Measuring Air Void Characteristics of Oklahoma Air-Entrained Concrete using the Air Void Analyzer (AVA) / Analyzing AVA Sources of Error

FINAL REPORT - FHWA-OK-08-03

ODOT SPR ITEM NUMBER 2182

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January 2009

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENTS CATALOG NO.
FHWA-OK-08-03		

4. TITLE AND SUBTITLE	5. REPORT DATE / 6. PERFORMING ORGANIZATION CODE
Measuring Air Void Characteristics of Oklahoma Air-Entrained Concrete using the Air Void Analyzer (AVA) / Analyzing AVA Sources of Error	**January 2009**

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT
Steve Trost, Ph.D., P.E.	**SS-07-110-02**

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NO. / 11. CONTRACT OR GRANT NO.
Strategic Solutions International, LLC **1212 S. Main St.** **Stillwater, OK 74074**	**ODOT Item Number 2182**

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED / 14. SPONSORING AGENCY CODE
Oklahoma Department of Transportation **Planning and Research Division** **200 N.E. 21st Street, Room 3A7** **Oklahoma City, OK 73105**	**FINAL** **April 2007 – September 2008**

15. SUPPLEMENTARY NOTES

Project performed in cooperation with the Oklahoma Department of Transportation and the Federal Highway Administration.

16 . ABSTRACT

The conventional method for measuring the size distribution of air voids in concrete (ASTM C457) requires a technician with highly-specialized training and can only be performed on hardened concrete. Waiting several days or even weeks for the concrete to harden enough to be tested does not provide the timely feedback needed for adequate quality control of the concrete's air void structure. To overcome this problem, a Danish company (Dansk Beton Teknik) developed a device to measure the size distribution of air in *fresh* concrete. The device, known as the Air Void Analyzer (AVA), relies on Stoke's law to measure bubble size distribution by timing the bubbles as they rise through a column of glycerol and water.

The Oklahoma Department of Transportation contracted with Strategic Solutions International, LLC to use the AVA to quantify the air void characteristics of standard air-entrained concrete mixes in Oklahoma and to quantify the sources of error inherent in AVA measurements.

The investigation included the following broad tasks:

1. Quantify the air void characteristics of standard mixes being used throughout the state of Oklahoma using the Air Void Analyzer (AVA);
2. Quantify the sources of sampling and testing error inherent in the AVA test procedures and equipment; and
3. Develop and evaluate modifications to the AVA test procedures and/or equipment to improve the precision of the measurements.

The investigation revealed the following:

- Seventy-five percent of mixes tested had their average Spacing Factor above the 0.010-inch threshold.
- Sixty-five percent of the mixes tested had their 95% Lower Confidence Limit above the 0.010-inch threshold.
- Pumping bridge concrete using a conventional pump truck increased the measured Spacing Factor by 0.0018 inches on average.
- The temperature of the liquids in the AVA riser column was found to be the most influential source of potential error. In addition, temperature sensing and control capabilities of the current AVA equipment were found to be lacking, especially in light of the strong influence of temperature on the measured results.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Concrete, Air Voids, Air Void Analyzer, AVA, Spacing Factor, Specific Surface, Freeze/Thaw Durability	**No restrictions. This publication is available from the Planning & Research Division, Oklahoma DOT.**

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	**Unclassified**	**56**	

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectacres	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallon	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
˚F	degrees Fahrenheit	(˚F-32)/1.8	degrees Celsius	˚C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yds
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectacres	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallon	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
˚C	degrees Fahrenheit	9/5(˚C)+32	degrees Celsius	˚F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

Table of Contents

List of Figures

List of Tables

1. Overview

Background

Notice to proceed on Task Order #001 was given by the Oklahoma Department of Transportation (ODOT) to Strategic Solutions International, LLC (SSI) on January 3, 2008. Task Order #001 was issued as a follow-up to work started in FY07 and included the following broad tasks:

1. Quantify the air void characteristics of standard ODOT mixes being used throughout the state using the Air Void Analyzer (AVA);
2. Quantify the sources of sampling and testing error inherent in the AVA test procedures and equipment; and
3. Develop and evaluate modifications to the AVA test procedures and/or equipment to improve the precision of the measurements.

Task 1 – Quantify the air void characteristics of standard ODOT mixes being used throughout the state

Over 300 AVA specimens were sampled and tested between April 2007 and September 2008. The specimens represent a cross-section of approved ODOT air-entrained concrete mixes being used throughout the state. Concrete specimens were sampled from all eight ODOT divisions, from paving mixes and bridge mixes. For each mix, multiple specimens were sampled and tested from multiple batches. For a subset of the bridge mixes, specimens were sampled both before and after the pump. Similarly, for a subset of paving mixes, specimens were sampled both before and after the paving machine. A total of 54 different batches of concrete were sampled and tested.

Task 2 – Quantify the sources of sampling and testing error inherent in the AVA test procedures and equipment

A thorough evaluation of three potential sources of error for AVA measurements has been conducted. The sources of error investigated include volume of glycerol (i.e. “blue liquid”), specimen size, and temperature of the liquids in the riser column. The results of the investigation are presented in Appendix A. In addition, an evaluation of the effect of external vibration was conducted and equipment-to-equipment variation was quantified via side-by-side testing and a round-robin study coordinated by the Kansas Department of Transportation. The round robin involved 19 AVA machines from across the country simultaneously sampling and testing identical batches of concrete. The results of the round robin study are included in Appendix D.

Task 3 – Develop modifications to the AVA test procedures and/or equipment to improve the precision of the measurements

After evaluating the results of Task 2, the investigators compiles a list of recommended improvements, such as improving the temperature-measurement system and improving the device for measuring glycerol volume. In addition, while conducting routine AVA tests, the investigators observed that many times visibly-discernable air bubbles remained in the riser column after the AVA software had ended the test. In an attempt to correct this deficiency, the investigators developed a vacuum-based procedure and fabricated a vacuum chamber to enable measurement of these ultra-small air bubbles.

A complete discussion of the recommended improvements is presented in Section 4. The results of SSI's vacuum-chamber investigation are presented in Appendix B. In addition, a continuous mass measurement add-on has been developed and is discussed in Appendix B and Appendix C.

2. Concrete Air Void Characteristics across Oklahoma

A total of 54 batches of concrete were sampled and tested from 20 different mixes (12 bridge mixes; 8 paving mixes). Summary statistics for Spacing Factor for each mix tested are provided in Appendix E. The step-by-step AVA test procedure used during the study is provided in Appendix F. AVA test results for each specimen are presented in Appendix G.

Figure 1 shows the correlation between Spacing Factor (SF) and Durability Factor (DF) that was established by the U.S. Bureau of Reclamation (Backstrom 1956). The Bureau's experimental results demonstrated that a Spacing Factor less than or equal to 0.008 inches is required if a 90% Durability Factor is to be reliably achieved. Similarly, a Spacing Factor less than or equal to 0.010 inches is required to consistently achieve a Durability Factor of 75% or better.

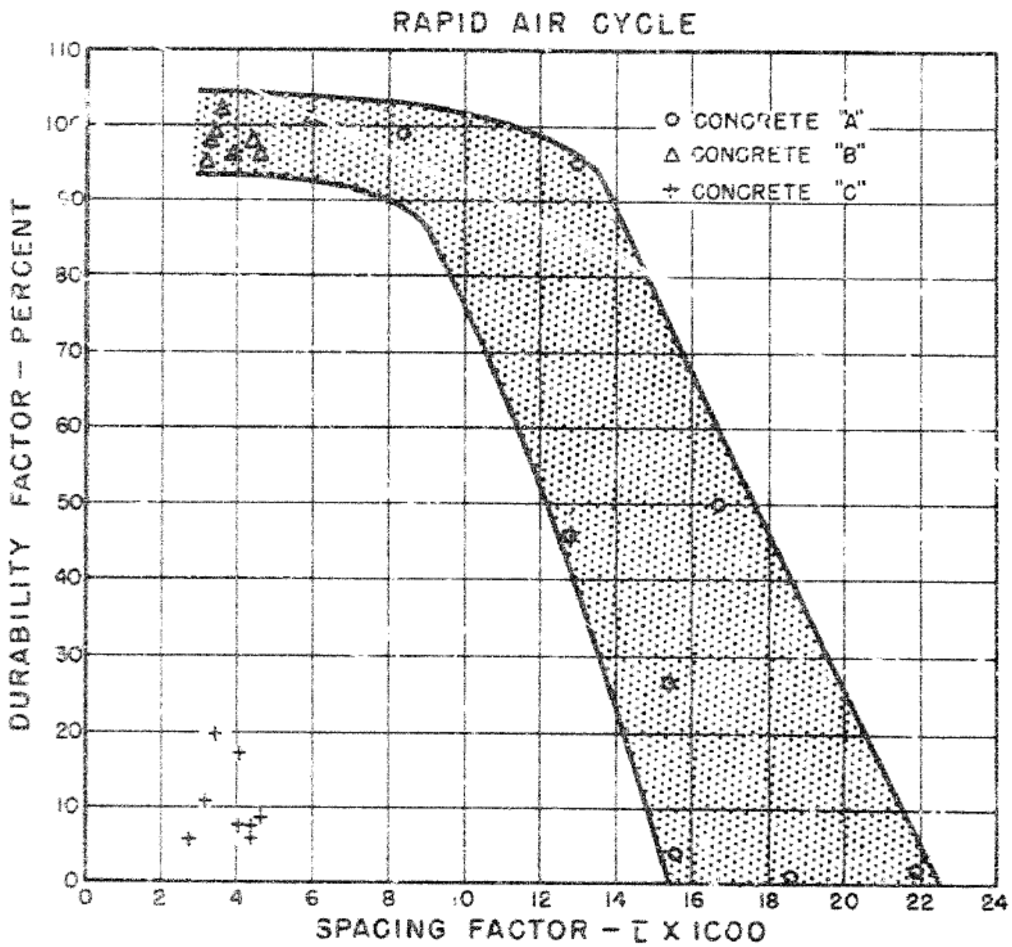


Figure 1 – Durability Factor versus Spacing Factor (from Backstrom 1956)

Table 1 provides the average and median SF values for the 20 different Oklahoma mixes evaluated, along with the number of specimens tested and their within-mix standard deviations. Table 2 and Table 3 divide the data into two subsets – the 8 paving mixes and the 12 bridge mixes respectively. These tables show that *none* of the Oklahoma mixes (paving or bridge) met the stringent 0.008-inch SF threshold recommended by the U.S. Bureau of Reclamation. In addition, only 25% had Spacing Factors less than 0.010 inches, which is the maximum allowable SF specified by the Kansas Department of Transportation (KDOT 2007) and 25% had average Spacing Factors above 0.014-inch, which relates to a Durability Factor of only 20%.

Table 1 – Summary of AVA Spacing Factor Data for Oklahoma Concrete Mixes

Division	Mix #	# of AVA Specimens	Mix Type	Average SF (in.)	Standard Deviation (in.)	Median SF (in.)
1	1-1	9	Bridge	0.0096	0.0020	0.0103
1	1-2	30	Paving	0.0130	0.0018	0.0128
1	1-3	5	Bridge	0.0144	0.0032	0.0141
2	2-1	20	Paving	0.0109	0.0020	0.0110
3	3-1	4	Bridge	0.0085	0.0009	0.0085
3	3-2	11	Bridge	0.0105	0.0008	0.0105
3	3-3	13	Paving	0.0118	0.0011	0.0117
3	3-4	18	Bridge	0.0130	0.0018	0.0137
3	3-5	7	Paving	0.0093	0.0011	0.0098
4	4-1	5	Paving	0.0114	0.0009	0.0112
4	4-2	18	Bridge	0.0126	0.0014	0.0127
4	4-3	34	Bridge	0.0093	0.0015	0.0092
4	4-4	24	Paving	0.0137	0.0013	0.0140
5	5-1	5	Paving	0.0120	0.0024	0.0117
5	5-2	6	Bridge	0.0118	0.0017	0.0114
6	6-1	20	Bridge	0.0093	0.0023	0.0090
7	7-1	25	Bridge	0.0142	0.0029	0.0134
7	7-2	14	Paving	0.0136	0.0028	0.0140
8	8-1	27	Bridge	0.0133	0.0022	0.0133
8	8-2	16	Bridge	0.0146	0.0019	0.0146
Less than 0.010 (> 75% Durabilty Factor)				25%		20%
Greater than 0.010 (< 75% Durabilty Factor)				75%		80%
Greater than 0.014 (< 20% Durability Factor)				25%		25%

Figure 2 provides the average Spacing Factor along with the Upper and Lower 95% Confidence Limits for each mix (based on a pooled standard deviation and the number of specimens tested from each mix). Figure 2 shows that only 7 of the 20 mixes tested (35%) had lower confidence limits below the 0.010-inch threshold and only 2 of the 20 (10%) had lower limits below the 0.008-inch threshold. In addition, all but one of the mixes (95%) had their upper confidence limits above the 0.010-inch threshold.

These data suggest that Oklahoma bridges and concrete pavements currently being constructed may experience durability problems sometime in the future. However, before full reliance can be made upon the data presented in Table 1 and Figure 2, development of a direct prediction model between AVA Spacing Factor and/or AVA Specific Surface and AASHTO T-161 Durability

Factor is recommended. In addition, the actual susceptibility of a given concrete structure to freeze/thaw degradation will be a function of the local climatic conditions (i.e. the cumulative occurrence of actual freeze/thaw cycles).

Table 2 – Summary of AVA Spacing Factor Data for Oklahoma Concrete Paving Mixes

Division	Mix #	# of AVA Specimens	Mix Type	Average SF (in.)	Standard Deviation (in.)	Median SF (in.)
1	1-2	30	Paving	0.0130	0.0018	0.0128
2	2-1	20	Paving	0.0109	0.0020	0.0110
3	3-3	13	Paving	0.0118	0.0011	0.0117
3	3-5	7	Paving	0.0093	0.0011	0.0098
4	4-1	5	Paving	0.0114	0.0009	0.0112
4	4-4	24	Paving	0.0137	0.0013	0.0140
5	5-1	5	Paving	0.0120	0.0024	0.0117
7	7-2	14	Paving	0.0136	0.0028	0.0140
Less than 0.010 (> 75% Durabilty Factor)				12%		12%
Greater than 0.010 (< 75% Durabilty Factor)				88%		88%
Greater than 0.014 (< 20% Durability Factor)				25%		25%

Table 3 – Summary of AVA Spacing Factor Data for Oklahoma Concrete Bridge Mixes

Division	Mix #	# of AVA Specimens	Mix Type	Average SF (in.)	Standard Deviation (in.)	Median SF (in.)
1	1-1	9	Bridge	0.0096	0.0020	0.0103
1	1-3	5	Bridge	0.0144	0.0032	0.0141
3	3-1	4	Bridge	0.0085	0.0009	0.0085
3	3-2	11	Bridge	0.0105	0.0008	0.0105
3	3-4	18	Bridge	0.0130	0.0018	0.0137
4	4-2	18	Bridge	0.0126	0.0014	0.0127
4	4-3	34	Bridge	0.0093	0.0015	0.0092
5	5-2	6	Bridge	0.0118	0.0017	0.0114
6	6-1	20	Bridge	0.0093	0.0023	0.0090
7	7-1	25	Bridge	0.0142	0.0029	0.0134
8	8-1	27	Bridge	0.0133	0.0022	0.0133
8	8-2	16	Bridge	0.0146	0.0019	0.0146
Less than 0.010 (> 75% Durabilty Factor)				33%		25%
Greater than 0.010 (< 75% Durabilty Factor)				67%		75%
Greater than 0.014 (< 20% Durability Factor)				25%		25%

Most of the sampling of AVA specimens occurred directly at the project sites immediately after the concrete was discharged from the delivery truck. Where possible, additional specimens from paving mixes were sampled after the paver and from bridge mixes after the pump.

Unfortunately, the investigators were not able to sample enough paving mixes after the paver to obtain conclusive data regarding possible changes in Spacing Factor due to consolidation by the paving machine.

However, an evaluation of the bridge mix data revealed a statistically-significant *increase* in Spacing Factor after pumping versus before the pump (p = 0.036). Table 4 shows that Spacing Factor increased by 0.0018 inches on average as a result of pumping. This strongly suggests that pumping the concrete eliminates a portion of the entrained air.

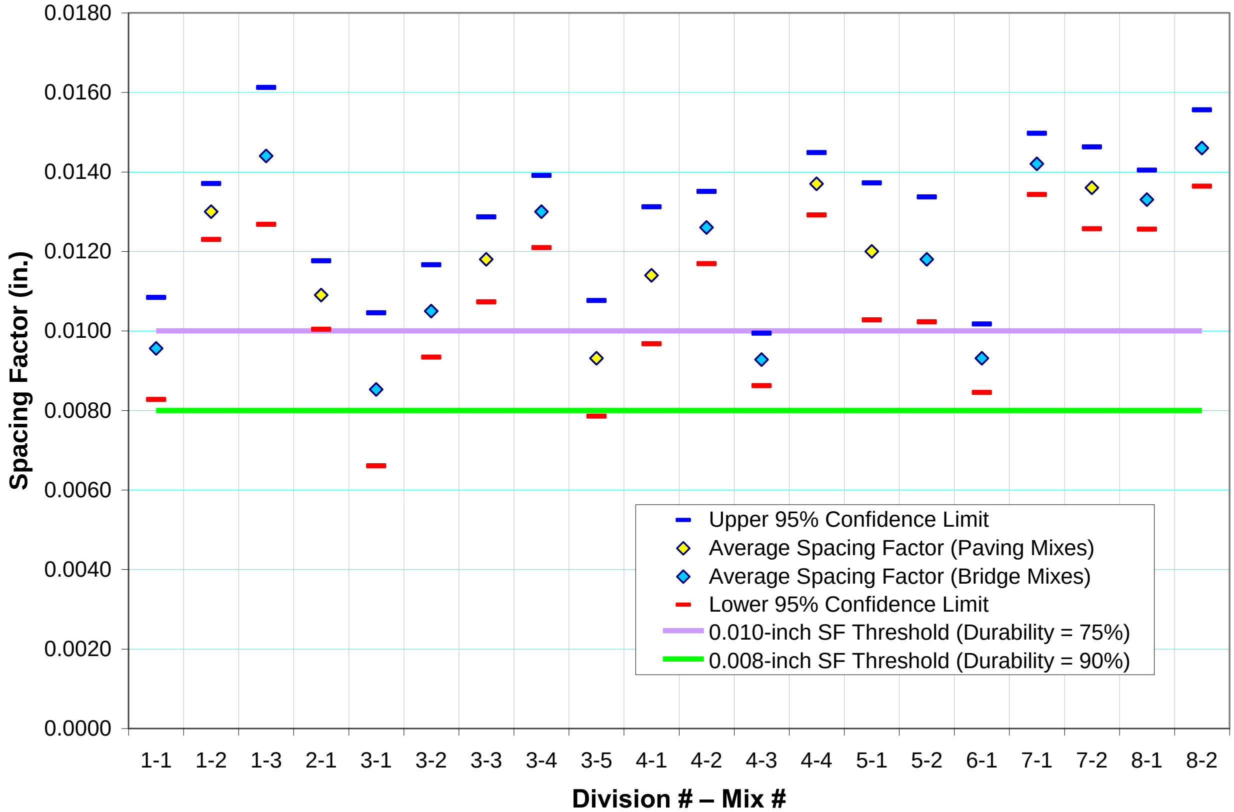


Figure 2 – Average Spacing Factors with Upper and Lower Confidence Limits

Table 4 – Comparison of Spacing Factors for Bridge Mixes Before versus After Pumping

Division	Mix #	Before Pump (1)		After Pump (2)		(2) - (1)
		Avg. SF (in.)	# of AVA Specimens	Avg. SF (in.)	# of AVA Specimens	Change in SF (in.)
4	4-2	0.0125	9	0.0127	9	0.0002
4	4-3	0.0085	18	0.0102	16	0.0017
6	6-1	0.0076	9	0.0116	5	0.0040
7	7-1	0.0141	10	0.0143	15	0.0002
8	8-1	0.0114	11	0.0147	16	0.0032
8	8-2	0.0138	8	0.0154	8	0.0016
Average Difference (After minus Before)						0.0018

3. Sampling and Testing Error Evaluation

Steps Taken to Evaluate Sampling and Testing Error

The following steps were taken to quantify AVA sampling and testing errors:

1. Two designs-of-experiments (DOEs) were completed analyzing the effects of glycerol volume, specimen size, and temperature of the liquids in the riser column.
2. The second DOE was completed with side-by-side testing using two different AVAs – one owned by SSI and one owned by the Federal Highway Administration (FHWA). In addition, SSI participated in a round-robin equipment-variation study that was coordinated by the Kansas Department of Transportation.
3. The probable ranges of two key input variables, glycerol volume and specimen size, were quantified through precision measurements taken during repeated sampling and specimen-preparation actions that were performed in accordance with the manufacturer's recommended testing procedures.
4. Testing error was estimated using the prediction models developed during Steps 1 and 2 in conjunction with the probable ranges determined during Step 3.
5. A separate vibration study was conducted to quantify the impact of external sources of vibration on the measured results.

Overview of Sampling and Testing Error Results

The results of Step 1 showed that, of the three variables analyzed, *temperature* exhibits the greatest impact on the measured values for both specific surface (SS) and spacing factor (SF), followed closely by glycerol volume. Of the three variables, specimen size demonstrated the least impact.

Step 2 demonstrated that considerable equipment-to-equipment variation can be expected. During the round-robin study, the pooled coefficients of variation (COVs) for SS and SF were 16% and 22% respectively. However, due to the fact that a given AVA specimen can only be tested by a single AVA machine, the aforementioned equipment-to-equipment COVs represent sampling and testing variability in addition to equipment-to-equipment variability. During the side-by-side testing, the stirring mechanism on the FHWA machine appeared to provide greater agitation. A subsequent analysis of the two stirrers identified a 6-percent difference in revolutions per minute between the two machines. Given the fact that the function of the stirring mechanism is to disperse the AVA specimen throughout the glycerol, the observed difference in stirring should not significantly affect the outcome of the test as long as each specimen is completely dispersed.

Step 3 showed that the volume of glycerol added to the riser column can be expected to vary from minus 4 to plus 3 percent when using the manufacturer's recommended procedure for measuring and adding glycerol. Similarly, the range for specimen size can be expected to vary from minus 3 to plus 5 percent.

Step 4 showed that the effect of temperature can cause SS and SF to each vary by minus 7 to plus 3 percent across the manufacturer's recommended temperature range (21 to 25 C for the liquids in the riser column). By contrast, variations in specimen size can be expected to produce measurement differences ranging from minus 1 to plus 2 percent for SS and minus 2 to plus 1 percent for SF. The influence of glycerol volume was more pronounced than specimen size, resulting in expected measurement differences ranging from minus 4 to plus 2 percent for SS and minus 2 to plus 5 for SF.

During Step 5, tests were performed using SSI's AVA under four types of vibration: (1) table vibration, (2) intermittent air flow, (3) continuous air flow, and (4) no vibration. The purpose of the experiment was to determine how different sources of external vibration affect the AVA's scale and the resulting measurements of SS and SF. Twenty-four specimens were tested and an analysis of the data was performed. The analysis demonstrated that intermittent air flow across the AVA, such as from indoor HVAC systems or external wind gusts, can have a significant impact on the scale measurements and also on the AVA measurements. This suggests that extreme care should be taken to shield AVA equipment from sources of air flow. Table vibration was also found to have some effect on the scale measurements. However, the scope of the experiment and analysis did not allow the effect of vibration on AVA measurements to be fully quantified.

The impact of external vibration on AVA results is exacerbated by the fact that the AVA software relies upon only three scale measurements per minute. A method for reducing the impact of vibration by taking continuous mass measurements was developed.

4. Improvements to AVA Equipment and Procedures

While quantifying the sources of AVA measurement error, the investigators identified several pitfalls associated with the current AVA equipment and procedures:

- The AVA software ends the test after 25 minutes even if *measurable* bubbles are still in the riser column. This can result in significant amounts of entrained air that are completely excluded from the test.
- In many instances, extremely small but *visibly-discernable* air bubbles remain in the riser column at the end of the test. These bubbles are not measurable by the AVA scale due to the very slow speed with which they are rising in the column. This also can result in significant amounts of entrained air that are completely excluded from the test. This may explain why other researchers have reported a conservative bias for SF measured by the AVA compared to ASTM C457.
- Prior to the current study, the temperature probe on SSI's AVA required replacement numerous times. In some instances, the errors were extremely large, leading the investigators to immediately replace the probe. However, at other times, the errors were relatively small, on the order of 5 to 10 C, causing significant overheating of the liquids in the riser column. In view of the large impact temperature exerts on AVA measurements, the investigators believe this issue must be addressed before conventional AVA equipment can be routinely relied upon. The manufacturer of the AVA equipment has produced a new version of the AVA that uses a different temperature measurement system. The comparative reliability of the new system is not known.
- Differences in rotation rates of the magnetic stirrers for different AVA machines were observed. However, the investigators do not consider this a likely cause of significant measurement error.

- The current procedure for measuring and adding glycerol to the riser column results in relatively large variations in the actual volume of glycerol added. In light of the significant impact glycerol volume exerts on AVA test results, this represents a noteworthy issue that warrants attention.
- Consistently achieving a full 20-cc specimen size was found at times to be very difficult, especially with relatively dry concrete mixes (as are common in concrete paving operations).
- The AVA software only takes a measurement from the scale three times per minute. As such, fluctuations to the scale due to vibrations (especially due to air flow) exert a profound influence on the AVA test results.
- The AVA software errantly uses absolute value of the difference between successive measurements when deciding to end a test. This sometimes causes tests to continue several minutes longer than they should, with no additional benefit. The impact of this error on the reported results could not be determined without an evaluation of the underlying equations. The investigators requested access to the equations from the manufacturer, but the request was denied.

In recognition of the above limitations, the investigators identified numerous recommended improvements to the existing equipment and procedures:

1. Apply vacuum pressure to the AVA riser column during the test or immediately after the "normal" AVA test. Vacuum pressure will cause the air bubbles in the riser column to expand, thus causing them to rise more quickly. By applying increasing vacuum pressure in a stepwise fashion, the overall time required to perform the test can be greatly reduced. In addition, the vacuum pressure can enable much smaller bubbles to be measured during the overall test duration.
2. Implement a more reliable temperature measurement system.
3. Consider measuring temperature and applying a temperature correction factor before calculating SS and SF rather than attempting to control temperature with a heater (as the current system does).
4. Implement a graduated-cylinder or volumetric-style apparatus for measuring glycerol to more precisely control the volume of glycerol used for each test.
5. Consider using a standard specimen size between 15 and 18 cc rather than 20 cc.
6. Take continuous mass measurements from the AVA scale rather than only three per minute.
7. Revise the equations used to calculate AVA Spacing Factor and Specific Surface to take advantage of the continuous mass measurements mentioned in Improvement #6.
8. Revise the equations used to calculate AVA Spacing Factor and Specific Surface to eliminate the ASTM-C457-based empirical adjustments the AVA currently applies.
9. Directly relate AVA-based Spacing Factor and Specific Surface measurements to freeze/thaw durability measurements (AASHTO T-161).

Regarding the nine improvements mentioned above, SSI has fabricated systems to address #1 (vacuum pressure) and #6 (continuous mass measurements). A description of the work conducted to-date regarding the use of vacuum pressure is provided in Appendix B. Appendix C provides an account of SSI's work related to continuous mass measurement and its use in the evaluation of external vibration.

5. Summary, Conclusions, Recommendations

The investigation has revealed that the vast majority of air-entrained concrete mixes currently being produced for the Oklahoma Department of Transportation has a significant likelihood of experiencing future durability problems due to freeze/thaw damage. However, this conclusion needs to be confirmed by a prediction model directly relating AVA measurements to AASHTO T-161 Durability Factor. In addition, the actual susceptibility of a given concrete structure to freeze/thaw degradation will also be a function of the local climatic conditions (i.e. the cumulative occurrence of actual freeze/thaw cycles).

The investigation has also proved to be extremely valuable in contributing to a better understanding of the potential sources of error related to AVA measurements. Worthwhile advancements have been made related to improving the equipment and procedures that will eventually enable more reliable and more robust measurements of the distribution of air voids in fresh concrete.

The most noteworthy conclusions are as follows:

- Seventy-five percent of mixes tested had their average Spacing Factor above the 0.010-inch (75% Durability Factor) threshold. In addition, sixty-five percent of the mixes tested had their 95% Lower Confidence Limit above the 0.010-inch threshold.
- Pumping bridge concrete using a conventional pump truck increased the measured Spacing Factor by 0.0018 inches on average. This suggests that a loss of entrained air is likely to occur whenever concrete is pumped.
- The temperature of the liquids in the riser column was found to be the most influential source of potential error. In addition, temperature sensing and control capabilities of the current AVA equipment were found to be lacking, especially in light of the strong influence of temperature on the measured results.

Other noteworthy conclusions are:

- Volume of glycerol in the riser column was found to be an influential source of potential error. The manufacturer's recommended equipment and procedures for measuring and adding glycerol were found to be lacking in light of the significant influence of glycerol volume on the measured results.
- The current AVA equipment was unable to measure or account for the extremely small air voids found in many concrete mixes. This was evidenced by the presence of visibly-discernible air bubbles in the riser column after the conclusion of the test.

Given the high percentage of Oklahoma mixes that exhibited Spacing Factors above the recommended thresholds, the investigators recommend that the Oklahoma Department of Transportation:

- Develop a direct prediction relationship between AVA-based Spacing Factor and/or Specific Surface measurements and AASHTO T-161 Durability Factor.
- Develop mix qualification procedures similar to those used by the Kansas Department of Transportation (KDOT 2007). The procedures would be used during the mix design

stage to establish the target air content for a given concrete mix such that an adequate Spacing Factor can be consistently achieved. Daily field control of air content would still be based on current total-air measurement techniques (i.e. pressure meter).

Although not as urgent, the investigators also present the following recommendations for future research:

- Incorporate continuous mass measurements into the AVA test procedure. Revise the equations used to calculate AVA Spacing Factor and Specific Surface to take advantage of the continuous mass measurements. Develop numerical algorithms to help counteract the negative effects of external vibration.
- Continue to evaluate the use of vacuum pressure to facilitate the measurement of extremely small air voids.
- Develop an improved volumetric device for measuring and adding glycerol to the riser column.
- Incorporate a more reliable system to measure the temperature of the liquids in the AVA riser column. Consider eliminating the existing temperature control mechanism and incorporating a temperature-correction factor to adjust AVA test results based on the actual temperature of the liquids in the riser column.

Potential avenues for facilitating the aforementioned research activities include:

- Continued sponsorship of related research activities via ODOT's State Planning & Research (SPR) Program.
- Sponsorship of a pooled-fund study in cooperation with other states interested in reliable methods for measuring air void characteristics of fresh concrete.
- Cooperative sponsorship of related research activities with the Oklahoma Transportation Center.
- Cooperative sponsorship of related research activities with the National Concrete Pavement Technology Center.
- Cooperative sponsorship of related research activities with one or more industry groups such as Portland Cement Association or American Concrete Pavement Association.
- Sponsorship of one or more research needs statements in conjunction with Transportation Research Board (TRB) Committees AFN30 (Durability of Concrete), AFH50 (Portland Cement Concrete Pavement Construction), or AFN10 (Basic Research and Emerging Technologies Related to Concrete).
- Dissemination of research results via AASHTO's AVA Technology Implementation Group.
- Presentation of research results at one or more of TRB's technical sessions or committee meetings.
- Publication of related articles in relevant journals such as TRB's *Transportation Research Record, ACI Materials Journal,* or *Cement and Concrete Research.*

6. References

The air-void systems of Highway Research Board cooperative concretes. Backstrom, J.E. (U.S. Dept. of the Interior Bureau of Reclamation); *Concrete Laboratory Report No. C-824*, April 6, 1956.

Section 401 - Concrete. Kansas Department of Transportation (KDOT), *2007 Standard Specifications for State Road and Bridge Construction*, 2007.

7. Appendix A – Results of Error Evaluation

Two designs-of-experiments (DOEs) were performed to quantify the sources of error associated with the following three variables:

- Temperature of the liquids in the riser column,
- Volume of glycerol in the riser column, and
- Specimen size.

Each DOE was analyzed with respect to the following two response variables:

- Specific Surface (SS), and
- Spacing Factor (SF).

The first DOE was performed solely with SSI's Air Void Analyzer (AVA). The second DOE was performed both on SSI's and FHWA's AVA equipment. The model and Analysis of Variance (ANOVA) results were essentially identical for both pieces of equipment. Table 5 and Table 6 provide the ANOVA results for the second DOE for Specific Surface and Spacing Factor respectively. Figure 3 and Figure 4 show the 3D surface of the resulting numerical models for the two most significant factors (temperature and glycerol). Figure 5 through Figure 7 show the expected errors (based on the numerical models) across the normal range of each input variable.

Table 5 – Analysis of Variance for Specific Surface for SSI's AVA

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.51	5	0.70	31.97	< 0.0001	significant
A-Glycerol	*0.27*	*1*	*0.27*	*12.14*	*0.0028*	
B-Temp	*2.16*	*1*	*2.16*	*98.50*	*< 0.0001*	
C-Specimen Size	*0.076*	*1*	*0.076*	*3.46*	*0.0802*	
BC	*0.079*	*1*	*0.079*	*3.59*	*0.0753*	
B^2	*0.83*	*1*	*0.83*	*37.79*	*< 0.0001*	
Residual	0.37	17	0.022			
Cor Total	3.88	22				

The Model F-value of 31.97 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Std. Dev.	0.15	R-Squared	0.9039
Mean	6.03	Adj R-Squared	0.8756
C.V. %	2.46	Pred R-Squared	0.8180

Table 6 – Analysis of Variance for Spacing Factor for SSI's AVA

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.774E-004	5	7.549E-005	65.17	< 0.0001	significant
A-Glycerol	*4.521E-005*	*1*	*4.521E-005*	*39.03*	*< 0.0001*	
B-Temp	*1.850E-004*	*1*	*1.850E-004*	*159.72*	*< 0.0001*	
C-Specimen Size	*1.907E-005*	*1*	*1.907E-005*	*16.47*	*0.0008*	
BC	*1.051E-005*	*1*	*1.051E-005*	*9.08*	*0.0078*	
B^2	*1.216E-004*	*1*	*1.216E-004*	*104.97*	*< 0.0001*	
Residual	1.969E-005	17	1.158E-006			
Cor Total	3.971E-004	22				

The Model F-value of 65.17 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Std. Dev.	1.076E-003	R-Squared	0.9504
Mean	0.011	Adj R-Squared	0.9358
C.V. %	9.80	Pred R-Squared	0.9032

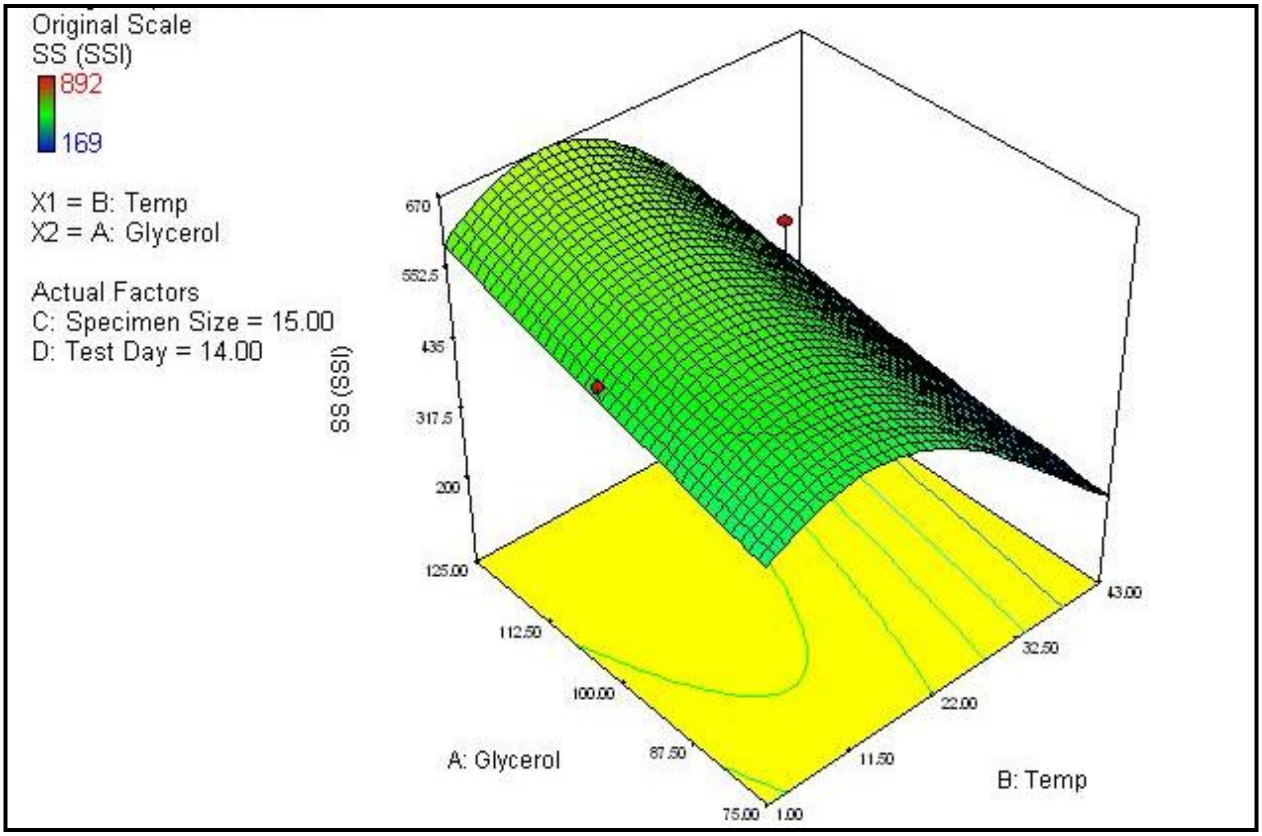


Figure 3 – Model Graph for Specific Surface

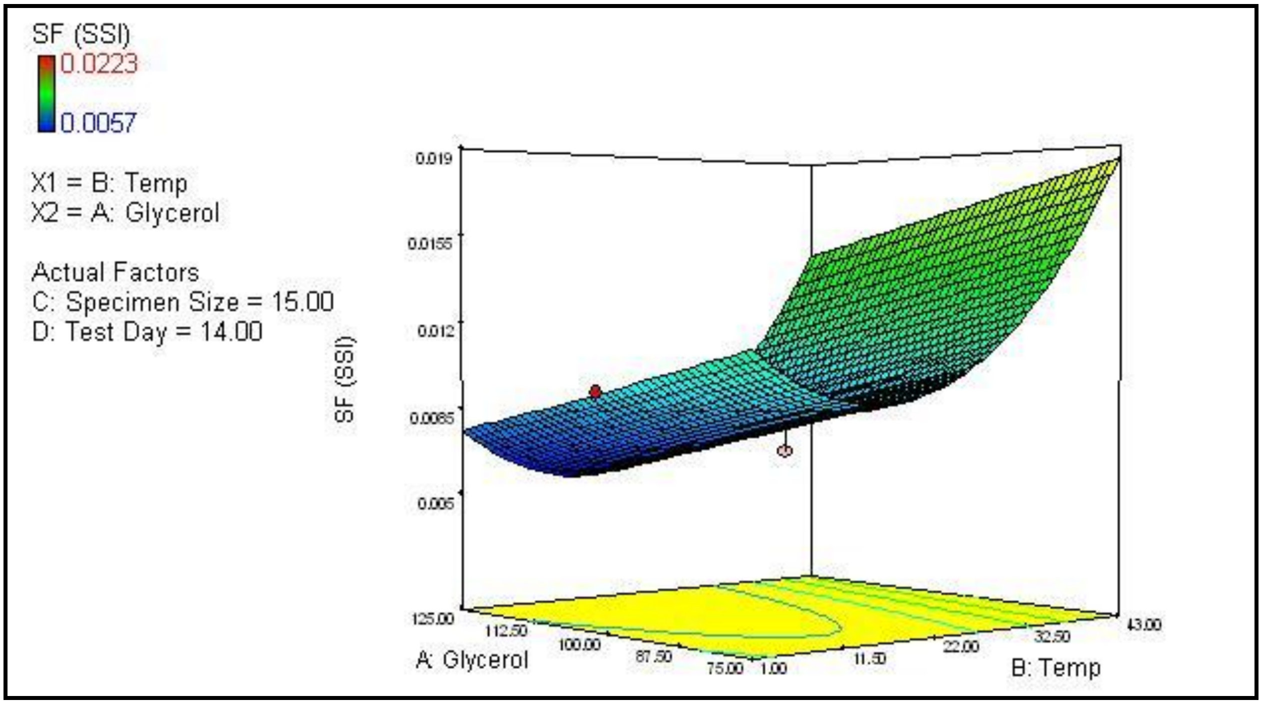


Figure 4 – Model Graph for Spacing Factor

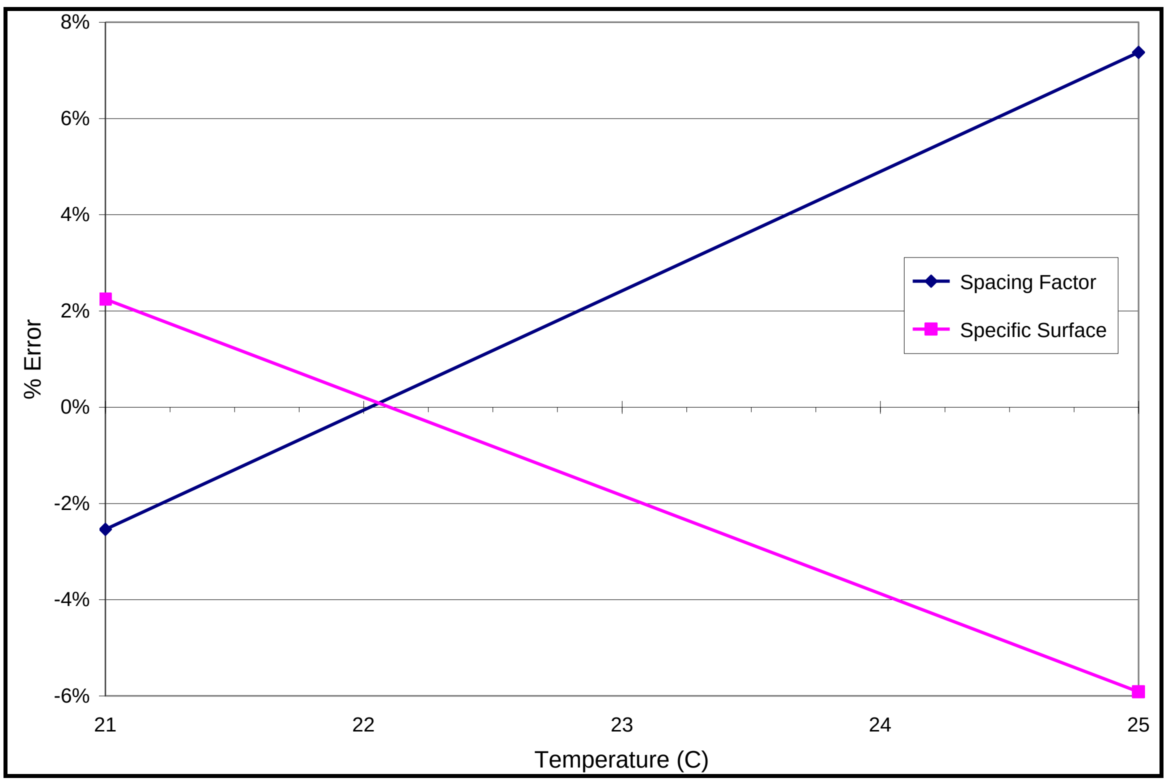


Figure 5 – Expected Error due to Temperature of the Liquids in the Riser Column

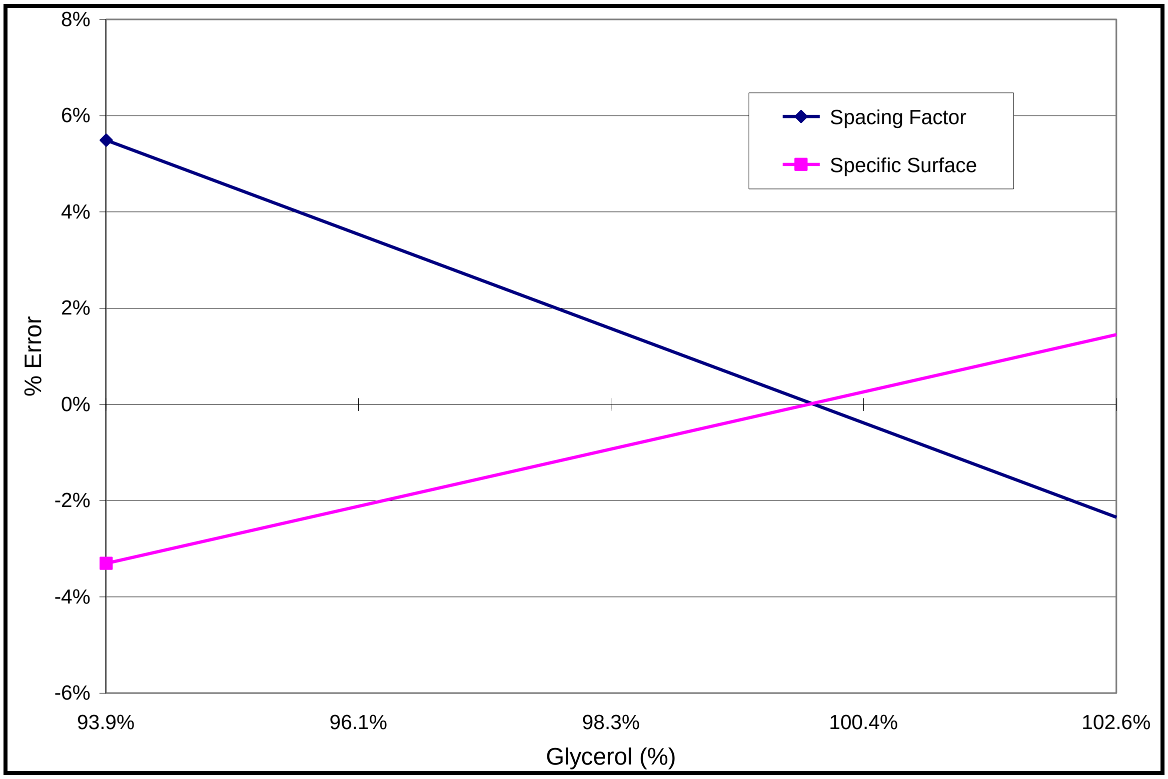


Figure 6 – Expected Error due to Volume of Glycerol in the Riser Column

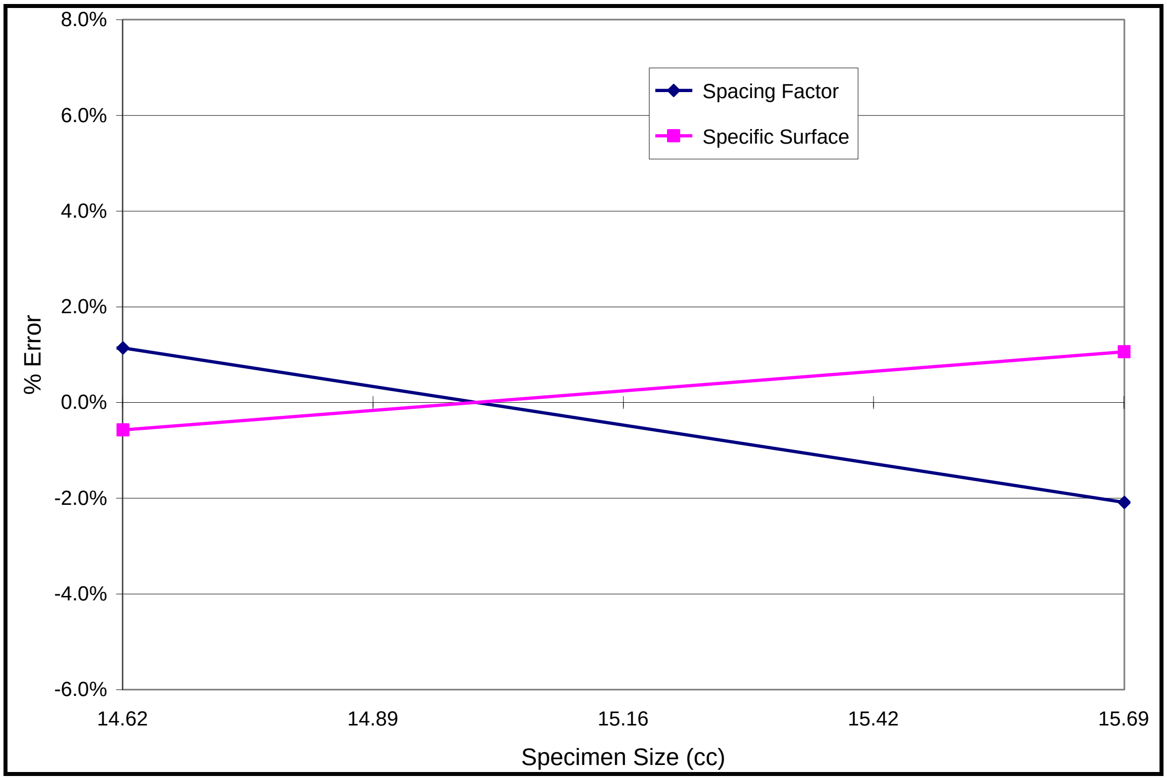


Figure 7 – Expected Error due to Deviations in Specimen Size (from 15 cc)

8. Appendix B – Vacuum Pressure

The investigators hypothesized that placing the riser column in a vacuum would yield significant potential improvements. However, due to the nature of the mass measurement device, the only way to achieve this was to place the entire AVA apparatus inside a vacuum chamber. To accomplish this, a large vacuum chamber was fabricated and tested. Figure 8 shows a photograph of the vacuum chamber and the AVA.

Figure 8 – Vacuum Chamber for AVA

The vacuum chamber as currently constructed is able to achieve approximately 90% of a full vacuum (27 in-Hg vacuum) using a ½ hp, 10 CFM vacuum pump. The investigators have observed that, at this level of vacuum, additional air bubbles are released from the "de-aerated" water into the riser column, thus leading to additional perceived increases in the amount of air in the concrete. Additional investigation is needed to determine whether the water can be more fully de-aerated prior to testing and/or whether the system can be calibrated to take into account the amount of microscopic or dissolved air in the water.

Two separate series of experiments were completed in which the Air Void Analyzer (AVA) was placed inside the vacuum chamber and under a vacuum:

- Paste & Air Entraining Agent Experiment.
- Static Bubble Experiment,

Paste & Air Entraining Agent Experiment

Seven samples of paste & air entraining agent (AEA) were tested with the AVA under vacuum. The samples were mixed with a 70/30 mass ratio of cement-to-water along with 3 cc of AEA to provide for adequate entrained air in the paste. Each sample was tested in the AVA to completion under ambient pressure first. Then the vacuum pump was started and the chamber was brought to 19 inches-Hg.

The results showed that bubble size increased as vacuum pressure increased, as was expected. In addition, a net increase in bubble size was observed after the system returned to ambient pressure. This was also expected in that visible air bubbles had been present in the AVA riser column even after the AVA test was complete under normal (ambient) conditions. However, the net increase in bubble size was beyond expected levels.

Static Bubble Experiment

The investigators hypothesized that this "excessive net increase" phenomenon was due to the presence of air in the "de-aerated" water being placed in the riser column. This hypothesis suggests that the manufacturer's recommended procedure for de-aerating the water may not adequately remove all the microscopic air bubbles from the riser-column water.

A Static Bubble Experiment was conducted to test this hypothesis. The experiment consisted of placing a static bubble into the riser column after it had been filled with "de-aerated" water, then placing the entire riser column under a partial vacuum. The vacuum pressure was brought to 19 inches-Hg. The pump was then turned off and the system was allowed to return to ambient pressure. During the experiment, SSI's StreamReader™ software was used to collect continuous real-time readings from the AVA scale. Seven runs were completed for this experiment investigating the effects of varying the initial bubble size.

The data collected from the StreamReader™ software was graphed and analyzed, showing that under vacuum pressure the bubble size increases dramatically (as it should). The data also showed that after the chamber returns to ambient pressure there remains an overall increase in bubble size (as was hypothesized). An example of this is shown in Figure 9. The original bubble displaced 2.9 g of water. Under 19 inches-Hg of vacuum pressure, the bubble displaced 11.3 g of water, representing a three-fold increase in bubble size. This is exactly what would be expected under a 65% vacuum (which was the level achieved during the experiment).

However, after the system returned to ambient pressure, the "original" bubble size had increased such that 3.2 g of water was being displaced. This represents a 10% net increase in bubble size. A follow up experiment was conducted wherein the riser column was again placed under a vacuum, then allowed to return to ambient pressure. This resulted in an additional 5% net increase in bubble size, suggesting that the first partial vacuum removed some but not all the air from the previously "de-aerated" water. As such, the investigators believe two alternative methods may prove beneficial in dealing with the air present in the "de-aerated" water:

- Use a full or near-full vacuum to fully de-aerate the water to be used in the riser column, or
- Perform a separate measurement during the vacuum-AVA test to quantify the amount of air in the water, then adjust the results of the AVA measurements accordingly.

In any event, additional investigation is needed to determine the feasibility of fully de-aerating the water used for the test and/or calibrating or otherwise accounting for the additional air in the water.

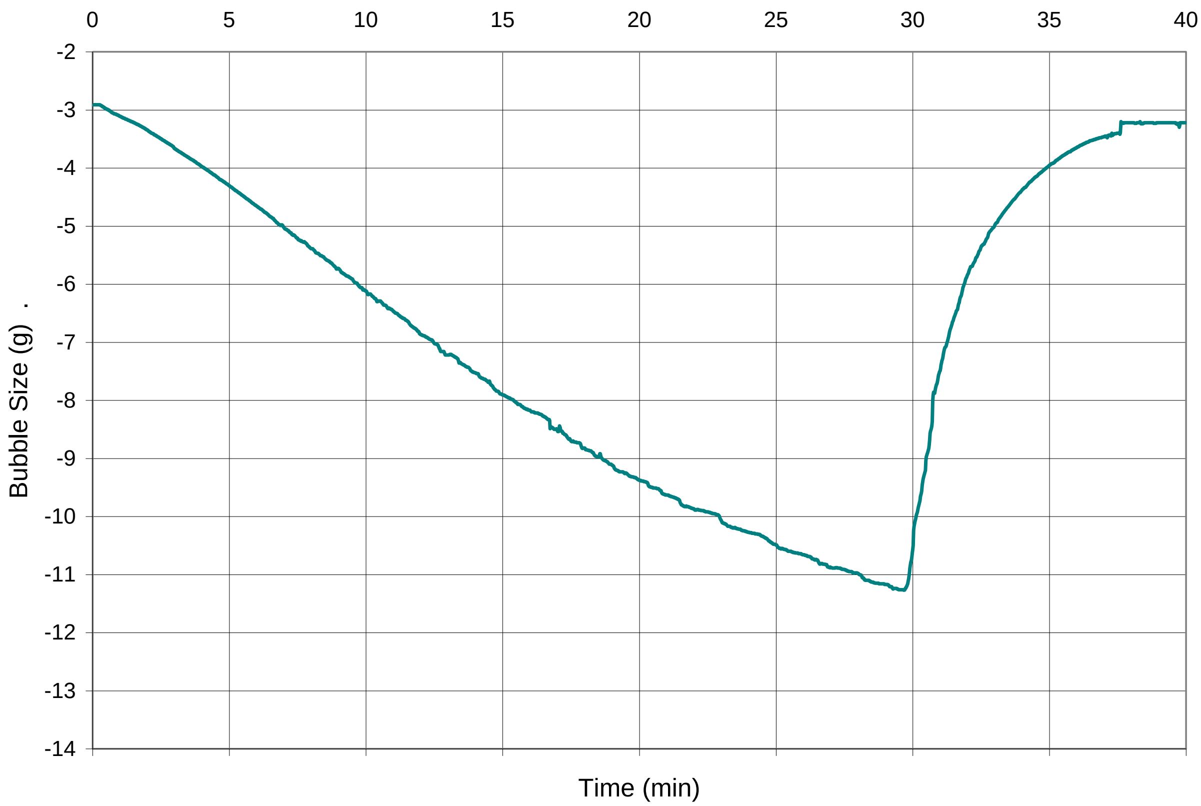


Figure 9 – Static Bubble in AVA under Ambient, then Decreasing, then Increasing, then Ambient Pressure

9. Appendix C – Continuous Mass Measurements and Evaluation of External Vibration

During a previous research project, SSI developed a Visual Basic software application (StreamReader™) for taking continuous readings from a digital scale. For the current project, a hardware device was developed and fabricated to directly interface the StreamReader™ software with the existing scale on SSI's AVA.

This enabled the investigators to capture continuous mass measurement data during AVA testing. In addition, the hardware device and software are configured such that there is no interference with the normal operation of the AVA equipment and software. As such, the investigators were able to collect continuous mass measurements simultaneously with conventional AVA testing.

Figure 10 shows an example of continuous mass measurement data collected during a conventional AVA test. Figure 11 shows the resulting AVA test and Figure 12 shows the data from Figure 10 formatted to display the same way the current AVA software displays mass measurement data (i.e. the difference in the mass of displaced water over a one-minute interval). The limitations inherent in the resolution of the existing AVA scale can be seen in the way the data points oscillate after the 7-minute mark in Figure 11 and Figure 12.

SSI's scale-interface hardware and StreamReader™ software also enabled the investigators to collect continuous mass data during the external-vibration study. Figure 13 shows continuous data collected during one of the external-vibration tests with the comparative "Conventional AVA" data from the same test shown in Figure 14.

Three sources of external vibration were analyzed with respect to their effect on AVA data collection and test results. Figure 15 shows the results from two same-batch tests with constant specimen size, one with no vibration and one with table vibration. As can be seen, the induced table vibration—which is comparable to engine vibrations generated by a motorized vehicle—produced a small but observable effect on the StreamReader™ output. Figure 16 shows that intermittent air flow across the AVA, such as from indoor HVAC systems or external wind gusts, produces a substantial impact on the scale measurements and the resulting AVA output. This suggests that extreme care should be taken to shield AVA equipment from sources of air flow.

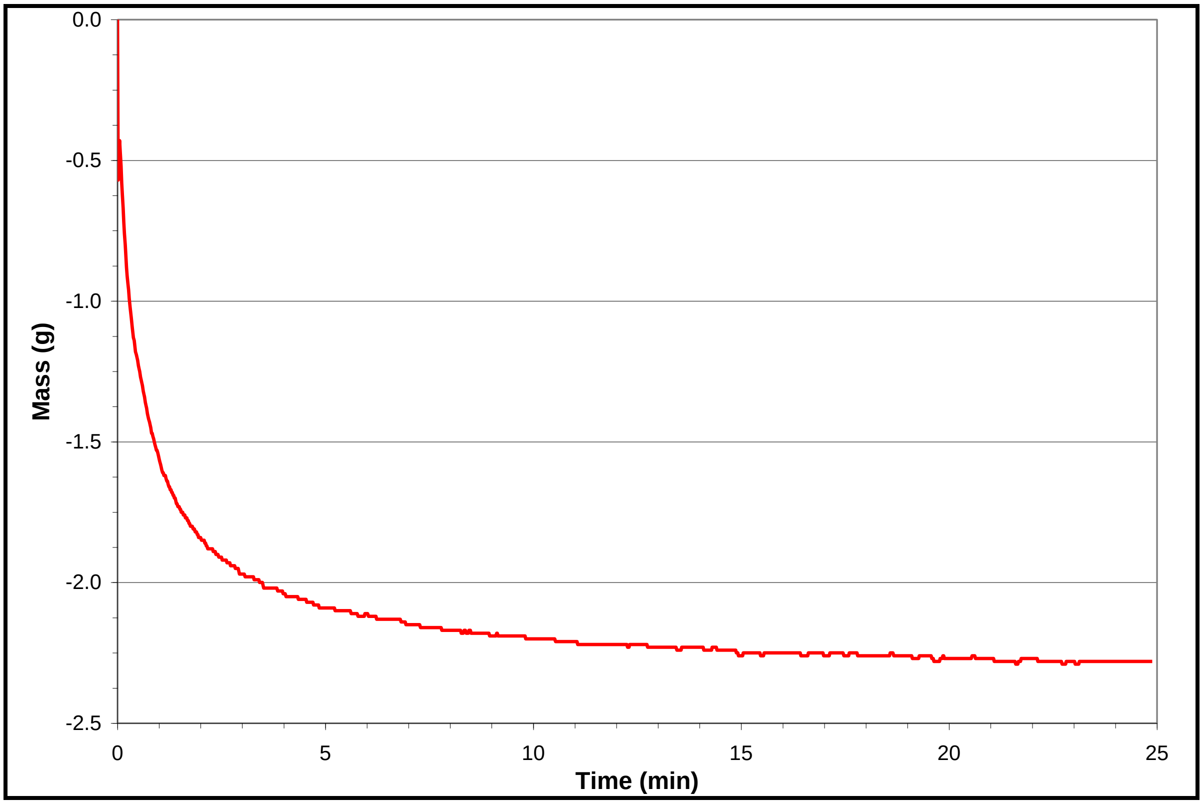


Figure 10 – Continuous Mass Measurement

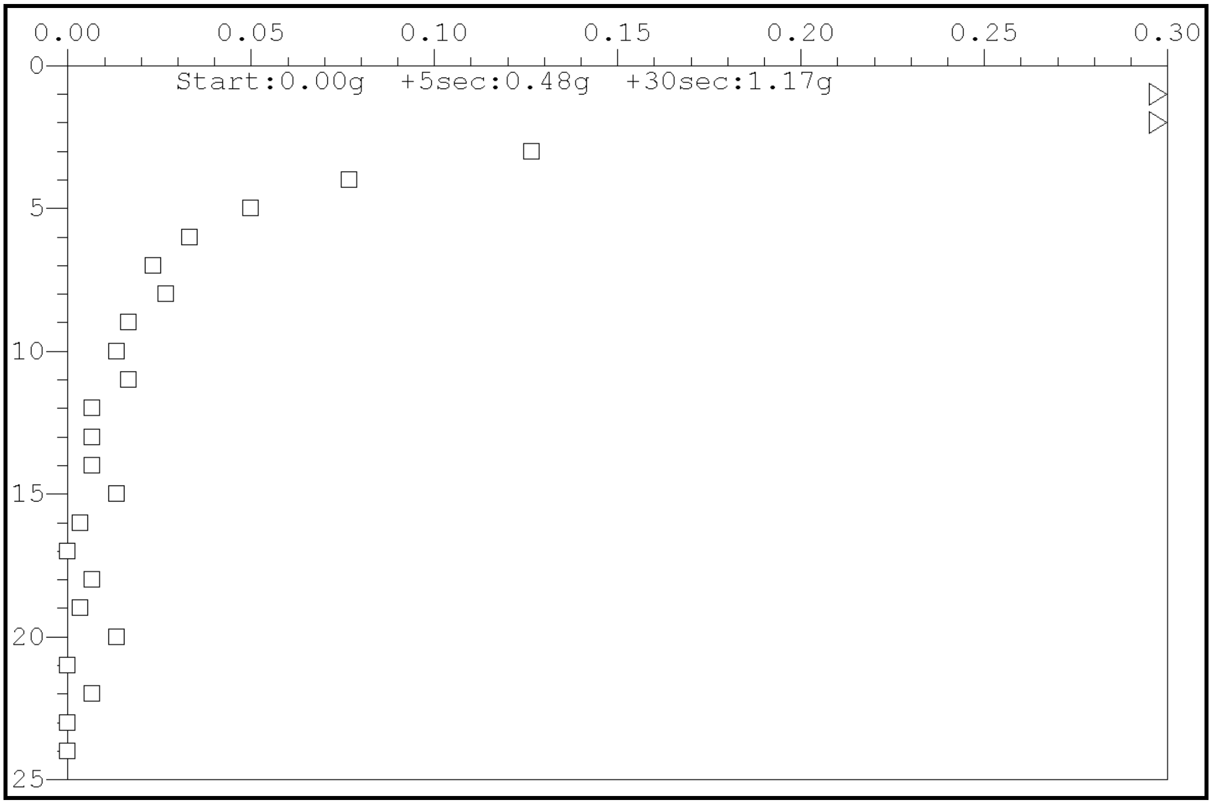


Figure 11 – Non-Continuous Mass Measurement (Conventional AVA Output)

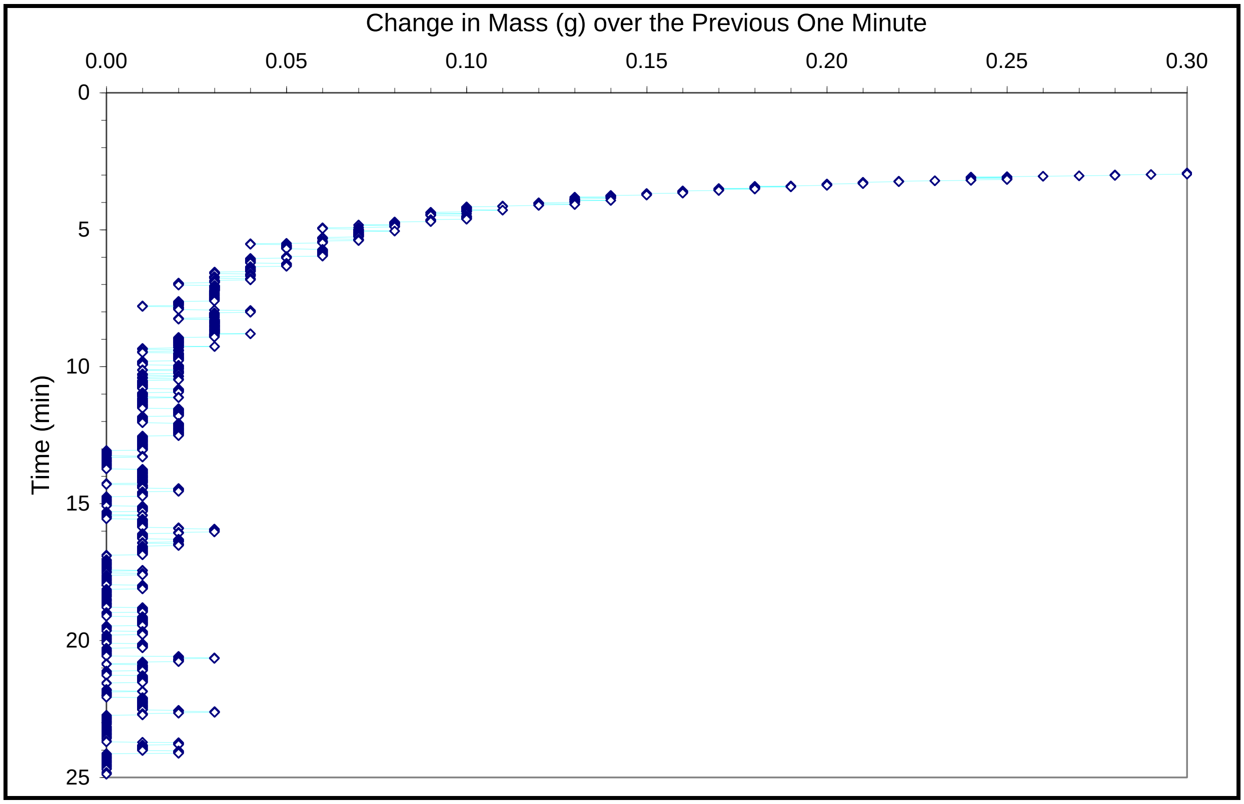


Figure 12 – Continuous Mass Measurement (Formatted to Match Conventional AVA Output)

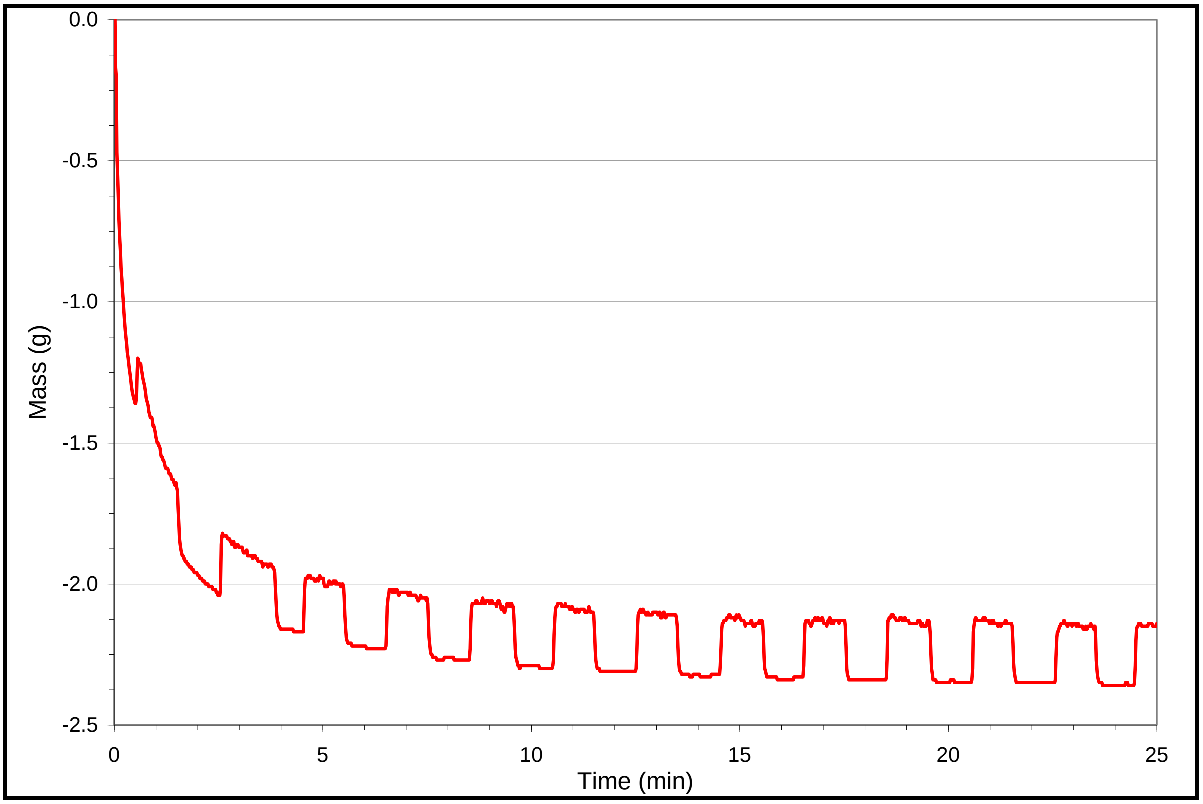


Figure 13 – Continuous Mass Measurement with Intermittent Air-Flow Vibration

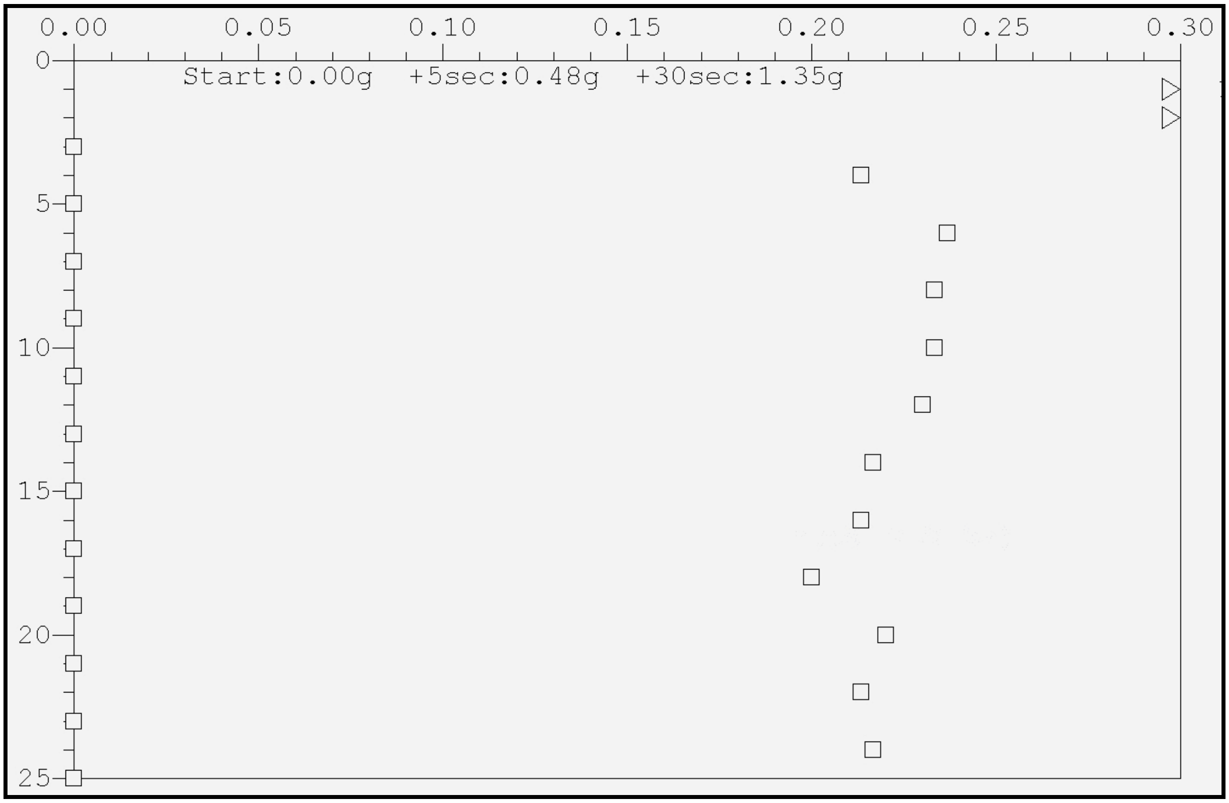


Figure 14 – Non-Continuous Mass Measurement with Intermittent Air-Flow Vibration

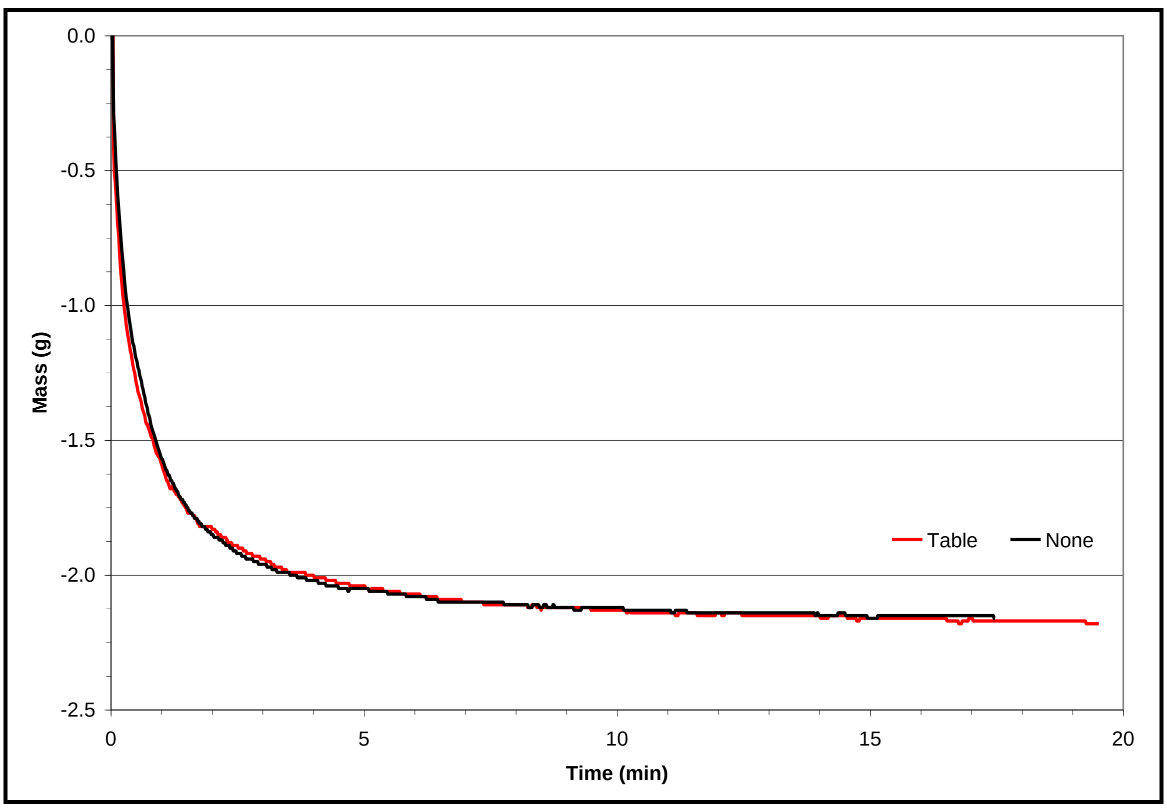


Figure 15 – Table Vibration versus No Vibration

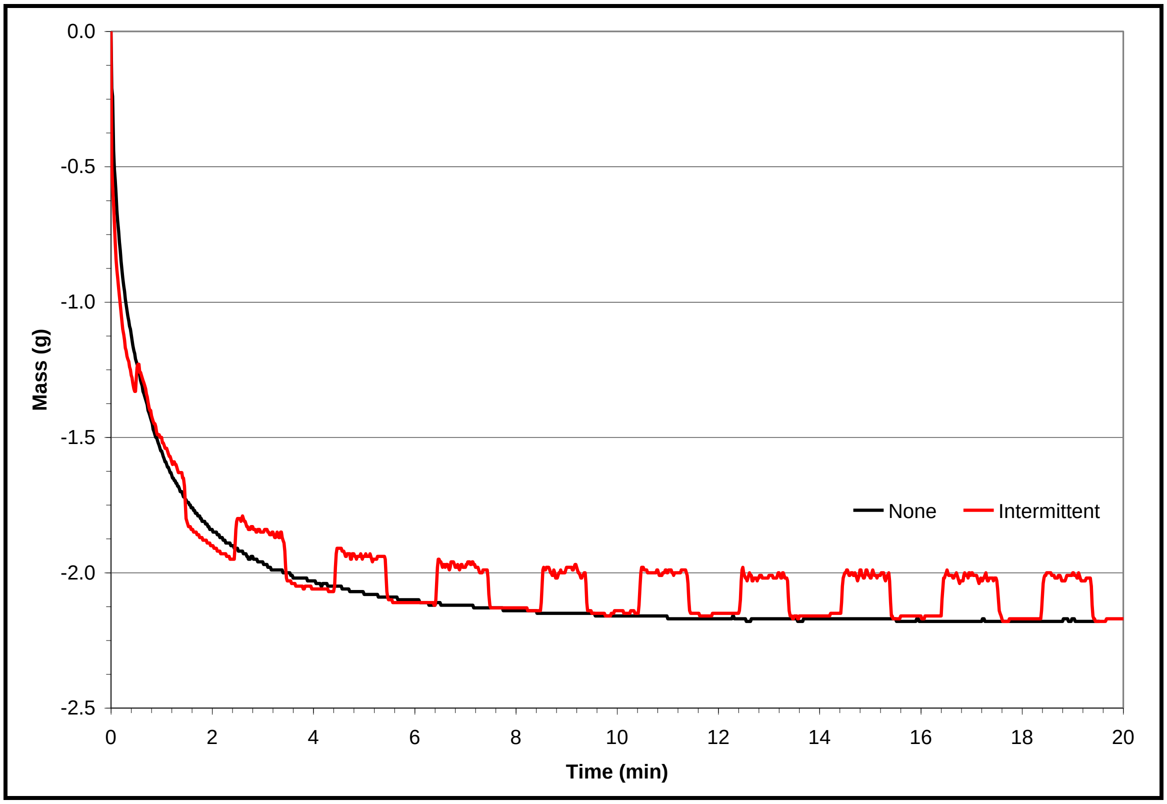


Figure 16 – Intermittent Air Flow versus No Vibration

10. Appendix D – Round-Robin Study Test Results

Table 7 – Round-Robin Test Data (Mix 2)

Mix number	2
Percent mortar (%)	73.7
Percent paste (%)	27.4
Total air content (%)	7.8
Slump (in.)	3.5
Unit Weight (pcf)	140.1
Temperature (F)	67.2

AVA #	**Sample Location**	**Spacing factor (mm)**			**Specific Surface (mm^{-1})**		
		Sample 1	**Sample 2**	**Average**	**Sample 1**	**Sample 2**	**Average**
1	E3	0.056	0.049	0.053	54.8	56.8	55.8
2	A2	0.052	0.047	0.050	47.1	46.9	47.0
3	D3	0.077	0.082	0.080	43.6	43.0	43.3
4	E1	0.099	0.055	0.077	41.9	67.4	54.7
5	C2	0.090	0.117	0.104	36.5	37.6	37.1
6	B1	0.109	0.112	0.110	37.8	45.3	41.6
7	D2	0.144	0.113	0.129	32.2	33.5	32.9
8	D1	0.120	0.074	0.097	38.0	42.2	40.1
9	B3	0.110	0.067	0.089	32.5	33.5	33.0
10	F1	0.093	0.181	0.137	49.6	27.8	38.7
11	C1	0.108	0.114	0.111	37.9	32.3	35.1
12	G2	0.103	0.075	0.089	42.2	57.7	50.0
13	G1	0.106	0.059	0.083	42.5	63.0	52.8
14	G3	0.095	0.075	0.085	42.9	41.3	42.1
15	A3	0.119	0.083	0.101	34.0	61.7	47.9
16	C3	0.081	0.089	0.085	54.4	60.7	57.6
17	F3	0.089	0.109	0.099	40.6	34.5	37.6
18	A1	0.101	0.142	0.122	49.7	28.3	39.0
19	B2	0.073	invalid	0.073	46.2	invalid	46.2

Average (Avg)	0.096	0.091	0.093	42.339	45.195	43.793
Std Dev (SD)	0.022	0.035	0.023	6.718	12.938	7.706
High	0.144	0.181	0.137	54.800	67.400	57.550
Low	0.052	0.047	0.050	32.200	27.800	32.850
Avg + 2 SD	0.140	0.161	0.139	55.775	71.072	59.205
Avg - 2 SD	0.052	0.021	0.047	28.902	19.319	28.382

Table 8 – Round-Robin Test Data (Mix 3)

Mix number	3
Percent mortar (%)	66.7
Percent paste (%)	23.7
Total air content (%)	7.1
Slump (in.)	2
Unit Weight (pcf)	141.6
Temperature (F)	59.7

AVA #	Sample Location	Spacing factor (mm)			Specific Surface (mm^{-1})		
		Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
1	A2	0.101	0.059	0.080	37.0	49.0	43.0
2	D3	0.062	0.060	0.061	47.3	46.8	47.1
3	E1	0.088	0.076	0.082	36.3	39.5	37.9
4	C1	0.092	0.071	0.082	32.6	42.8	37.7
5	B1	0.057	0.053	0.055	48.2	41.1	44.7
6	D2	0.086	0.097	0.091	36.3	34.4	35.3
7	D1	0.119	0.094	0.107	31.0	36.3	33.7
8	B3	0.046	0.050	0.048	51.1	45.2	48.2
9	F1	0.094	0.047	0.071	47.9	40.7	44.3
10	C1	0.076	0.070	0.073	41.5	38.2	39.9
11	G2	0.045	0.066	0.056	46.5	38.3	42.4
12	G1	0.086	0.074	0.080	57.3	42.3	49.8
13	G3	0.152	0.120	0.136	44.2	36.0	40.1
14	A3	0.086	0.089	0.088	39.8	34.5	37.2
15	C3	0.054	0.029	0.042	45.6	53.6	49.6
16	F3	0.061	0.062	0.062	47.9	58.4	53.2
17	A1	0.123	0.137	0.130	33.3	25.1	29.2
18	B2	0.054	0.056	0.055	47.3	42.1	44.7
19	F2	0.060	0.054	0.057	51.8	46.4	49.1

Average (Avg)	0.081	0.072	0.076	43.308	41.616	42.462
Std Dev (SD)	0.029	0.026	0.026	7.315	7.483	6.318

High	0.152	0.137	0.136	57.300	58.400	53.150
Low	0.045	0.029	0.042	31.000	25.100	29.200

Avg + 2 SD	0.139	0.124	0.128	57.939	56.583	55.097
Avg - 2 SD	0.024	0.020	0.025	28.678	26.650	29.827

Table 9 – Round-Robin Test Data (Mix 4)

Mix number	4
Percent mortar (%)	66.7
Percent paste (%)	23.7
Total air content (%)	8
Slump (in.)	2
Unit Weight (pcf)	139.8
Temperature (F)	61

AVA #	Sample Location	Spacing factor (mm)			Specific Surface (mm^{-1})		
		Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
1	D3	0.059	0.056	0.058	53.7	53.4	53.6
2	E1	0.060	0.060	0.060	45.6	46.2	45.9
3	C2	0.095	0.096	0.096	51.2	39.7	45.5
4	B1	0.061	0.037	0.049	51.7	58.1	54.9
5	D2	0.053	0.058	0.056	43.1	35.4	39.3
6	D1	0.074	0.076	0.075	35.9	40.5	38.2
7	B3	0.113	0.093	0.103	40.0	39.5	39.8
8	F1	0.051	0.063	0.057	55.6	46.5	51.1
9	C1	0.053	0.078	0.066	46.8	33.6	40.2
10	G2	0.064	0.078	0.071	50.4	26.7	38.6
11	G1	0.047	0.079	0.063	51.4	52.2	51.8
12	G3	0.080	0.049	0.065	58.1	55.0	56.6
13	A3	0.117	0.119	0.118	34.8	37.4	36.1
14	C3	0.082	0.082	0.082	40.2	40.4	40.3
15	F3	0.069	0.067	0.068	49.4	45.8	47.6
16	A1	0.064	0.050	0.057	64.0	58.5	61.3
17	B2	0.106	0.101	0.104	33.0	38.1	35.6
18	F2	0.054	0.080	0.067	52.4	36.4	44.4
19	E2	0.042	0.061	0.052	56.3	45.0	50.7

Average (Avg)	0.071	0.073	0.072	48.084	43.599	45.841
Std Dev (SD)	0.023	0.020	0.020	8.441	8.755	7.604
High	0.117	0.119	0.118	64.000	58.500	61.250
Low	0.042	0.037	0.049	33.000	26.700	35.550
Avg + 2 SD	0.116	0.113	0.111	64.966	61.108	61.049
Avg - 2 SD	0.026	0.032	0.032	31.202	26.089	30.634

Table 10 – Round-Robin Test Data (Mix 5)

Mix number	5
Percent mortar (%)	66
Percent paste (%)	23.7
Total air content (%)	5
Slump (in.)	1.25
Unit Weight (pcf)	143.6
Temperature (F)	64

AVA #	**Sample Location**	**Spacing factor (mm)**			**Specific Surface (mm^{-1})**		
		Sample 1	**Sample 2**	**Average**	**Sample 1**	**Sample 2**	**Average**
1	E1	0.114	0.080	0.097	38.7	48.9	43.8
2	C2	0.092	0.109	0.101	37.0	37.8	37.4
3	B1	0.114	0.106	0.110	41.0	44.3	42.7
4	D2	0.080	0.101	0.091	39.0	49.6	44.3
5	D1	0.148	0.113	0.131	35.4	33.8	34.6
6	B3	0.130	0.089	0.109	34.0	44.8	39.4
7	F1	0.154	0.136	0.145	29.9	34.7	32.3
8	C1	0.102	0.095	0.099	39.8	42.3	41.1
9	G2	0.100	0.082	0.091	40.2	37.0	38.6
10	G1	0.096	0.100	0.098	39.8	46.1	43.0
11	G3	0.074	0.098	0.086	45.3	45.9	45.6
12	A3	0.092	0.097	0.095	64.3	42.0	53.2
13	C3	0.122	0.095	0.109	36.6	41.8	39.2
14	F3	0.126	0.131	0.129	35.0	37.9	36.5
15	A1	0.127	0.095	0.111	48.2	39.4	43.8
16	F2	0.072	0.085	0.079	54.3	52.3	53.3
17	B2	0.132	0.118	0.125	34.3	33.7	34.0
18	E2	0.097	0.137	0.117	44.8	27.1	36.0
19	E3	0.089	0.104	0.097	43.3	46.0	44.7
	Average (Avg)	0.108	0.104	0.106	41.101	41.335	41.218
	Std Dev (SD)	0.024	0.017	0.017	7.965	6.419	5.783
	High	0.154	0.137	0.145	64.300	52.300	53.300
	Low	0.072	0.080	0.079	29.900	27.100	32.300
	Avg + 2 SD	0.156	0.138	0.140	57.032	54.174	52.784
	Avg - 2 SD	0.061	0.070	0.072	25.170	28.496	29.652

Table 11 – Round-Robin Test Data (Mix 6)

Mix number	6
Percent mortar (%)	73.1
Percent paste (%)	27.4
Total air content (%)	5.6
Slump (in.)	1.5
Unit Weight (pcf)	143.9
Temperature (F)	66

AVA #	**Sample Location**	**Spacing factor (mm)**			**Specific Surface (mm^{-1})**		
		Sample 1	**Sample 2**	**Average**	**Sample 1**	**Sample 2**	**Average**
1	C2	0.102	0.107	0.105	51.2	46.9	49.1
2	B1	0.120	0.103	0.112	38.0	43.1	40.6
3	D2	0.149	0.142	0.146	39.2	37.4	38.3
4	D1	0.136	0.153	0.145	28.9	31.4	30.2
5	B3	0.163	0.138	0.151	25.5	35.1	30.3
6	F1	0.135	0.117	0.126	35.6	42.1	38.9
7	C1	0.160	0.133	0.147	29.5	38.0	33.8
8	G2	0.140	0.122	0.131	32.4	38.2	35.3
9	G1	0.108	0.148	0.128	41.3	31.1	36.2
10	G3	0.130	0.116	0.123	39.7	39.1	39.4
11	A3	0.109	0.108	0.109	41.4	41.1	41.3
12	C3	0.110	invalid	0.110	42.6	invalid	42.6
13	F3	0.173	0.153	0.163	29.2	33.8	31.5
14	A1	0.168	0.137	0.153	31.9	37.6	34.8
15	B2	0.147	0.153	0.150	32.4	33.5	33.0
16	F2	0.099	0.133	0.116	51.7	32.9	42.3
17	E2	0.162	0.145	0.154	30.3	36.3	33.3
18	E3	0.143	0.162	0.153	34.7	35.1	34.9
19	A2	0.145	0.159	0.152	32.5	30.9	31.7
	Average (Avg)	0.137	0.135	0.135	36.211	36.867	36.692
	Std Dev (SD)	0.023	0.019	0.019	7.241	4.442	4.991
	High	0.173	0.162	0.163	51.700	46.900	49.050
	Low	0.099	0.103	0.105	25.500	30.900	30.150
	Avg + 2 SD	0.183	0.173	0.173	50.693	45.751	46.674
	Avg - 2 SD	0.090	0.097	0.098	21.728	27.982	26.710

Table 12 – Round-Robin Test Data (Mix 7)

Mix number	7
Percent mortar (%)	73.7
Percent paste (%)	27.4
Total air content (%)	6.7
Slump (in.)	1.75
Unit Weight (pcf)	142.3
Temperature (F)	67

AVA #	Sample Location	Spacing factor (mm)			Specific Surface (mm^{-1})		
		Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
1	B1	0.093	0.080	0.087	44.8	47.6	46.2
2	D2	0.087	0.078	0.083	40.2	43.3	41.8
3	D1	0.134	0.118	0.126	37.0	41.3	39.2
4	B3	0.133	0.084	0.109	30.4	44.6	37.5
5	F1	0.140	0.117	0.129	27.1	38.3	32.7
6	C1	0.089	0.091	0.090	43.9	50.2	47.1
7	G2	0.107	0.103	0.105	36.8	36.7	36.8
8	G1	0.115	0.143	0.129	42.1	30.8	36.5
9	G3	0.159	0.128	0.144	28.0	34.7	31.4
10	A3	0.107	0.198	0.153	41.2	18.0	29.6
11	C3	0.163	0.098	0.131	29.0	36.2	32.6
12	F3	0.180	invalid	0.180	23.7	invalid	23.7
13	A1	0.097	0.088	0.093	40.0	48.4	44.2
14	B2	0.130	0.125	0.128	35.8	33.9	34.9
15	F2	0.109	0.120	0.115	39.1	33.9	36.5
16	E2	0.168	0.164	0.166	30.3	31.0	30.7
17	E3	0.135	0.083	0.109	28.4	43.7	36.1
18	A2	0.134	0.104	0.119	28.2	36.0	32.1
19	D3	0.100	0.119	0.110	46.5	34.6	40.6
	Average (Avg)	0.125	0.113	0.121	35.395	37.956	36.303
	Std Dev (SD)	0.028	0.031	0.026	6.985	7.784	5.968
	High	0.180	0.198	0.180	46.500	50.200	47.100
	Low	0.087	0.078	0.083	23.700	18.000	23.700
	Avg + 2 SD	0.181	0.176	0.174	49.365	53.524	48.239
	Avg - 2 SD	0.069	0.051	0.068	21.424	22.387	24.366

Table 13 – Round-Robin Test Data (Summary)

	Spacing Factor (mm)				Specific Surface (mm^{-1})			
	Avg	Std Dev	Var	COV	Avg	Std Dev	Var	COV
mix 2	0.0932	0.0230	0.000528	24.7%	43.8	7.71	59.4	17.6%
mix 3	0.0765	0.0258	0.000668	33.8%	42.5	6.32	39.9	14.9%
mix 4	0.0718	0.0197	0.000388	27.4%	45.8	7.60	57.8	16.6%
mix 5	0.1061	0.0171	0.000291	16.1%	41.2	5.78	33.4	14.0%
mix 6	0.1352	0.0187	0.000349	13.8%	36.7	4.99	24.9	13.6%
mix 7	0.1211	0.0263	0.000692	21.7%	36.3	5.97	35.6	16.4%
TOTAL	0.1006	0.0220	0.000486	21.9%	41.1	6.47	41.8	15.8%

11. Appendix E – Summary Spacing Factor Statistics by Mix by Division

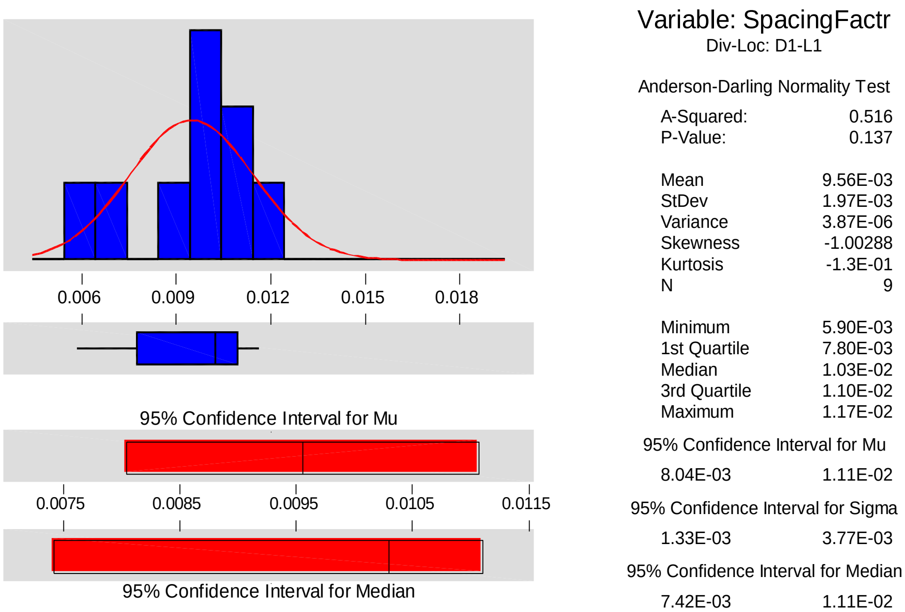


Figure 17 – Spacing Factor Summary Statistics for Division 1 Mix 1

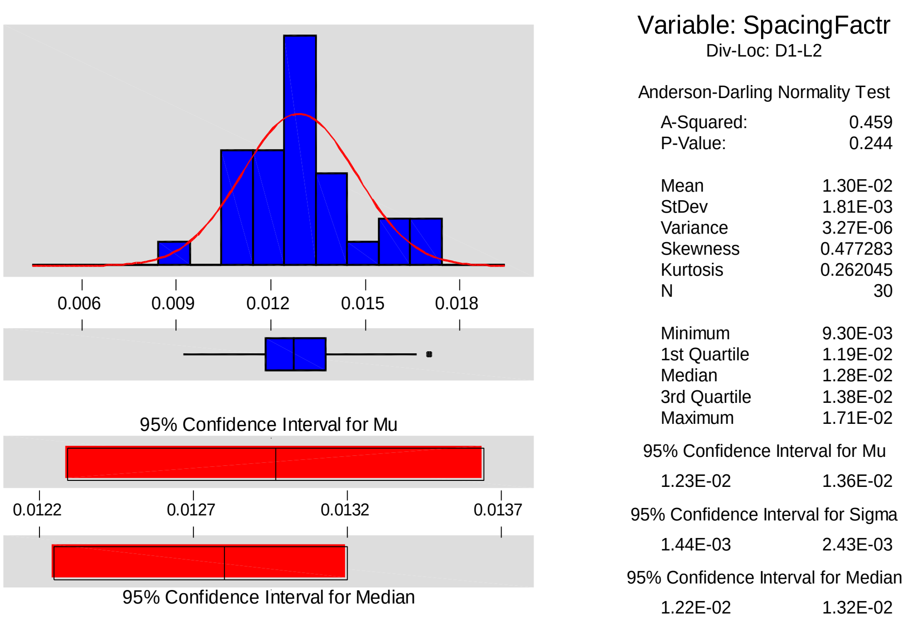


Figure 18 – Spacing Factor Summary Statistics for Division 1 Mix 2

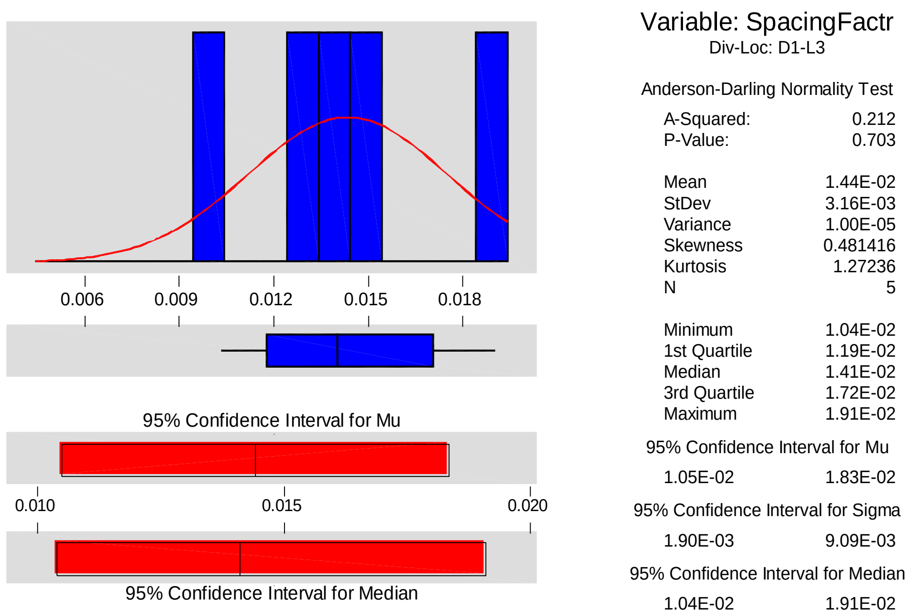


Figure 19 – Spacing Factor Summary Statistics for Division 1 Mix 3

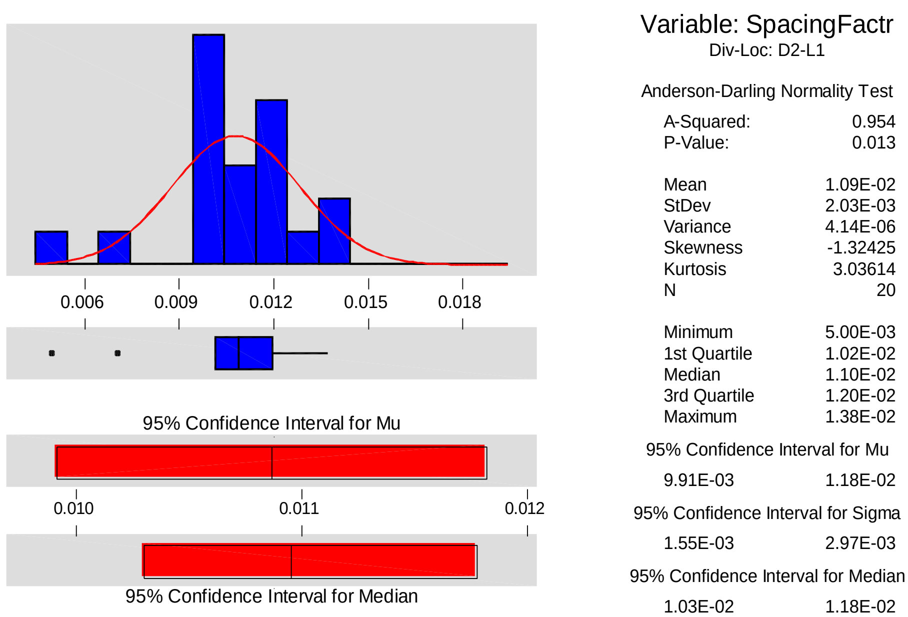


Figure 20 – Spacing Factor Summary Statistics for Division 2 Mix 1

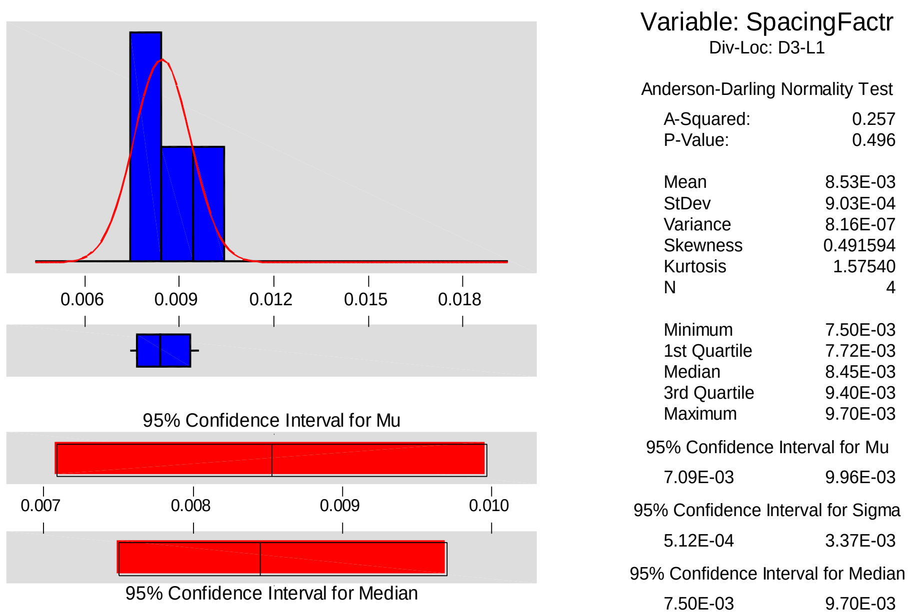


Figure 21 – Spacing Factor Summary Statistics for Division 3 Mix 1

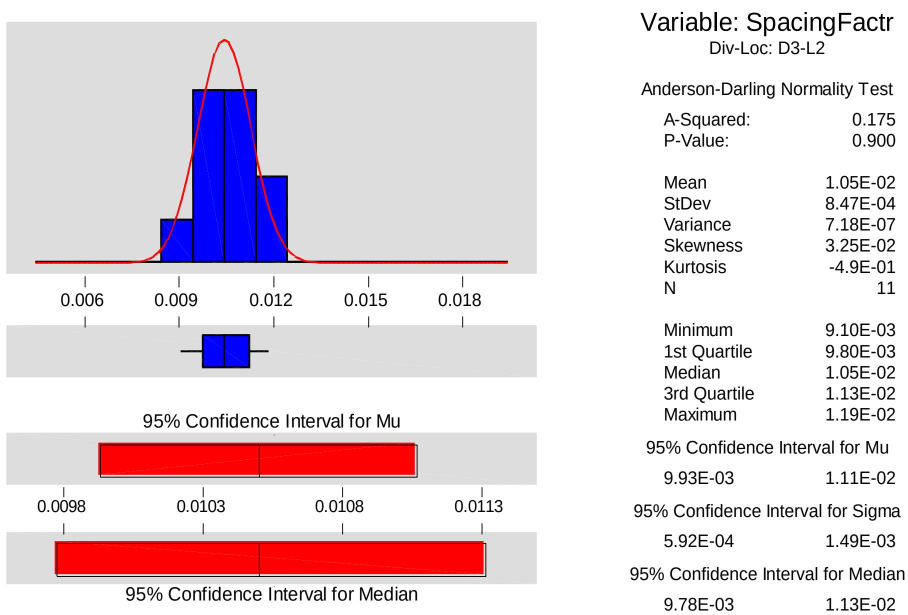


Figure 22 – Spacing Factor Summary Statistics for Division 3 Mix 2

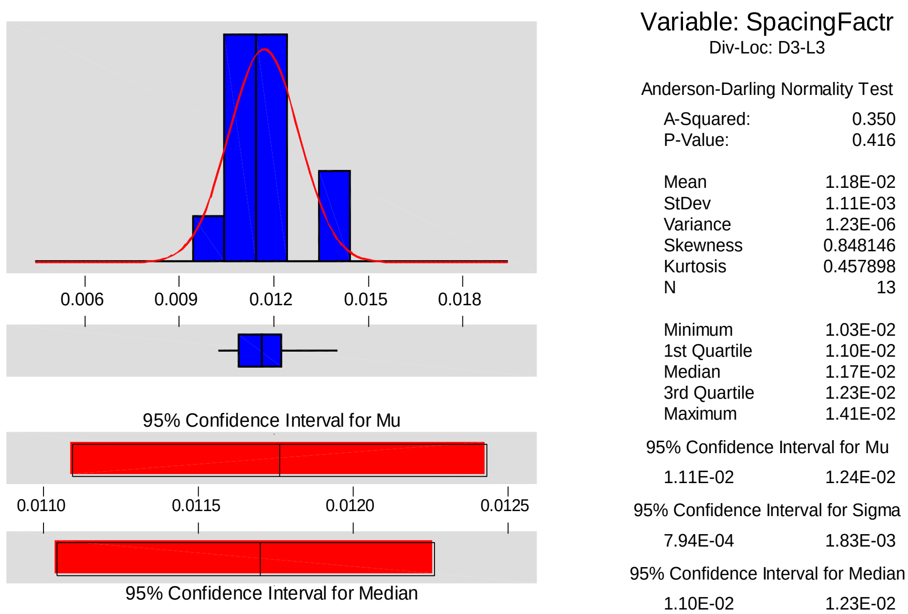


Figure 23 – Spacing Factor Summary Statistics for Division 3 Mix 3

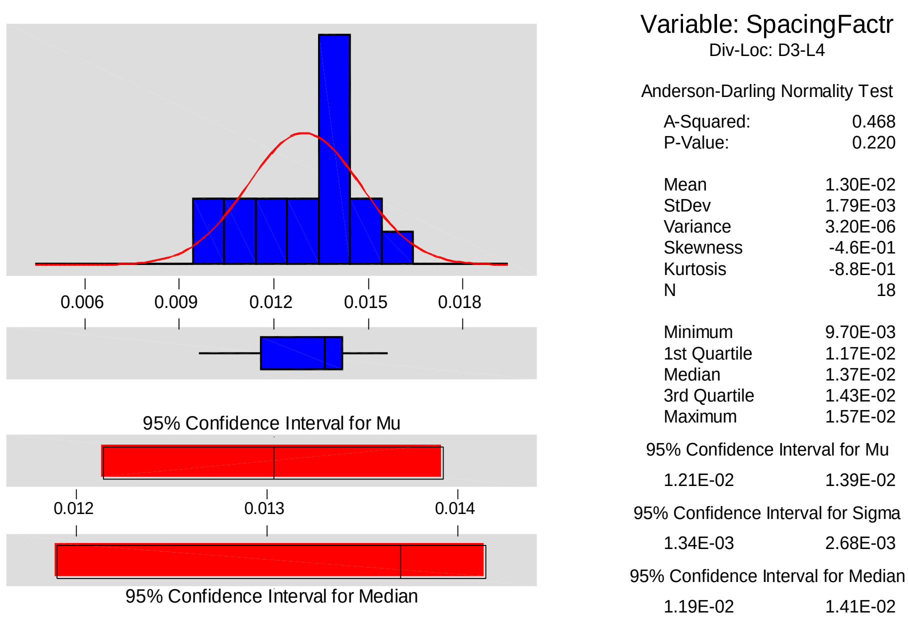


Figure 24 – Spacing Factor Summary Statistics for Division 3 Mix 4

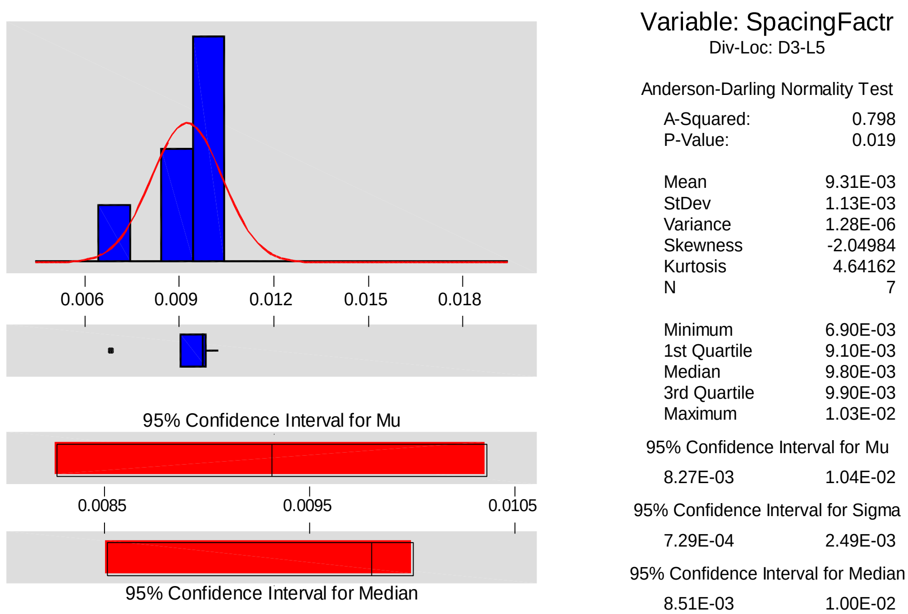


Figure 25 – Spacing Factor Summary Statistics for Division 3 Mix 5

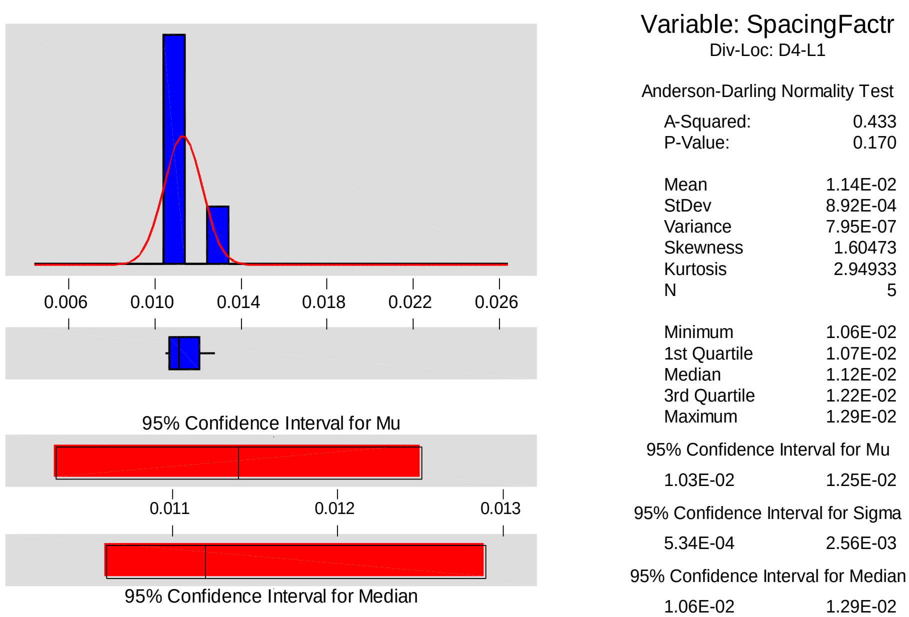


Figure 26 – Spacing Factor Summary Statistics for Division 4 Mix 1

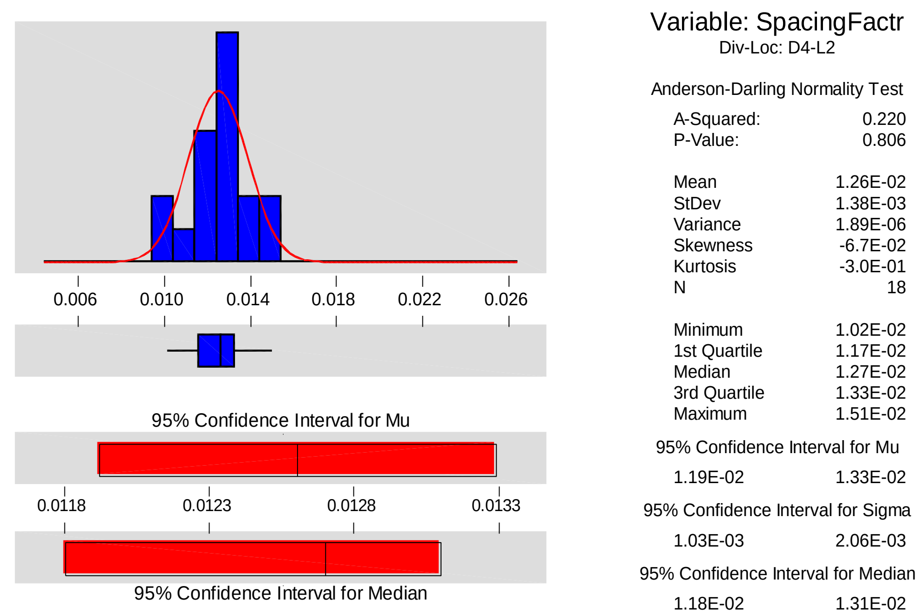


Figure 27 – Spacing Factor Summary Statistics for Division 4 Mix 2

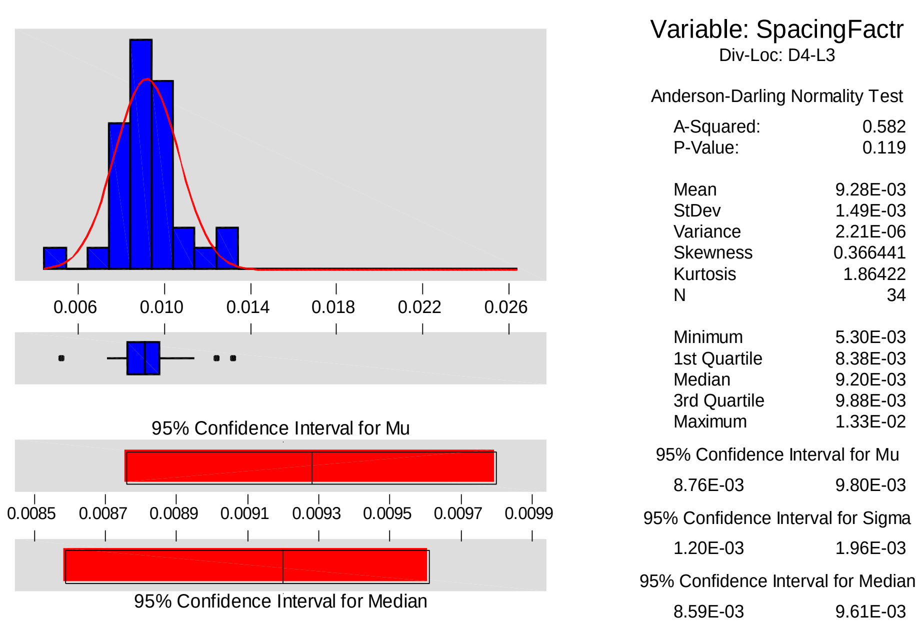


Figure 28 – Spacing Factor Summary Statistics for Division 4 Mix 3

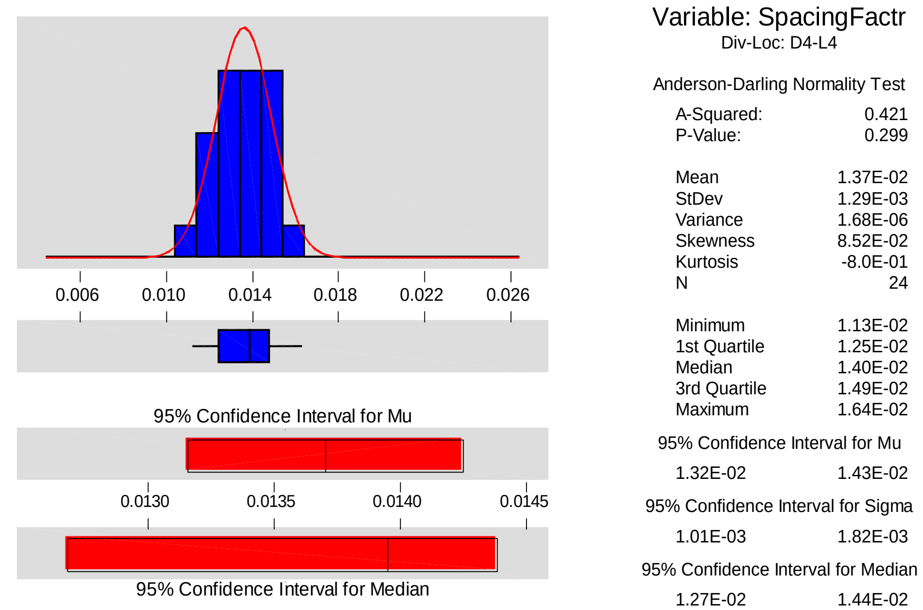


Figure 29 – Spacing Factor Summary Statistics for Division 4 Mix 4

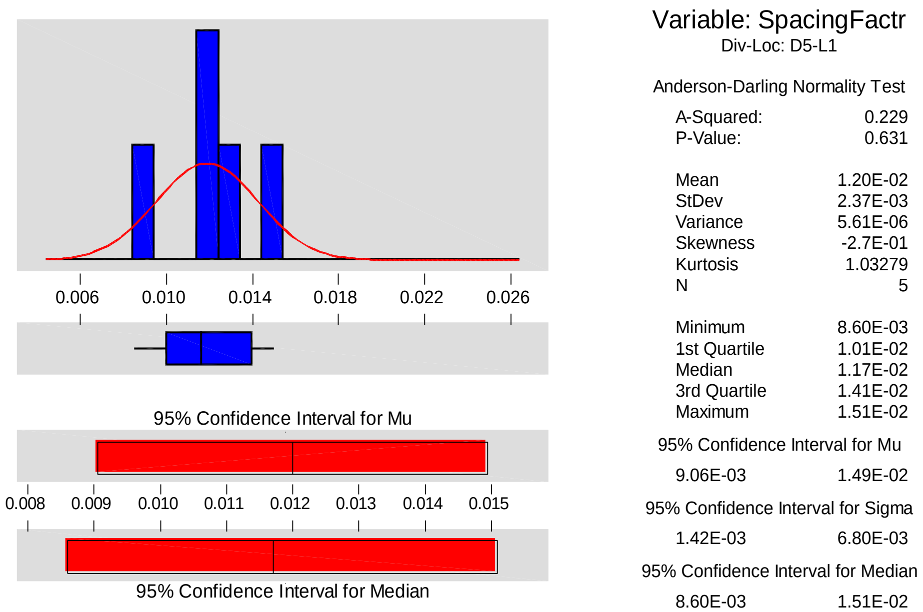


Figure 30 – Spacing Factor Summary Statistics for Division 5 Mix 1

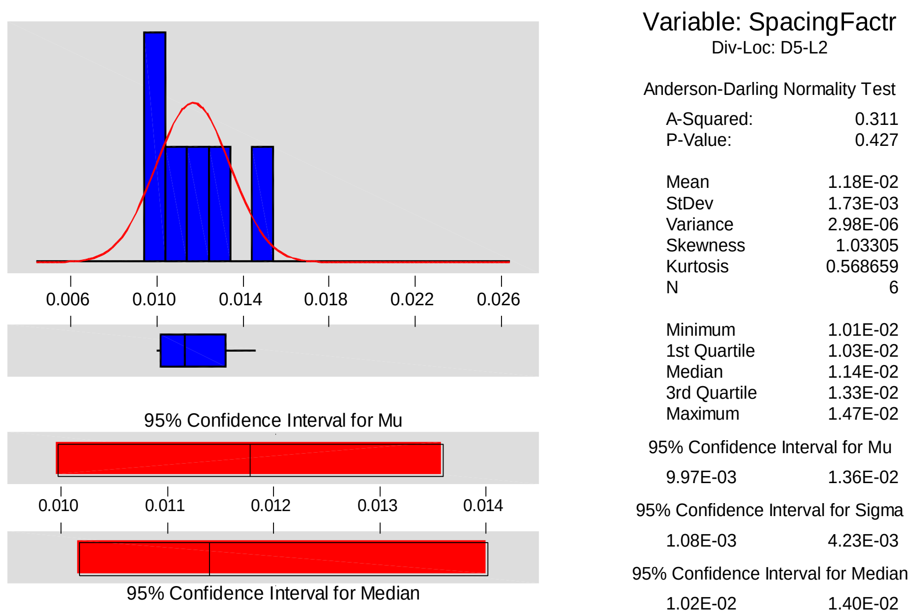


Figure 31 – Spacing Factor Summary Statistics for Division 5 Mix 2

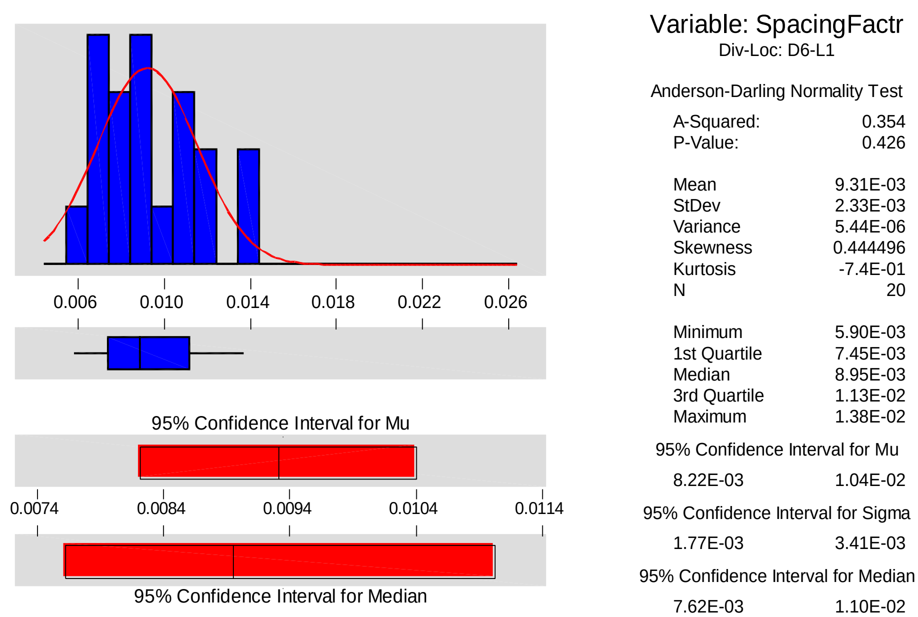


Figure 32 – Spacing Factor Summary Statistics for Division 6 Mix 1

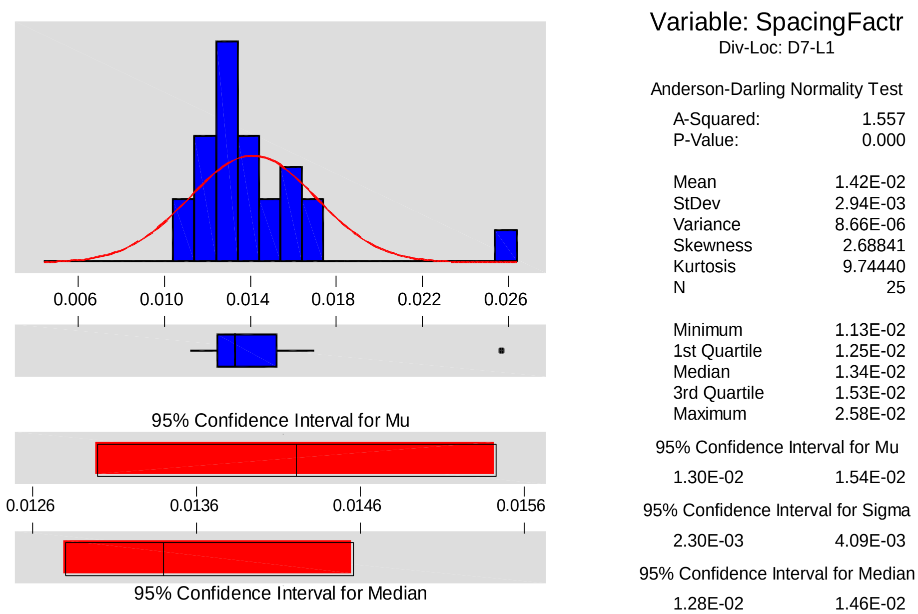


Figure 33 – Spacing Factor Summary Statistics for Division 7 Mix 1

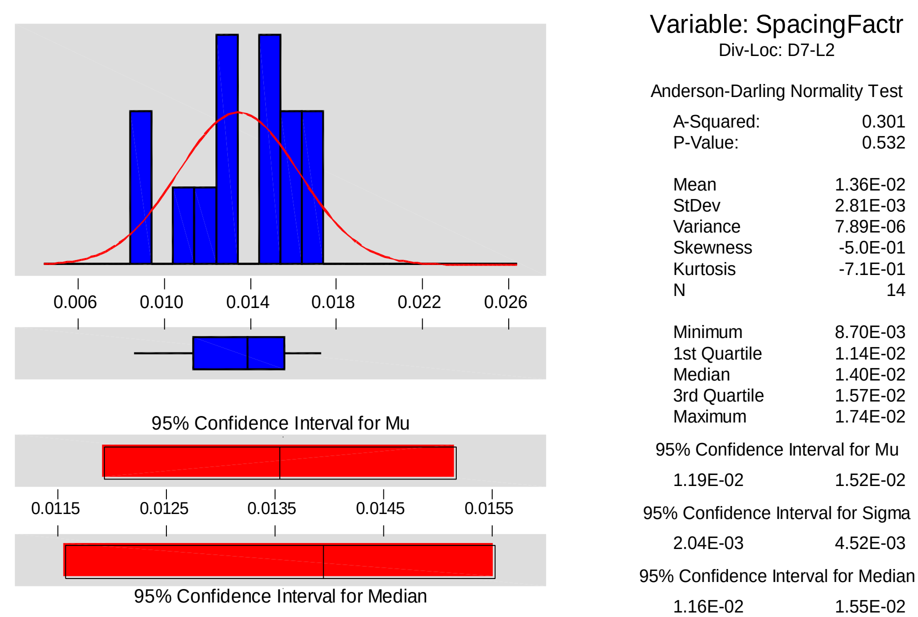
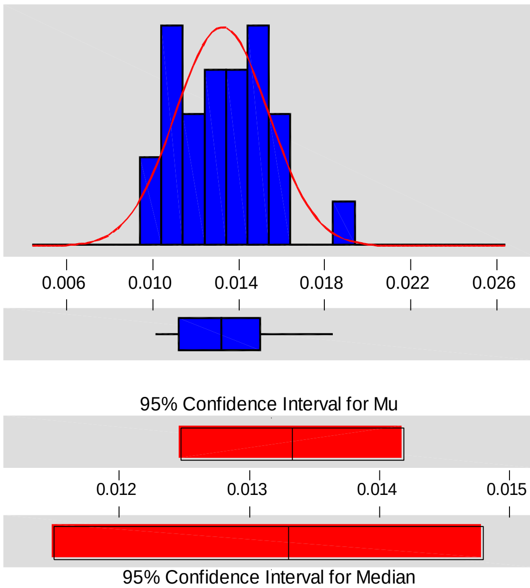


Figure 34 – Spacing Factor Summary Statistics for Division 7 Mix 2



Variable: SpacingFactr
Div-Loc: D8-L1

Anderson-Darling Normality Test

A-Squared:	0.390
P-Value:	0.358
Mean	1.33E-02
StDev	2.16E-03
Variance	4.68E-06
Skewness	0.312797
Kurtosis	-5.0E-01
N	27
Minimum	1.02E-02
1st Quartile	1.13E-02
Median	1.33E-02
3rd Quartile	1.51E-02
Maximum	1.85E-02

95% Confidence Interval for Mu

1.25E-02 1.42E-02

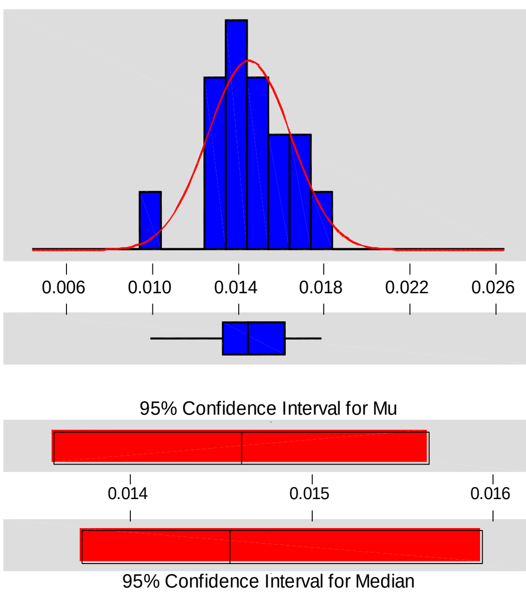
95% Confidence Interval for Sigma

1.70E-03 2.97E-03

95% Confidence Interval for Median

1.15E-02 1.48E-02

Figure 35 – Spacing Factor Summary Statistics for Division 8 Mix 1



Variable: SpacingFactr
Div-Loc: D8-L2

Anderson-Darling Normality Test

A-Squared:	0.321
P-Value:	0.503
Mean	1.46E-02
StDev	1.94E-03
Variance	3.75E-06
Skewness	-4.1E-01
Kurtosis	1.02293
N	16
Minimum	1.00E-02
1st Quartile	1.34E-02
Median	1.46E-02
3rd Quartile	1.63E-02
Maximum	1.80E-02

95% Confidence Interval for Mu

1.36E-02 1.56E-02

95% Confidence Interval for Sigma

1.43E-03 3.00E-03

95% Confidence Interval for Median

1.37E-02 1.59E-02

Figure 36 – Spacing Factor Summary Statistics for Division 8 Mix 2

12. Appendix F – AVA Test Procedure

1 Turn on AVA and weighing scale at least 5 minutes prior to first measurement.

2 Place magnetic stirrer in bottom of column.

3 Make sure temperature probe is through both sides of bottom chamber.

4 Add de-aerated water to just above larger diameter of riser column.

5 Remove air bubbles from riser column with angled brush.

6 Place and finger-tighten screws on bottom platform of riser column.

7 Fill glycerol "funnel" to black line with glycerol (i.e. "blue liquid").

8 Place glycerol funnel in riser column with stopper resting on bottom.

9 Lift glycerol funnel about 1 cm while holding stopper against bottom of riser column.

10 After level of glycerol in funnel has reached a minimum, close stopper and remove funnel from riser column.

11 Record temperature of water / glycerol (at bottom of riser column).

12 Fill large cup with hot water.

13 Record temperature of hot water (before specimen is placed into hot water).

14 Start the SSI StreamReader™ software and begin recording AVA scale data.

15 Start the AVA Software and enter mix and specimen identification information.

16 Remove syringe containing AVA specimen from freezer.

17 Clean dried mortar from exterior of syringe.

18 Place syringe in hot water for 120 seconds.

19 Place inverted Petri dish in water in riser column, remove air from dish, hang dish from AVA scale.

20 Add additional de-aerated water to just above top of welds on inverted Petri dish.

21 Tare the scale (i.e. reset to "zero").

22 Record temperature of hot water (after 120 seconds).

23 Cut mortar specimen to proper volume (18cc if possible); record specimen volume.

24 Place syringe on end of temperature probe in base of riser column.

25 Push syringe into left side of bottom chamber of riser column while pulling temperature probe out of left side.

26 Inject specimen into bottom chamber of riser column while using tip of temperature probe to "crush" specimen.

27 As soon as specimen is fully injected into chamber, start the test by clicking "Start Measurement" on the AVA software (NOTE: the magnetic stirrer should begin mixing the specimen and the glycerol together as soon as the "Start Measurement" button is clicked.).

28 Stop recording AVA scale data (i.e. click “Stop Recording” on SSI StreamReader™ software).

29 Record temperature of water / glycerol / mortar (at bottom of riser column).

30 Remove riser column from the AVA base and rinse the contents over a 0.6 mm screen.

31 Record comments about any clumps of cement paste or mortar visible on the screen; if the mortar specimen did not fully disperse, identify the test as “invalid”.

32 Retrieve the magnetic stir rod from the screen.

33 Clean the riser column and the screen.

13. Appendix G – Oklahoma Mixes: Complete AVA Test Results

Table 14 presents the detailed test results obtained from air-entrained concrete mixes sampled across the state of Oklahoma between April 2007 and September 2008.

A glossary of terms is provided below to aid in interpreting the data presented in Table 14:

Division – the ODOT Division where the concrete was produced and sampled.

Mix # – a unique identifier to distinguish different concrete mixes or similar concrete mixes sampled on different days.

Mix Type – the type of structure for which the concrete was being produced (i.e. bridge deck or concrete pavement).

Sample Location – whether the concrete was sampled before or after the pump (for bridge mixes) or before or after the paving machine (for paving mixes).

Mortar % – the percentage of mortar in the overall concrete mix design (where "mortar" is defined as all mix constituents that pass the #4 sieve, not including air); Mortar % is calculated from the mix design and is an input to the AVA software.

Paste % – the percentage of paste in the overall concrete mix design (where "paste" is defined as cement, supplementary cementitious materials, water, and admixtures, not including air); Paste % is calculated from the mix design and is an input to the AVA software.

Expected Air % – the design air content; Expected Air % is taken directly from the mix design and is an input to the AVA software.

Sample Volume – the volume of the mortar sample (in cubic centimeters) being injected into the riser column; Sample Volume is measured by graduated marks on the sampling syringe and is an input to the AVA software.

Air in Concrete – the percentage of entrained air in the concrete (calculated by the AVA software based on the mix design inputs and the entrained air measured by the AVA).

Air in Paste – the percentage of entrained air in the paste (calculated by the AVA software based on the mix design inputs and the entrained air measured by the AVA).

Air in Putty – the percentage of entrained air in the putty (where "putty" is defined as the paste plus the air entrained within the paste matrix) (calculated by the AVA software based on the mix design inputs and the entrained air measured by the AVA). NOTE: "Air in Putty" = "Air in Paste" / (1 + "Air in Paste")

Specific Surface – the surface area of the air voids divided by their volume; the calculation yields units of reciprocal length; Specific Surface is calculated by the AVA software based on the mix design inputs and the entrained air measured by the AVA.

Spacing Factor – a paste-void spacing parameter calculated as the distance from the surface of all air voids that encompasses a large fraction of the paste; a smaller spacing factor means that a greater percentage of the overall paste matrix is protected from freeze/thaw degradation; Spacing Factor is calculated by the AVA software based on the entrained air measured by the AVA without regard for the mix design inputs.

Table 14 – AVA Test Results for Oklahoma Air-Entrained Concrete Mixes

Division	Mix #	Mix Type	Sample Location	Mortar	Paste	Expected Air	Sample Volume (cm3)	Air in Concrete	Air in Paste	Air in Putty	Specific Surface (in-1)	Spacing Factor (in)
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	4.1%	15.7%	13.6%	724	0.0071
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	5.1%	19.9%	16.6%	417	0.0112
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	3.2%	12.1%	10.8%	559	0.0103
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	3.0%	11.2%	10.1%	592	0.0101
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	3.3%	12.5%	11.1%	488	0.0117
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	4.6%	17.6%	15.0%	452	0.0108
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	5.4%	20.9%	17.3%	765	0.0059
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	5.4%	21.1%	17.4%	434	0.0104
1	1	Bridge	Before Pump	56.3%	25.8%	5.3%	18	7.7%	30.5%	23.4%	396	0.0085
1	2	Paving	After Paver	57.6%	29.4%	6.5%	18	1.8%	5.8%	5.5%	747	0.0106
1	2	Paving	After Paver	57.6%	29.4%	6.5%	18	2.0%	6.5%	6.1%	607	0.0124
1	2	Paving	After Paver	57.6%	29.4%	6.5%	18	2.0%	6.4%	6.0%	528	0.0143
1	2	Paving	After Paver	57.6%	29.4%	6.5%	18	2.1%	6.9%	6.5%	544	0.0135
1	2	Paving	After Paver	57.6%	29.4%	6.5%	18	1.7%	5.4%	5.1%	625	0.0131
1	2	Paving	After Paver	57.6%	29.4%	6.5%	18	2.1%	6.8%	6.4%	536	0.0137
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.1%	10.2%	9.2%	584	0.0106
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.0%	9.9%	9.0%	523	0.0120
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	17	2.8%	9.1%	8.4%	531	0.0122
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	4.2%	13.9%	12.2%	584	0.0093
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.8%	12.5%	11.1%	521	0.0109
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	1.5%	4.8%	4.6%	665	0.0129
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.2%	10.5%	9.5%	490	0.0125
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.9%	9.6%	8.7%	500	0.0127
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.7%	9.0%	8.2%	384	0.0171
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.2%	7.2%	6.7%	429	0.0167
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.7%	12.2%	10.9%	452	0.0126
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.8%	12.4%	11.1%	505	0.0112
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.7%	8.7%	8.0%	500	0.0132
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.9%	9.6%	8.8%	490	0.0130
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.3%	10.9%	9.8%	503	0.0119
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.2%	10.6%	9.6%	462	0.0132
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.7%	9.0%	8.2%	422	0.0156
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.8%	9.0%	8.3%	429	0.0152
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.3%	10.8%	9.8%	478	0.0126
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.3%	11.0%	9.9%	381	0.0157
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	2.7%	8.7%	8.0%	465	0.0142
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	4.0%	13.2%	11.7%	422	0.0131
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.0%	10.0%	9.1%	564	0.0111
1	2	Paving	Before Paver	57.6%	29.4%	6.5%	18	3.6%	11.8%	10.6%	488	0.0119
1	3	Bridge	After Pump	60.6%	27.9%	6.1%	18	5.1%	18.2%	15.4%	251	0.0191
1	3	Bridge	Before Pump	60.6%	27.9%	6.1%	12.5	3.8%	13.3%	11.7%	391	0.0141
1	3	Bridge	Before Pump	60.6%	27.9%	6.1%	18	4.1%	14.4%	12.6%	401	0.0133
1	3	Bridge	Before Pump	60.6%	27.9%	6.1%	18	2.4%	8.4%	7.7%	648	0.0104
1	3	Bridge	Before Pump	60.6%	27.9%	6.1%	18	5.1%	18.0%	15.2%	318	0.0152

Table 14 – AVA Test Results for Oklahoma Air-Entrained Concrete Mixes (cont.)

Division	Mix #	Mix Type	Sample Location	Mortar	Paste	Expected Air	Sample Volume (cm3)	Air in Concrete	Air in Paste	Air in Putty	Specific Surface (in-1)	Spacing Factor (in)
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.3%	8.1%	7.5%	615	0.0111
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.4%	8.6%	7.9%	650	0.0103
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	0.9%	3.3%	3.2%	1999	0.0050
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.6%	9.1%	8.4%	919	0.0071
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.6%	9.4%	8.6%	630	0.0102
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.7%	9.5%	8.7%	625	0.0102
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.2%	7.9%	7.3%	592	0.0117
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.8%	10.0%	9.1%	561	0.0111
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.7%	9.5%	8.7%	625	0.0102
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	3.0%	10.7%	9.7%	561	0.0108
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.8%	9.9%	9.0%	518	0.0121
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.8%	9.9%	9.0%	605	0.0104
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.5%	8.9%	8.1%	559	0.0118
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	3.2%	11.5%	10.3%	569	0.0103
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.3%	8.3%	7.7%	549	0.0123
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.2%	7.9%	7.3%	526	0.0131
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.7%	9.6%	8.8%	546	0.0117
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.6%	9.3%	8.5%	472	0.0137
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	1.7%	5.9%	5.6%	757	0.0104
2	1	Paving	Before Paver	55.3%	25.4%	5.0%	18	2.5%	8.9%	8.2%	478	0.0138
3	1	Bridge	Before Pump	57.6%	25.8%	5.0%	18	4.3%	16.6%	14.2%	592	0.0085
3	1	Bridge	Before Pump	57.6%	25.8%	5.0%	18	3.3%	12.4%	11.0%	589	0.0097
3	1	Bridge	Before Pump	57.6%	25.8%	5.0%	18	3.0%	11.5%	10.3%	790	0.0075
3	1	Bridge	Before Pump	57.6%	25.8%	5.0%	18	4.1%	15.7%	13.5%	615	0.0084
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	2.5%	8.9%	8.2%	569	0.0115
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	3.9%	14.2%	12.5%	478	0.0113
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	4.0%	14.6%	12.8%	556	0.0095
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	4.6%	17.2%	14.7%	470	0.0105
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	4.3%	16.1%	13.8%	475	0.0107
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	5.2%	19.3%	16.1%	483	0.0098
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	4.8%	17.7%	15.1%	475	0.0103
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	5.2%	19.3%	16.2%	518	0.0091
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	4.7%	17.3%	14.8%	478	0.0103
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	4.9%	18.2%	15.4%	406	0.0119
3	2	Bridge	Before Pump	57.3%	26.7%	5.5%	18	5.5%	20.7%	17.1%	432	0.0106
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.8%	11.1%	10.0%	528	0.0113
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.4%	9.4%	8.6%	615	0.0105
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	3.4%	13.6%	12.0%	465	0.0118
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.9%	11.3%	10.2%	577	0.0103
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.8%	11.1%	10.0%	533	0.0112
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.6%	10.1%	9.2%	584	0.0107
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.6%	10.4%	9.4%	526	0.0117
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.8%	10.8%	9.8%	485	0.0124
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.4%	9.6%	8.7%	455	0.0141
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.4%	9.2%	8.4%	533	0.0122
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	3.1%	12.4%	11.0%	478	0.0119
3	3	Paving	Before Paver	55.3%	24.8%	5.0%	18	2.7%	10.6%	9.6%	452	0.0135
3	3	Paving	Before Paver	55.3%	24.8%	5.0%		2.8%	11.1%	10.0%	528	0.0113

Table 14 – AVA Test Results for Oklahoma Air-Entrained Concrete Mixes (cont.)

Division	Mix #	Mix Type	Sample Location	Mortar	Paste	Expected Air	Sample Volume (cm3)	Air in Concrete	Air in Paste	Air in Putty	Specific Surface (in-1)	Spacing Factor (in)
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.4%	8.8%	8.1%	462	0.0144
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.1%	7.4%	6.9%	503	0.0141
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	3.3%	13.0%	11.5%	511	0.0110
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.4%	8.7%	8.0%	470	0.0142
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	3.5%	13.7%	12.1%	533	0.0102
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	1.9%	7.6%	7.0%	480	0.0148
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	3.0%	12.0%	10.7%	460	0.0126
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.1%	7.8%	7.2%	447	0.0157
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	1.9%	7.3%	6.8%	607	0.0119
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.1%	8.1%	7.5%	450	0.0153
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	3.2%	13.3%	11.7%	437	0.0126
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.9%	11.5%	10.3%	422	0.0140
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.4%	9.2%	8.5%	475	0.0137
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.8%	11.0%	9.9%	439	0.0137
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	3.8%	15.1%	13.1%	538	0.0097
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.2%	8.8%	8.1%	617	0.0107
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.4%	9.6%	8.7%	538	0.0119
3	4	Bridge	Before Pump	58.7%	26.8%	5.0%	18	2.6%	10.4%	9.4%	437	0.0141
3	5	Paving	After Paver	56.9%	26.2%	5.3%	18	1.9%	6.6%	6.2%	820	0.0091
3	5	Paving	After Paver	56.9%	26.2%	5.3%	18	2.2%	7.7%	7.2%	709	0.0099
3	5	Paving	After Paver	56.9%	26.2%	5.3%	18	1.9%	6.9%	6.4%	747	0.0098
3	5	Paving	After Paver	56.9%	26.2%	5.3%	18	2.4%	8.5%	7.8%	683	0.0098
3	5	Paving	After Paver	56.9%	26.2%	5.3%	18	1.6%	5.6%	5.3%	780	0.0103
3	5	Paving	After Paver	56.9%	26.2%	5.3%	18	2.6%	9.3%	8.5%	688	0.0094
3	5	Paving	Before Paver	56.9%	26.2%	5.3%	18	4.6%	16.7%	14.3%	729	0.0069
4	1	Paving	Before Paver	53.1%	23.6%	6.0%	18	2.1%	8.6%	7.9%	594	0.0112
4	1	Paving	Before Paver	53.1%	23.6%	6.0%	18	2.1%	8.7%	8.0%	627	0.0106
4	1	Paving	Before Paver	53.1%	23.6%	6.0%	18	2.7%	10.9%	9.9%	551	0.0109
4	1	Paving	Before Paver	53.1%	23.6%	6.0%	18	2.9%	11.8%	10.6%	511	0.0114
4	1	Paving	Before Paver	53.1%	23.6%	6.0%	18	2.8%	11.3%	10.1%	460	0.0129
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	3.03.4%	11.0%	9.9%	460	0.0131
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	3.1%	11.3%	10.1%	465	0.0128
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	3.4%	12.3%	11.0%	498	0.0115
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	3.7%	13.7%	12.0%	434	0.0126
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	4.0%	14.5%	12.7%	422	0.0126
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	3.0%	10.8%	9.8%	429	0.0141
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	3.6%	13.2%	11.7%	399	0.0140
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	4.3%	15.8%	13.7%	432	0.0119
4	2	Bridge	After Pump	57.4%	26.9%	5.0%	18	3.5%	12.9%	11.4%	480	0.0117
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	2.8%	10.2%	9.2%	610	0.0102
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	2.9%	10.6%	9.5%	417	0.0147
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	2.6%	9.3%	8.5%	493	0.0131
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	2.8%	10.3%	9.4%	478	0.0130
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	2.9%	10.5%	9.5%	406	0.0151
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	3.0%	10.9%	9.8%	544	0.0111
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	3.1%	11.2%	10.1%	490	0.0122
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	2.8%	10.1%	9.2%	612	0.0102
4	2	Bridge	Before Pump	57.4%	26.9%	5.0%	18	3.6%	13.0%	11.5%	429	0.0130

Table 14 – AVA Test Results for Oklahoma Air-Entrained Concrete Mixes (cont.)

Division	Mix #	Mix Type	Sample Location	Mortar	Paste	Expected Air	Sample Volume (cm3)	Air in Concrete	Air in Paste	Air in Putty	Specific Surface (in-1)	Spacing Factor (in)
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	2.8%	9.9%	9.0%	851	0.0074
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	3.3%	11.7%	10.5%	594	0.0098
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	3.7%	13.4%	11.8%	528	0.0104
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.8%	17.5%	14.9%	597	0.0082
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.3%	15.5%	13.4%	531	0.0097
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	3.0%	10.8%	9.7%	678	0.0089
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.1%	14.9%	13.0%	505	0.0104
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.1%	15.1%	13.1%	546	0.0096
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.4%	16.2%	13.9%	503	0.0101
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.5%	16.3%	14.0%	460	0.0110
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	2.3%	9.3%	8.5%	516	0.0125
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	2.1%	7.3%	6.8%	538	0.0133
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.6%	16.7%	14.3%	462	0.0108
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	2.9%	10.4%	9.4%	640	0.0096
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.5%	16.4%	14.1%	437	0.0115
4	3	Bridge	After Pump	57.4%	26.9%	5.5%	18	4.8%	17.5%	14.9%	516	0.0095
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.5%	16.2%	14.0%	630	0.0080
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	3.9%	14.2%	12.4%	610	0.0088
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.1%	15.0%	13.0%	653	0.0080
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	3.9%	14.3%	12.5%	622	0.0086
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.3%	15.7%	13.6%	549	0.0093
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.3%	15.5%	13.4%	592	0.0087
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.3%	15.6%	13.5%	549	0.0094
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.0%	14.5%	12.6%	650	0.0082
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	5.1%	18.9%	15.9%	622	0.0076
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	3.9%	14.2%	12.4%	1011	0.0053
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.9%	17.8%	15.1%	582	0.0084
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.3%	15.6%	13.5%	564	0.0091
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.2%	15.3%	13.2%	531	0.0098
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.1%	14.7%	12.8%	625	0.0085
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.1%	14.9%	13.0%	582	0.0090
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	5.0%	18.4%	15.5%	518	0.0093
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.7%	17.3%	14.8%	589	0.0083
4	3	Bridge	Before Pump	57.4%	26.9%	5.5%	18	4.1%	14.7%	12.8%	625	0.0085
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	1.5%	5.4%	5.2%	495	0.0164
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	3.0%	10.8%	9.8%	490	0.0123
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.4%	8.7%	8.0%	531	0.0125
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.6%	9.3%	8.5%	488	0.0132
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	3.0%	10.9%	9.8%	498	0.0121
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.2%	7.7%	7.2%	462	0.0151
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.5%	9.0%	8.2%	536	0.0122
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.9%	10.3%	9.3%	488	0.0127
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.6%	9.1%	8.4%	455	0.0143
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	3.2%	11.5%	10.3%	424	0.0139
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.6%	9.2%	8.4%	427	0.0152
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.7%	9.7%	8.9%	424	0.0149
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	3.1%	11.0%	9.9%	419	0.0143
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.5%	9.0%	8.2%	445	0.0148
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.2%	7.7%	7.1%	457	0.0153
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	3.1%	11.1%	10.0%	526	0.0113
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.3%	8.4%	7.7%	470	0.0143
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	1.7%	5.9%	5.6%	592	0.0132
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.7%	9.5%	8.7%	455	0.0140
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	1.9%	6.7%	6.3%	498	0.0149
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	3.1%	11.2%	10.1%	475	0.0126
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.8%	10.0%	9.1%	505	0.0124
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.9%	10.4%	9.5%	475	0.0129
4	4	Paving	Before Paver	58.7%	26.3%	5.5%	18	2.6%	9.3%	8.5%	457	0.0141

Table 14 – AVA Test Results for Oklahoma Air-Entrained Concrete Mixes (cont.)

Division	Mix #	Mix Type	Sample Location	Mortar	Paste	Expected Air	Sample Volume (cm3)	Air in Concrete	Air in Paste	Air in Putty	Specific Surface (in-1)	Spacing Factor (in)
5	1	Paving	Before Paver	55.8%	25.3%	4.5%	18	5.2%	20.9%	17.3%	528	0.0086
5	1	Paving	Before Paver	55.8%	25.3%	4.5%	18	1.2%	4.5%	4.3%	587	0.0151
5	1	Paving	Before Paver	55.8%	25.3%	4.5%	18	2.6%	10.0%	9.1%	544	0.0116
5	1	Paving	Before Paver	55.8%	25.3%	4.5%	18	3.9%	15.1%	13.1%	447	0.0117
5	1	Paving	Before Paver	55.8%	25.3%	4.5%	16	1.6%	6.3%	5.9%	592	0.0130
5	2	Bridge	At Plant	57.4%	26.2%	5.0%	18	2.9%	11.0%	9.9%	597	0.0101
5	2	Bridge	At Plant	57.4%	26.2%	5.0%	18	2.7%	10.0%	9.1%	488	0.0128
5	2	Bridge	At Plant	57.4%	26.2%	5.0%	18	1.8%	6.6%	6.2%	508	0.0147
5	2	Bridge	At Plant	57.4%	26.2%	5.0%	18	1.7%	6.2%	5.8%	673	0.0115
5	2	Bridge	At Plant	57.4%	26.2%	5.0%	18	3.1%	11.7%	10.4%	569	0.0103
5	2	Bridge	At Plant	57.4%	26.2%	5.0%	18	2.9%	10.8%	9.8%	536	0.0113
6	1	Bridge	After Pump	54.4%	28.0%	6.0%	18	3.4%	11.7%	10.5%	681	0.0086
6	1	Bridge	After Pump	54.4%	28.0%	6.0%	18	3.3%	11.3%	10.2%	533	0.0111
6	1	Bridge	After Pump	54.4%	28.0%	6.0%	18	4.1%	14.4%	12.5%	493	0.0108
6	1	Bridge	After Pump	54.4%	28.0%	6.0%	18	3.2%	11.1%	10.0%	432	0.0138
6	1	Bridge	After Pump	54.4%	28.0%	6.0%	18	3.4%	11.7%	16.910.5%	429	0.0136
6	1	Bridge	At Plant	54.4%	28.0%	6.0%	13	4.7%	16.6%	14.2%	681	0.0074
6	1	Bridge	At Plant	54.4%	28.0%	6.0%	18	2.9%	10.0%	9.1%	630	0.0099
6	1	Bridge	At Plant	54.4%	28.0%	6.0%	18	2.7%	9.2%	8.4%	554	0.0117
6	1	Bridge	At Plant	54.4%	28.0%	6.0%	17	2.8%	9.6%	8.8%	556	0.0115
6	1	Bridge	At Plant	54.4%	28.0%	6.0%	18	2.6%	8.9%	8.2%	579	0.0113
6	1	Bridge	At Plant	54.4%	28.0%	6.0%	18	2.7%	9.4%	8.6%	803	0.0080
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	3.7%	12.9%	11.4%	953	0.0059
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	4.1%	14.5%	12.7%	691	0.0077
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	3.5%	12.3%	10.9%	617	0.0093
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	3.8%	13.3%	11.7%	587	0.0094
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	2.8%	9.6%	8.8%	737	0.0086
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	3.5%	12.1%	10.8%	846	0.0068
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	4.4%	15.4%	13.4%	780	0.0066
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	5.4%	19.3%	16.2%	716	0.0066
6	1	Bridge	Before Pump	54.4%	28.0%	6.0%	18	4.6%	16.0%	13.8%	673	0.0076
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	3.7%	13.4%	11.8%	419	0.0131
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	3.4%	12.1%	10.8%	368	0.0156
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	2.5%	9.0%	8.2%	404	0.0162
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	2.2%	7.7%	7.2%	498	0.0141
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	3.1%	11.1%	10.0%	470	0.0127
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	2.8%	9.9%	9.0%	373	0.0168
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	4.6%	16.9%	14.4%	389	0.0128
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	3.7%	13.6%	11.9%	373	0.0146
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	2.6%	9.3%	8.5%	394	0.0164
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	3.6%	13.1%	11.6%	472	0.0117
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	3.4%	12.2%	10.9%	480	0.0119
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	3.6%	13.2%	11.6%	427	0.0130
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	1.3%	4.6%	4.4%	511	0.0171
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	18	2.6%	9.9%	9.0%	455	0.0139
7	1	Bridge	After Pump	57.8%	25.3%	5.0%	16.5	3.5%	13.7%	12.0%	378	0.0144

Table 14 – AVA Test Results for Oklahoma Air-Entrained Concrete Mixes (cont.)

Division	Mix #	Mix Type	Sample Location	Mortar	Paste	Expected Air	Sample Volume (cm3)	Air in Concrete	Air in Paste	Air in Putty	Specific Surface (in-1)	Spacing Factor (in)
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	4.0%	14.3%	12.5%	356	0.0150
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	4.4%	16.0%	13.8%	386	0.0132
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	4.6%	16.6%	14.3%	368	0.0136
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	1.5%	5.3%	5.0%	318	0.0258
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	4.8%	17.4%	14.8%	434	0.0113
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	4.2%	15.4%	13.3%	404	0.0128
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	3.5%	12.7%	11.3%	455	0.0124
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	3.5%	12.5%	11.1%	422	0.0134
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	3.7%	13.2%	11.7%	452	0.0122
7	1	Bridge	Before Pump	57.8%	25.3%	5.0%	18	3.5%	13.7%	12.1%	483	0.0113
7	2	Paving	After Paver	56.1%	24.8%	5.0%	18	1.5%	5.8%	5.5%	498	0.0159
7	2	Paving	After Paver	56.1%	24.8%	5.0%	18	2.4%	9.6%	8.8%	734	0.0087
7	2	Paving	After Paver	56.1%	24.8%	5.0%	18	2.3%	9.0%	8.2%	490	0.0134
7	2	Paving	After Paver	56.1%	24.8%	5.0%	18	1.6%	6.3%	6.0%	500	0.0153
7	2	Paving	After Paver	56.1%	24.8%	5.0%	18	1.6%	6.2%	5.8%	442	0.0174
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	2.4%	9.3%	8.5%	508	0.0127
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	2.4%	9.6%	8.8%	734	0.0087
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	2.0%	7.9%	7.4%	597	0.0116
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	1.7%	6.5%	6.1%	597	0.0126
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	1.8%	7.0%	6.5%	668	0.0110
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	1.2%	4.5%	4.3%	544	0.0162
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	1.8%	7.1%	6.6%	478	0.0152
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	1.7%	6.8%	6.4%	511	0.0145
7	2	Paving	Before Paver	56.1%	24.8%	5.0%	18	1.5%	5.8%	5.5%	470	0.0169
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	4.5%	16.4%	14.1%	389	0.0130
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.7%	13.5%	11.9%	411	0.0133
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	5.2%	18.9%	15.9%	338	0.0139
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	5.0%	18.4%	15.5%	378	0.0126
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.6%	13.1%	11.6%	300	0.0185
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.5%	12.7%	11.2%	353	0.0159
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	4.4%	16.1%	13.8%	358	0.0142
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	4.1%	14.8%	12.9%	353	0.0148
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	5.1%	18.8%	15.8%	333	0.0143
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.4%	12.2%	10.9%	445	0.0129
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.9%	14.1%	12.4%	340	0.0158
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	4.2%	15.2%	13.2%	320	0.0163
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	4.2%	15.2%	13.2%	345	0.0151
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	4.9%	18.1%	15.3%	351	0.0138
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	4.9%	17.9%	15.2%	318	0.0152
8	1	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.8%	13.7%	12.1%	366	0.0148
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	4.7%	17.0%	14.5%	488	0.0102
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	5.0%	18.5%	15.6%	460	0.0104
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	4.8%	17.4%	14.8%	432	0.0113
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	3.9%	14.1%	12.4%	465	0.0115
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	4.6%	16.8%	14.4%	452	0.0110
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	4.4%	16.1%	13.9%	409	0.0124
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	4.0%	14.6%	12.7%	480	0.0110
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	5.3%	19.7%	16.4%	439	0.0106
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	4.7%	17.0%	14.5%	472	0.0105
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	5.3%	19.3%	16.2%	409	0.0115
8	1	Bridge	Before Pump	56.9%	26.2%	5.3%	18	3.8%	13.6%	12.0%	361	0.0151

Table 14 – AVA Test Results for Oklahoma Air-Entrained Concrete Mixes (cont.)

Division	Mix #	Mix Type	Sample Location	Mortar	Paste	Expected Air	Sample Volume (cm3)	Air in Concrete	Air in Paste	Air in Putty	Specific Surface (in-1)	Spacing Factor (in)
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	2.8%	10.0%	9.1%	450	0.0139
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	2.9%	10.2%	9.3%	422	0.0147
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	2.3%	8.3%	7.7%	404	0.0169
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.6%	12.9%	11.4%	373	0.0149
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	2.0%	7.0%	6.6%	462	0.0158
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	2.9%	10.4%	9.4%	442	0.0139
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	1.7%	6.1%	5.8%	457	0.0169
8	2	Bridge	After Pump	56.9%	26.2%	5.3%	18	3.2%	11.5%	10.4%	358	0.0164
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	2.0%	7.3%	6.8%	556	0.0129
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	2.7%	9.7%	8.8%	480	0.0132
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	3.0%	10.8%	9.7%	419	0.0144
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	2.3%	8.1%	7.5%	488	0.0140
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	3.3%	11.9%	10.7%	579	0.0100
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	2.5%	9.1%	8.3%	493	0.0132
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	2.2%	7.9%	7.3%	470	0.0147
8	2	Bridge	Before Pump	56.9%	26.2%	5.3%	18	2.1%	7.3%	6.8%	396	0.0180