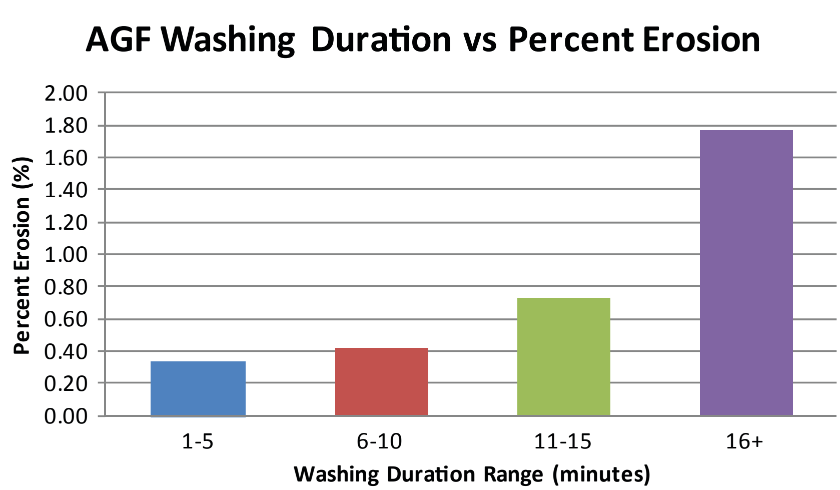

Figure 4-9 Percent increase in degradation of fine aggregates with increase in mechanical washing duration.

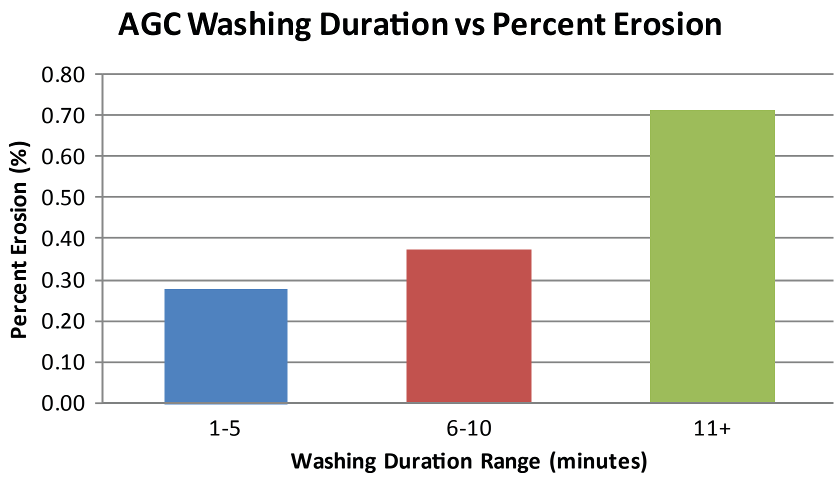

Figure 4-10 Percent increase in degradation of coarse aggregates with increase in mechanical washing duration.

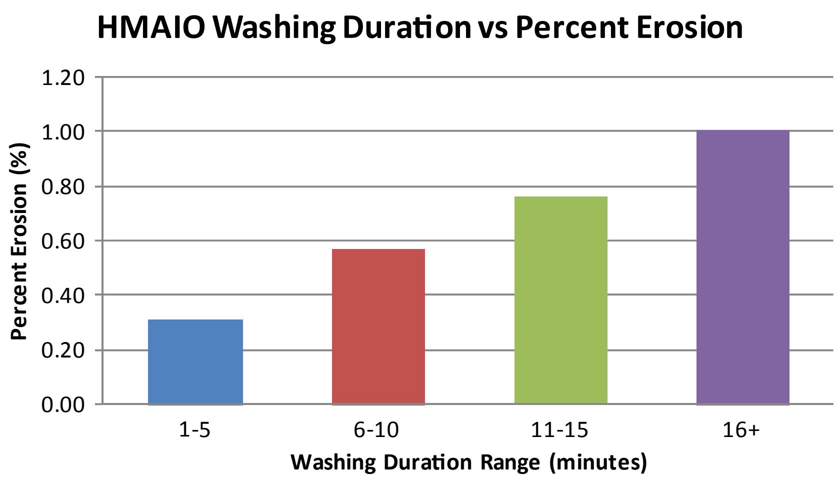

Figure 4-11 Percent increase in degradation of ignition oven aggregate with increase in mechanical washing duration.

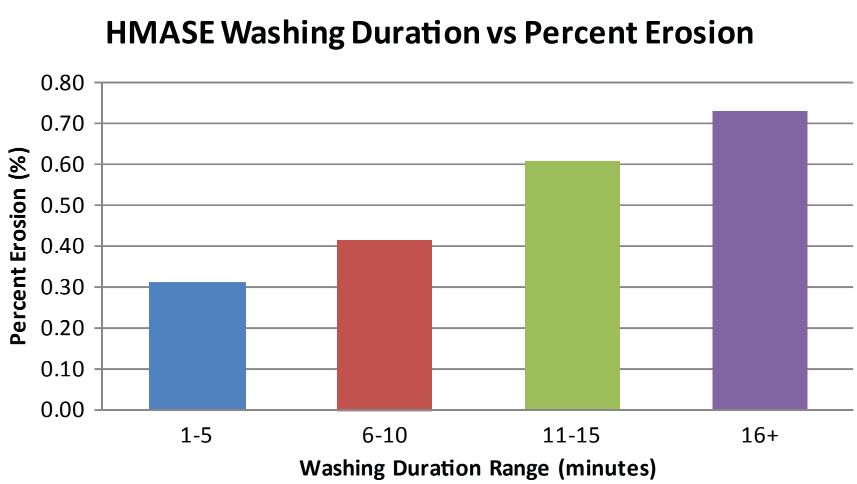

Figure 4-12 Percent increase in degradation of solvent extracted aggregates with increase in mechanical washing duration.

CHAPTER 5—CONCLUSIONS AND PROPOSED CHANGES TO STANDARD TEST METHODS

5.1 Summary and Conclusions

This digest was prepared for Task Order #2 of NCHRP Project 10-87 to update precision estimates of three test methods pertaining to aggregate materials: T 96, Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Testing Machine; T 304, Uncompacted Void Content of Fine Aggregate; and T 11, Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing. As part of updating the precision estimates of AASHTO T 11, the effect of minimum sample size on the repeatability and reproducibility of the test results was investigated. The data from Fine Aggregate (AGF) and Coarse Aggregate (AGC) testing programs of the AMRL Proficiency Sample Program (PSP) were used for the evaluation of precision estimates.

In addition to updating the precision estimates, the effect of manual and mechanical methods of washing on sieve analysis of the aggregates was investigated. For this analysis, the aggregate gradation data from the Hot Mix Asphalt Ignition Oven (HMAIO) and Hot Mix Asphalt Solvent Extraction (HMASE), as well as AGF and AGC testing programs of PSP, were analyzed. The aggregate gradation data from HMAIO and HMASE were obtained according to AASHTO T 30, Mechanical Analysis of Extracted Aggregate, while the aggregate gradation data from AGF and AGC were collected according to AASHTO T 11 and T 27, Sieve Analysis of Fine and Coarse Aggregates. The following conclusions are drawn from the results of the study.

5.1.1 Precision Estimates of AASHTO T 96

For AASHTO T 96, the existing precision estimates are based on an average percent loss in the range of 10% to 45%, while the new set of precision estimates is based on an average percent loss in the range of 13% to 57%. The comparison of the new and existing sets of precision estimates indicates that the 1s% single-operator coefficient of variation of 3% computed in this study is larger than the existing 1s% single-operator coefficient of variation of 2% in ASTM C 131. Similarly, the new 1s% multilaboratory coefficient of variation of 6.2% is larger than the existing 1s% multilaboratory coefficient of variation of 4.5% in ASTM C 131. The increase in both the single-operator and multilaboratory coefficients of variation is likely due to inclusion of data from a greater variety of coarse aggregates with a wider range of degradation resistance than those used for developing the precision estimates of ASTM C 131.

5.1.2 Precision Estimates of AASHTO T 304

For AASHTO T 304, the comparison of the new and existing sets of precision estimates indicates that the new standard deviations are larger than the existing standard deviations. The new precision estimates, based on testing of the PSP fine aggregates with uncompacted void content in a range of 42% to 45%, include the 1s single-operator standard deviation of 0.33% and the 1s multilaboratory standard deviation of 0.81%, which are significantly larger than the existing single-operator standard deviation of 0.13% and multilaboratory standard deviation of 0.33%, respectively. The larger standard deviations based on the PSP data compared with the existing standard deviations are expected since the basis of the existing precision estimates are the uncompacted voids of the "graded standard silica sand," as described in ASTM C 778, with round particles in a range of 600 µm (No. 30) to 150 µm (No. 100), which is not typical of other fine aggregates.

5.1.3 Precision Estimates of AASHTO T 11

For the precision estimates of AASHTO T 11, the new 1s single-operator standard deviation is 0.10% and the 1s multilaboratory standard deviation is 0.21%, based on coarse aggregates with percent materials finer than a 75-µm (No. 200) sieve by washing in a range of 0.19 % to 1.23%. These values are similar to the existing AASHTO T 11 single-operator standard deviation of 0.10% and multilaboratory precision of 0.22%, respectively. The existing set of precision estimates for coarse aggregate is based on aggregates having a nominal maximum size of 19.0 mm (¼ in.) with less than 1.5% finer than the 75-µm (No. 200) sieve.

Likewise, the new 1s single-operator standard deviation is 0.14% and the 1s multilaboratory standard deviation is 0.32%, based on PSP fine aggregates with materials finer than a 75-µm (No. 200) sieve by washing in a range of 0.31% to 2.54%. These values are also comparable with the existing single-operator standard deviation of 0.15% and multilaboratory precision of 0.29%, respectively. The existing precision estimates are based on fine aggregates having 1.0% to 3.0% finer than the 75-µm (No. 200) sieve.

5.1.4 Evaluation of the Effect of Sample Size on T 11 Test Results

The comparison of the repeatability and reproducibility standard deviations of the percent passing No. 200 sieve using 300-g and 500-g sample sizes indicated that from a statistical point of view, significantly smaller multilaboratory standard deviation can be achieved using 500-g sample sizes. However, a difference of 0.01% in the multilaboratory standard deviations of 300-g and 500-g samples translates to an allowable difference of 0.03 % in percent passing No. 200 sieve from two laboratories, which is not considered practically significant.

5.1.5 Comparison of the Method of Washing

The comparison of the average percent passing various sieve sizes from manual and mechanical washing of AGC, AGF, HMAIO, and HMASE indicated that mechanical washing would result in a statistically significant larger percent passing for a majority of sieve sizes, as compared with manual washing. This could indicate better removal of dust and filler, more degradation of aggregates using mechanical washing than using manual washing, or both.

The results of the F-test on variance for the comparison of the repeatability and reproducibility standard deviations of percent passing various sieve sizes from manual and mechanical washing indicated that for the AGC and AGF samples, the variability of the percent passing of a majority of sieve sizes is improved when samples are mechanically washed. However, for the HMAIO and HMASE aggregates, although not statistically significant, repeatability and reproducibility standard deviations are predominantly larger when samples are washed mechanically. This might be due to vulnerability of the aggregates to breakage after exposure to heat and chemical solvents during the removal of the asphalt binder.

5.1.6 Evaluation of Degradation from Mechanical Washing

The fact that a significantly larger percentage of materials would pass through various sieve sizes from mechanical washing might indicate that in addition to removal of filler, some degradation of aggregates is taking place. To evaluate the amount of aggregate degradation during mechanical washing, the percent loss or gain of aggregates for each sieve size was computed. The summation of losses from larger sieve sizes, which is equal to the summation of gains in smaller sieve sizes, was used as the measure of degradation. It was discovered that, on average, the aggregates from ignition oven and solvent extraction have an overall degradation of 0.45% and the virgin fine or coarse aggregates have an overall degradation of 0.33%. For both virgin and extracted aggregates, the overall degradation values are nevertheless considerably smaller than the multilaboratory acceptable range of two results (d2s) for total percentage of material passing specified in AASHTO T 27 and AASHTO T 30. Therefore, it may be concluded that use of mechanical washing does not significantly degrade the aggregates.

5.1.7 Effect of Duration of Mechanical Washing on Degradation

The gradation data were organized into mechanical washing duration groups of 1-5 min, 6-10 min, 11-15 min, and more than 16 min, and the amount of degradation was computed for each duration group. The results showed that there is a significant increase in the amount of degradation when the washing time exceeds 10 minutes. Moreover, the amount of degradation for washing durations of less than 10 min is considerably smaller than the multilaboratory d2s values in AASHTO T 27 and AASHTO T 30. Use of various washing durations by the participating laboratories may contribute to the multilaboratory variability of the sieve analysis results with mechanical washing. Therefore, limiting the washing duration to 10 minutes should improve the multilaboratory variability of sieve analysis results.

5.2 Proposed Changes to AASHTO Standard Test Methods T 96, T 304, and T 11

From the analysis of AMRL Proficiency Sample data in this research, the following changes to the three standard test methods are proposed.

1. Adopt the new precision statement for AASHTO T 96 developed as part of this study and presented in Appendix E. Although the new precision estimates indicate increases in both single-operator and multilaboratory coefficients of variation, the new

precision estimates are based on the properties of a greater variety of coarse aggregates with a wider range of degradation resistance than those used for developing the precision estimates of ASTM C 131.

2. Adopt the new precision statement for AASHTO T 304 developed as part of this study and presented in Appendix E. The new precision estimates are significantly larger than the existing single-operator and multilaboratory standard deviations; however, the new precision estimates are based on properties of a wide selection of fine aggregates, while the existing precision estimates are based on the uncompacted voids of a "graded standard silica sand," which is not typical of other fine aggregates.
3. Adopt the new precision estimates for AASHTO T 11 developed as part of this study and presented in Appendix E. Although the new and existing precision estimates are comparable, there is a slight decrease in the multilaboratory standard deviation of the percent finer than 75-µm sieve for both coarse and fine aggregates, which could reflect improvement in the sieve analysis process.
4. For the fine aggregate sample size of AASHTO T 11, the multilaboratory standard deviation of percent passing 75-µm sieve size using a 500-g sample was 0.01% smaller than that using a 300-g sample, which was statistically significant. However, from a practical standpoint, this is not considered significant since a difference of 0.01% in the standard deviation translates into a 0.03% percent allowable difference between the two results, which is considerably smaller than the multilaboratory d2s of 0.82% specified in AASHTO T 11. Therefore, the minimum sample size of fine aggregates in AASHTO T 11 should remain as 300 g.
5. Based on the sieve analysis of virgin and extracted aggregates used in the PSP, use of mechanical washing is acceptable despite the significantly larger percent of materials passing all sieve sizes from mechanical washing than from manual washing. This is because the amount of degradation that could occur during mechanical washing was found not to be significant from a practical standpoint.
6. Since the amount of degradation greatly depends on the aggregate type, a comparison of sieve analysis results from manual and mechanical washing of a laboratory-prepared aggregate blend of known gradation should be made for each aggregate type. If the difference between the percent passing of each sieve size from manual and mechanical washing is smaller than the multilaboratory d2s values specified in T 11, T 27, or T 30, then mechanical washing can be used for evaluation of other samples of the same aggregate.
7. The duration of the mechanical washing should be limited to 10 minutes. This limitation would improve the multilaboratory variability from mechanical washing and would reduce the degradation of aggregates. The washing process can be ended earlier if water becomes clear before the end of the 10-minute period. On the other hand, lack of clarity in water at the end of the 10-minute period would indicate that a considerable amount of filler is being produced as a result of aggregate degradation and, therefore, manual washing should be used.

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UNPUBLISHED APPENDIXES

The following appendixes are not published herein, but can be found online at http://www.trb.org by searching for NCHRP Project 10-87. The appendixes are titled as follows:

Appendix A: Proficiency Sample Data Sheets and Instructions
Appendix B: T 96 Coarse Aggregate Graphs
Appendix C: T 304 Fine Aggregate Graphs
Appendix D: T 11 Coarse and Fine Aggregate Graphs
Appendix F: Coarse Aggregate—Washing Method Tables and Graphs
Appendix G: Fine Aggregate—Washing Method Tables and Graphs
Appendix H: Hot Mix Asphalt Ignition Oven—Washing Method Tables and Graphs
Appendix I: Hot Mix Asphalt Solvent Extraction—Washing Method Tables and Graphs

APPENDIX E—PRECISION STATEMENTS FOR T 96, T 304, AND T 11

Precision Estimate for AASHTO T 96—Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Testing Machine

E.1 Precision and Bias

E.1.1 Precision. Criteria for judging the acceptability of resistance to degradation results obtained by this method are given in Table E-1.

E.1.1.1 Single-Operator Precision (Repeatability). The figures in Column 2 of Table E-1 are the coefficients of variation that have been found to be appropriate for the conditions of test described in Column 1. Two results obtained in the same laboratory, by the same operator using the same equipment, in the shortest practical period of time, should not be considered suspect unless

Table E-1 Precision estimates.

Statistics	Coefficient of Variation 1s (%)[a]	Acceptable Range of Two Test Results d2s (%)[a]
Single-Operator Precision LA Abrasion Loss (%)	3.0	8.5
Multilaboratory Precision LA Abrasion Loss (%)	6.2	17.6

[a]These values represent the 1s% and d2s% limits described in ASTM Practice C 670.
Note – The precision estimates given in Table E-1 are based on the analysis of test results from 15 pairs of AMRL coarse aggregate proficiency samples. The data analyzed consisted of results from 290 to 513 laboratories for each of the 15 pairs of samples. The average percent LA Abrasion Loss ranged from 13% to 57%. The details of this analysis are presented in the main text of *NCHRP Research Results Digest 389*.

the difference in the two results, expressed as a percent of their mean, exceeds the values given in Table E-1, Column 3.

E.1.1.2 Multilaboratory Precision (Reproducibility). The figures in Column 2 of Table E-1 are the coefficients of variation that have been found to be appropriate for the conditions of test described in Column 1. Two results submitted by two different operators testing the same material in different laboratories shall not be considered suspect unless the difference in the two results, expressed as a percent of their mean, exceeds the values given in Table E-1, Column 3.

E.1.2 Bias. The bias of the procedure in this test method cannot be determined.

Precision Estimate for AASHTO T 304—Uncompacted Void Content of Fine Aggregate

E.2 Precision and Bias

E.2.1 Precision. Criteria for judging the acceptability of void content obtained by this method are given in Table E-2.

E.2.1.1 Single-Operator Precision (Repeatability). The figures in Column 2 of Table E-2 are the standard deviations that have been found to be appropriate for the conditions of test described in Column 1. Two results obtained in the same laboratory, by the same operator using the same equipment, in the shortest practical period of time, should not be considered suspect unless the difference in the two results exceeds the values given in Table E-2, Column 3.

E.2.1.2 Multilaboratory Precision (Reproducibility). The figures in Column 2 of Table E-2 are the standard deviations that have been found to be appropriate for the conditions of test described in Column 1. Two results submitted by two different operators testing the same material in different laboratories shall not be considered suspect unless the difference in the two results exceeds the values given in Table E-2, Column 3.

E.2.2 Bias. The bias of the procedure in this test method cannot be determined.

Precision Estimate for AASHTO T 11—Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing

E.3 Precision and Bias

E.3.1 Precision. Criteria for judging the acceptability of the percentage of materials finer than a 75-µm (No. 200) sieve by washing obtained by this method are given in Table E-3.

E.3.1.1 Single-Operator Precision (Repeatability). The figures in Column 2 of Table E-3 are the standard deviations that have been found to be appropriate for the conditions of test described in Column 1. Two results obtained in the same laboratory, by the same operator using the same equipment, in the shortest practical period of time, should not be considered suspect unless the difference in

Table E-2 Precision estimates.

Statistics	Standard Deviations 1s [a]	Acceptable Range of Two Test Results d2s [a]
Single-Operator Precision Uncompacted Voids (%)	0.33	0.95
Multilaboratory Precision Uncompacted Voids (%)	0.81	2.29

[a]These values represent the 1s (or 1s%) and d2s (or d2s%) limits described in ASTM Practice C 670.

Note – The precision estimates given in Table E-2 are based on the analysis of test results from 14 pairs of AMRL fine aggregate proficiency samples. The data analyzed consisted of results from 183 to 535 laboratories for each of the 14 pairs of samples. The average percent uncompacted voids ranged from 42% to 45%. The details of this analysis are presented in the main text of *NCHRP Research Results Digest 389*.

Table E-3 Precision estimates.

Condition of Test	Standard Deviation 1s [a]	Acceptable Range of Two Test Results d2s [a]
Single-operator Precision Percent finer than75- µm sieve by washing (%)		
Coarse Aggregate	0.10	0.28
Fine Aggregate	0.14	0.39
Multilaboratory Precision Percent finer than 75- µm sieve by washing (%)		
Coarse Aggregate	0.21	0.59
Fine Aggregate	0.32	0.90

[a]These values represent the 1s (or 1s%) and d2s (or d2s%) limits described in ASTM Practice C 670.

Note – The precision estimates given in Table E-3 are based on the analysis of test results from 14 pairs of coarse aggregate and 14 pairs of fine aggregate of the AMRL Proficiency Sample Program. The data analyzed consisted of results from 552 to 1,380 laboratories for each of the 14 pairs of samples of both coarse and fine aggregates. The average percent finer than a 75- µm sieve was less than 1.5% for coarse aggregate and in a range of 1% to 3% for fine aggregate. The details of this analysis are presented in the main text of *NCHRP Research Results Digest 389*.

the two results, exceeds the values given in Table E-3, Column 3.

E.3.1.2 Multilaboratory Precision (Reproducibility). The figures in Column 2 of Table E-3 are the standard deviations that have been found to be appropriate for the conditions of test described in Column 1. Two results submitted by two different operators testing the same material in different laboratories shall not be considered suspect unless the difference in the two results exceeds the values given in Table E-3, Column 3.

E.3.2 Bias. The bias of the procedure in this test method cannot be determined.

Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

ISBN 978-0-309-28400-4

Subscriber Categories: Materials

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