DETERMINING THE AIR-VOID DISTRIBUTION

OF

FRESH CONCRETE WITH THE SEQUENTIAL

PRESSURE METHOD

By

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Bachelor of Science in CIVIL ENGINEERING

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2012

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2014

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Date of Degree: DECEMBER, 2014

Title of Study: DETERMING THE AIR-VOID DISTRIBUTION OF FRSH CONCRETE WIT HTHE SEQUENTIAL PRESSURE METHOD

Major Field: CIVIL ENGINEERING

Abstract: This work consist of the validation of a novel testing procedure, called the SAM, using sequential pressures. The SAM testing procedure uses a new measurement value, called the SAM number, to determine the quality of the air-void system. This research also looks at the reliability, repeatability, and variability of the SAM testing procedure. This study looked into 9 different mixture types with varying w/cm ratios and admixtures. The difference between identical air entrained (AEA) concrete mixtures with and without polycarboxylates (PC) were also examined by the SAM. Concrete mixtures for this study were made in a climate controlled laboratory environment. All concrete mixtures in this study had hardened air-void analysis (ASTM C 457) conducted in them. The parameters that were determined by ASTM C 457 were then compared to the SAM number. The results of this study show that the SAM provides a good indication of the air-void system, and a SAM number limit of 0.20 psi has been shown to correlate well to a spacing factor of 0.008" or less. The second study in this research shows a possible mechanism for the SAM. This study looked into how air entrained air bubbles reacted to an applied pressure, and these findings were compared to what would be predicted by Boyle's Law, Henry's Law, and the Laplace-Young Equation. This study found that air bubbles dissolved along a linear line that was little affected by the air content in the sample. Also, these air bubbles dissolved approximately in order of size, starting with the smallest first. The study also found that clustered air bubbles behaved differently than bubbles spaced farther apart. This finding is a possible explanation for the SAM testing procedure. The results in this study were also compared to actual concrete testing data. This was done to further show that the phenomenon shown in the research could be happening in actual concrete that is being tested with the SAM.

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CHAPTER I

INTRODUCTION

Concrete is readily available in most areas of the world, can easily be constructed in any shape, and is a naturally a durable material. However, one of the mechanisms that challenges of concrete durability is the cyclic freezing and thawing of water. Freeze-thaw damage can be significantly reduced by entraining air into a concrete mixture. This is done by adding a chemical admixture, called an air entraining admixture, to the concrete mixture. A high quality air-void system is needed to mitigate the damage caused by freezing and thawing cycles and occurs when there is a large amount of well dispersed air-voids in a concrete mixture.

T.C. Powers conducted research in 1949 (Powers 1949) that developed the hardened air-void parameters that are used today. The work was further developed by the United Stated Bureau of Reclamation, which established the limiting values 0.008 inches for the spacing factor and 600 in^{-1} for the specific surface to ensure that a concrete is freeze-thaw durable (Backstrom et al. 1956). The limits for these two parameters have now been adopted by ACI 201. Also, Kleiger (1956) determined that the minimum volume of air needed to ensure freeze-thaw durability is 18% of the cement paste. This recommended air volume was then adopted by ACI 318, and implemented with the paste volume being a function of the maximum nominal aggregate size of a concrete mixture.

The practice of measuring the air volume in a concrete mixture has been common for many years. However, with the invention and use of modern chemical admixtures, like polycarboxylate superplasticizers, the traditional relationship established by Kleiger between the air volume and the hardened air-void parameter does not hold true (Felice 2012; Freeman 2012; Saucier, Pigeon, and Plante 1990; and Saucier, Pigeon, and Cameron 1991). Hardened air-void analysis (ASTM C457) has shown that as the dosage of a superplasticizer increases, the air-void system coarsens. This results in a higher spacing factor and a lower specific surface, and inherently, a lower durability to freeze-thaw effects. This phenomenon can happen even at recommended air volumes.

Previous work by Ley and Tabb (2012) have shown a testing procedure that utilizes sequential pressures that gives an indication of the hardened air-void parameters, most notability the spacing factor. However, this test could not be easily conducted in the field and was not fast enough. The goal of this thesis is to determine a quicker testing method utilizing similar sequential pressures to determine a correlation to the hardened air-void parameters. The thesis is written in a journal paper format instead of the traditional thesis format. The next two chapters will investigate a method that determines the quality of an air-void system and a mechanism behind the testing method. That method uses a device called the Super Air Meter, or SAM. This device applies sequential pressures to a sample of fresh concrete whose results are shown to correlate well with frost durability parameters like spacing factor and specific surface. The first chapter describes the test method and its correlation to the hardened air-void parameters, while the second chapter of this thesis describes the mechanism involved in the physical phenomenon that occur during the SAM test.

CHAPTER II

A RAPID TEST METHOD TO MEASURE THE AIR-VOID SIZE DISTRIBUTION IN FRESH CONCRETE BY USING SEQUENTIAL PRESSURES

Introduction

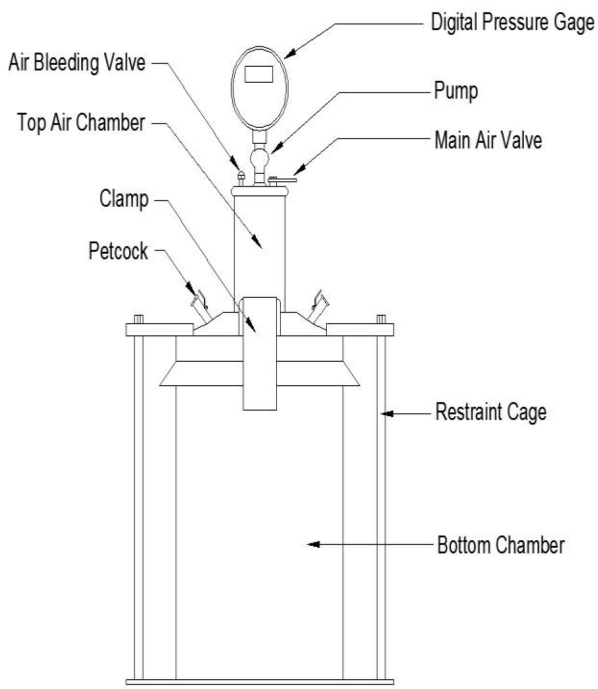
Concrete suffers from damage when it is saturated and freezes. This damage can be limited by the incorporation of small air-voids in the material while the concrete is being mixed. The most common way to incorporate these air-voids is with an air-entraining admixture (AEA). Currently it is common to measure the total volume of air in concrete with the pressure method (ASTM C231), volumetric (ASTM C173), and gravimetric (ASTM C138) test methods. However, these methods only measure the total volume of air and not the size distribution of the air in the concrete. Currently, the only established test to measure the size distribution of air in the concrete is to examine the material with a hardened air-void analysis (ASTM C457). One challenge with this method is that it takes at least one week to complete. However, the results show a better prediction of freeze thaw durability then the total air-void volume. Work by the United States Bureau of Reclamation went on to show that a spacing factor of 0.008 inches and a specific surface of 600 in^{-1} were needed to provide a sufficient air-void system (Backstrom1956). ACI 201 now suggests these limits to be used to determine the freeze-thaw durability of concrete. Therefore, it is considered desirable to have a concrete mixture with a low spacing factor, and a high specific surface. Unfortunately, because of the time and expense to complete the ASTM C 457 test it is not used regularly. Research by Felice (2012); Freeman (2012); Saucier, Pigeon, and Plante (1990); and Saucier, Pigeon, and Cameron (1991) have shown that concrete mixtures with and without superplasticizers can have the same air content, but have different void size distributions. This can be problematic if one is just measuring the air volume of these mixtures.

Research completed at Oklahoma State University has shown that the use of sequential pressures of fresh concrete can give an indication of the spacing factor (Ley and Tabb, 2013). The meter is called the Sequential Air Meter or Super Air Meter (SAM). This test needs to be further investigated and improved to better accommodate field users. The objective of this work is to develop an easier and expedited test method using the SAM.

Experimental Methods

Testing Method

The SAM consists of a typical ASTM C231 Type B pressure meter with a few modifications. The SAM uses a digital pressure gauge and an outer restraint cage as shown in Figure 2.1. The digital pressure gauge has a pressure limit of 50 psi with an accuracy of 0.01 psi. Since the SAM is subjected to higher pressures than the typical ASTM C231 type B pressure meter, a restraint cage was required to handle the higher pressures.



(A)

(B)

Figure 2.1 (A) Shows a SAM diagram with labeled parts, (B) shows an actual SAM with the restraint cage (Ley and Tabb 2013)

The SAM testing procedure is similar to the ASTM C231 type B procedures with a few modifications. The SAM testing method used in this research is outlined in Table 2.1. After the bottom chamber is filled and consolidated with fresh concrete according to ASTM C 231, the rim of the bottom chamber is checked to ensure that it is void of any material prior to securing the lid. The operator can do this by running a finger along the top of the rim on the bottom chamber. The lid is then secured to the bottom chamber by the clamps and the restraint cage. Water is added through the petcocks to remove all remaining air from the system, and then the petcocks are closed. Next the top air chamber is pressurizes to 14.5 ±0.05 psi. Once the pressure is allowed to settle, the main air valve is pressed and held for approximately 10 seconds to bring the top and bottom chamber to equilibrium. While the lever is being held, the bottom chamber is hit sharply on all sides with a rubber mallet. The lever should still be held down until the pressure is equalized. The pressure is considered to be equalized when the digital pressure gauge reads a constant pressure over a period of 4 seconds. After the pressure is equalized, the value on the gauge should be recorded. Now, without opening the petcocks, the top chamber is pressurized to 30 ± 0.05 psi. The main air valve is held to bring the chambers to equilibrium. After the equilibrium pressure has been recorded, the top chamber is similarly pressurized to 45 ± 0.05 psi. The main air valve is then held to bring the chambers to equilibrium and the value is recorded. The petcocks are then opened and the main air valve is held down allowing all the air pressure to leave the top and bottom chambers. With the top still securely fastened to the bottom chamber, the petcocks are refilled with water and re-pressurized using the same pressure steps as described previously. Figure 2.2 shows a typical data set. This test can be completed in about eight minutes by an experienced user.

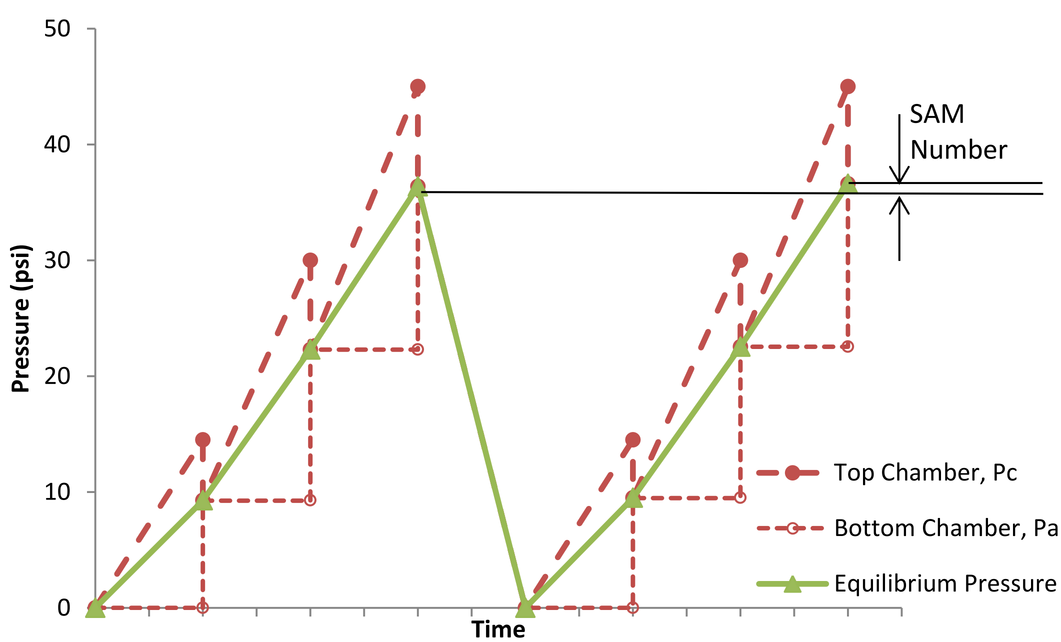


Figure 2.2 SAM testing procedure - examples pressures

Table 2.1 SAM Test Method

Step	Description of Procedure
1	Place and consolidate concrete according to ASTM C 231
2	Securely fastened the lid to the bottom chamber with clamps and restraint cage
3	Add water to the bottom chamber through the petcocks
4	Pressurize the top chamber to 14.5 ± 0.05 psi
5	Press and hold valve until equilibrium is reached
6	Record equilibrium pressure
7	Pressurize top chamber to 30 ± 0.05 psi
8	Press and hold valve until equilibrium is reached
9	Record equilibrium pressure
10	Pressure top chamber to 45 ± 0.05 psi
11	Press and hold valve until equilibrium is reached
12	Record equilibrium pressure
13	Depressurize the top and bottom chambers, allowing them to return to atmospheric pressure
14	Repeat steps 3 through 13 at least once

This version of the SAM test method differs from the original method proposed by Tabb. This one only uses three pressure steps and stops with a maximum pressure of 45 psi. The original test uses five pressure steps and stopped at 75 psi. Also, the digital pressuregauge was changed slightly to limit the pressure to 50 psi with a higher accuracy.

SAM Number

For this research, the SAM number was calculated by comparing the first and second equilibrium pressures at 45 psi. The calculation is shown by Equation 2.1.

Equation 2.1: $$SAM\ Number = (P_{45\ sequence\ 2} - P_{45\ sequence\ 1})_{45\ pressure\ step}$$

The 45 psi pressure step was chosen to provide the SAM number because it has shown to havea measureable difference between the first and second pressures sets. The SAM number will be compared to various numbers measured in the ASTM C457 hardened air-void analysis. Other comparisons were made between the first and second pressure sequence, but this method was used as it was simple and provided as good a correlation as any other comparison method. SAM numbers in this research ranged from 0.07 psi to 0.89 psi.

Air Content Calculation and Meter Calibration

The volume of air in the concrete sample can be determined by using Boyle's Law. Equation 2.2 shows Boyle's Law when it is applied to the top air chamber.

Equation 2.2: $$P_{c1}V_{c1} = P_{c2}V_{c2}$$

P_{c1} and P_{c2} are the pressures of the top air chamber before and after the main pressure valve has been pressed to bring the system toequilibrium.V_{c1} and V_{c2} are the volumes of the air from the top air chamber before and after the system have come to equilibrium. $V_{c1}$is the initial volume of air in the top air chamber, and is a known value based on the geometry of the top chamber. $V_{c2}$is then determined from Equation 2.2. The volume change caused by the applied pressure is equal for the top air chamber and the bottom chamber. This is shown in Equation 2.3. $V_{a1}$is the volume of air in the bottom chamber at atmospheric pressure. V_{a2} is the volume of air in the bottom chamber after the system has been pressurized and come to equilibrium.

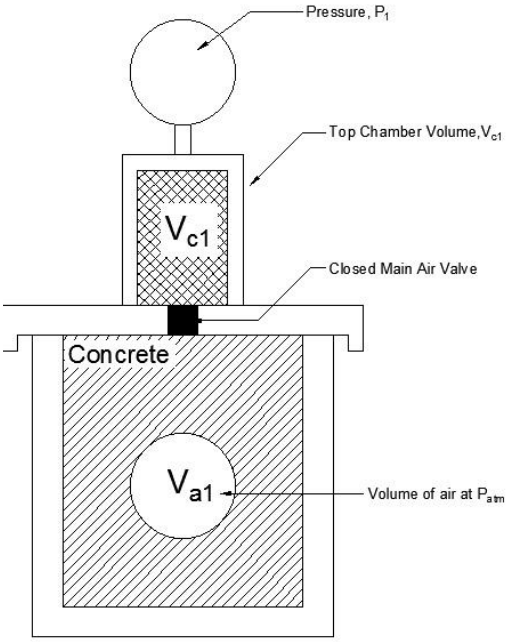


Figure 2.3 Boyle's Law applied to the SAM at (A) atmospheric pressure and then (B) at an applied equilibrium pressure

Boyle's Law is applied to the bottom chamber, as in Equation 2.4, with P_{a1} and P_{a2} being the pressure in the bottom chamber. P_{a1} is assumed to be atmospheric pressure and P_{a2} is equal to P_{c2} after the system has reached equilibrium. These variables are all shown with their corresponding locations in Figure 2.3. Equation 2.3 and 2.4 can then be simultaneously solved to determine V_{a1}. The volume of air in the original concrete sample is then determined using Equation 2.5. V_b is the volume of the bottom chamber. These calculations for air volume are very comparable to the traditional ASTM C231 Type B pressure meter. This process has been shown to be effective by Tabb (2013) and Hover (1988). Past experiments by Ley and Tabb (2014) have shown that the air content from the SAM very closely matched results from the ASTM C231 pressure method. Because the procedures are the same then this will not be investigated further.

Equation 2.3: $$\Delta V = V_{c1} - V_{c2} = V_{a1} - V_{a2}$$

Equation 2.4: $$P_{a1}V_{a1} = P_{a2}V_{a2}$$

Equation 2.5: $$Air\ \% = \frac{V_{a1}}{V_b} * 100$$

The SAM is calibrated using three different air contents with the top air chamber pressured to a standard pressure. The calibrations procedures are outlined in Table 2.2. The three air contents used to calibrate the SAM is 0%, 5%, and 10% air. These air contents were achieved by using a calibrating device that represents an air-void of about 5% of the bottom chamber volume of 0.25 ft^3. The 0% air content is achieved by filling the bottom chamber completely with water. The 5% air content is achieved by placing one calibration device in the bottom chamber and then filling the chamber with water. The 10% air content is achieved by placing two calibration devices in the bottom chamber and then filling the chamber with water. This process is similar to the calibration method described by Ley and Tabb (2013).

Table 2.2 – SAM calibration procedure summary

Step	Procedure Description
1	Fill the bottom chamber with water
2	Securely place and fasten lid to bottom chamber
3	Add water through the petcocks
4	Pressurize top air chamber to 14.5±0.05 psi
5	Hold valve down and record equilibrium pressure, P_0
6	Release all pressure from top and bottom chambers and return to atmospheric pressure
7	Repeat steps 3 through 6 two more times
8	Remove lid and add a calibration device to the bottom chamber
9	Repeat steps 2 through 7, while recording the equilibrium pressure as P_5

10	Remove lid and add another calibration device to the bottom chamber
11	Repeat steps 2 through 7, while recording the equilibrium pressure as P_{10}

Super Air Meter Variability

This research used multiple SAMs to investigate the variability between two different meters run by two different operators. The volumes of these meters were measured and found to be less than 1% different. The same concrete mixture was used in both meters to compare their variability and the operators ran their testing simultaneously. The SAM testing procedure was then conducted with just a calibration vessel and water. The use of a calibration device accounted for 4.9% air volume for the .25 cubic foot of volume. Using this procedure allowed the variability of the test method to be investigated without introducing the variability of the concrete.

Materials

All the concrete mixtures in this research used a type I cement that met the requirements of ASTM C150. The oxide analysis for this cement used is shown in Table 2.3. The aggregates used were locally available crushed limestone and natural sand used in commercial concrete. The crushed limestone had a maximum nominal aggregate size of ¾ inch. Both the crushed limestone and the sand met ASTM C33 specifications. All the admixtures used are described in Table 2.4 and met the requirements of ASTM C260 and C494.

Table 2.3 – Type I cement oxide analysis

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	Na_2O eq (%)	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	Fe_2O_3 (%)
21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	0.4	56.7	17.8	8.2	7.8	2.6

Table 2.4 – Admixture references

Short Hand	Description	Application
WROS	Wood Rosin	Air-entraining agent
SYNTH	Synthetic chemical combination	Air-entraining agent
PC	Polycarboxylate	Superplasticizer

The wood rosin (WROS) and synthetic (SYNTH) air-entraining admixtures (AEA) were used because they represent two popular air-entraining agents that are used commercially. Six different mixture designs were investigated and are shown in Table 2.5. Both of the AEAs were also investigated with the use of a polycarboxylate (PC) superplaticizer. The PC was used at a dosage of 3 oz/cwt. This dosage was used as it increased the slump by about 6 inches. The dosages of the AEAs were varied to achieve different air contents for each mixture. A Class C fly-ash was used in several of the mixtures with a 20% cement replacement by weight. An optimized graded pavement mixture with a low paste content was also investigated. The coarse aggregate was an ASTM C33 #57 stone with a maximum nominal aggregate size of ¾ inch and an ASTM C33 #8 stone with a maximum nominal aggregate size of 3/8 inch. Both aggregates were crushed limestone from the same source.

Table 2.5–SSD Mixture proportions

w/cm	Cement lb/yd^3	Fly-Ash lb/yd^3	Paste Volume (%)	Coarse lb/yd^3	Fine lb/yd^3	Water lb/yd^3	Admixture Used
0.45	611	0	29	1850	1203	275	WROS
0.45	611	0	29	1850	1203	275	WROS + PC
0.45	611	0	29	1850	1203	275	SYNTH
0.45	611	0	29	1850	1203	275	SYNTH + PC
0.41	611	0	28	1900	1217	250	WROS
0.53	611	0	32	1775	1150	324	WROS
0.39	611	0	27	1922	1230	238	WROS
0.45	488.8	112.2	30	1835	1195	275	WROS
0.45	376	94	23	1324/966*	1069	212	WROS

*Mixture contains ¾” (coarse) aggregate and 3/8” (intermediate) aggregate.

Concrete Mixture Procedures

Aggregates are collected from outside storage piles, and brought into a temperature controlled room at 73°F for at least 24 hours before mixing. Aggregates were placed in the mixer and spun and a representative sample was taken for a moisture correction. At the time of mixing all aggregate was loaded into the mixer along with approximately two thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition and ensure that the aggregates were evenly distributed.

Next, the cement and the remaining water was added and mixed for three minutes. The resulting mixture rested for two minutes while the sides of the mixing drum were scraped.

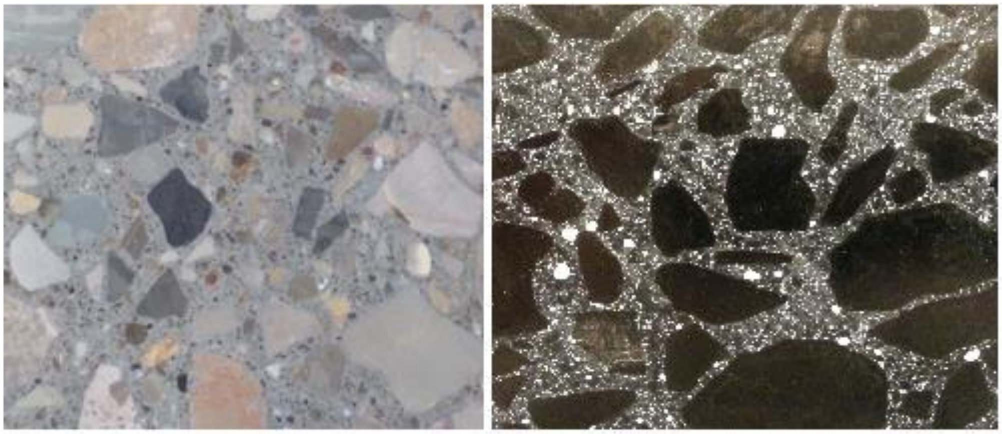
After the rest period, the mixer was turned and the admixtures were added. The water reducing agent was added first (if applicable) and was allowed to incorporate into the mixture for 15-30 seconds then the AEA was added. After the addition of admixtures the concrete was mixed for three minutes.

Tests Completed

Immediately after the mixing process was completed, the slump test (ASTM C143) and two unit weight measurements (ASTM C138) were conducted. Also, a sample for hardened air-void analysis was made at the same time. Next, the SAM test was performed on the concrete mixture.

Hardened Air-Sample Preparation

Each hardened concrete sample was allowed to cure for at least 3 days. After this time, the sample was cut into a ¾ inch thick section by an 18 inch diameter rock saw. A three parts acetone and one part lacquer mixture was applied to the sample. This mixture helped to reinforce the void wall during the polishing process. The hardened sample was then lapped on an 18 inch lapper with magnetically bonded diamond discs. The lapping continued with discs of increasing fineness until there was a high quality finish on the sample. After the samples obtained a satisfactory polish, the samples were soaked in acetone to remove the lacquer for around 15 minutes. After the acetone had evaporated, the polished surface of the sample was then colored black with a permanent marker and allowed to dry for 2-3 hours. A second coat of permanent marker was then added perpendicular to the first coat. The second coat must be allowed to dry for 8 hours or overnight. A thin layer of barium sulfate was then pressed on the colored surface of the sample twice with a stopper to force the powder into all the air-voids. Barium sulfate is a fine white powder with a particle size less than 4×10^{-5} inches (<1 um). This process left the surface of the concrete sample black and the voids white. The aggregates were then colored with a fine tip permanent marker to ensure that the aggregates couldn't be counted as air-voids. This technique is outlined in detail by Ley (2007). A satisfactory lapped sample and a finished sample are shown in Figure 2.4.



(A) (B)

Figure 2.4 (A) Satisfactory lapped samples, (B) Completed Sample

The sample is then measured for its air-void parameters using the Rapid Air 457 from Concrete Experts, Inc. This machine completes automated linear traverses with a camera that discerns the white stained air-voids from the remainder of the concrete that is black. A single threshold value of 185 was used for all samples in this research. The paste content required for the analysis was determined from the batch weights of the mixture design. The results of the hardened air-void analysis reported do not include chords smaller than 30 µm. This is done because a human does not easily detect chords smaller than this in an ASTM C457 analysis. This method has been done similarly by several researchers previously (Jakobsen et al 2006, Ley 2007, Peterson et al 2009).

Results

To show the utility of the SAM, two mixtures are compared with different air contents. These mixtures are very similar except one of them has a PC superplasticizer and the other does not. First in Figure 2.5, the results are shown with the air content versus the spacing factor. It is clear from the figure that if one wanted a spacing factor of 0.008” for the air-void system then one would need 4% air for the mixture with just an AEA in it and at least 8.5% air for the mixture with a PC and AEA. This large difference in required air content is problematic as the different mixtures would require different air contents in the field to achieve the desired spacing factor. This means that one would have to closely watch the admixture combinations used in a concrete mixture when it was being tested. However, when the SAM number and the spacing factor are compared in Figure 2.6, then one can see that a SAM number of 0.20 does a good job of predicting when the spacing factor was 0.008”. This example shows the usefulness of the SAM number as it correlates well with the spacing factor.

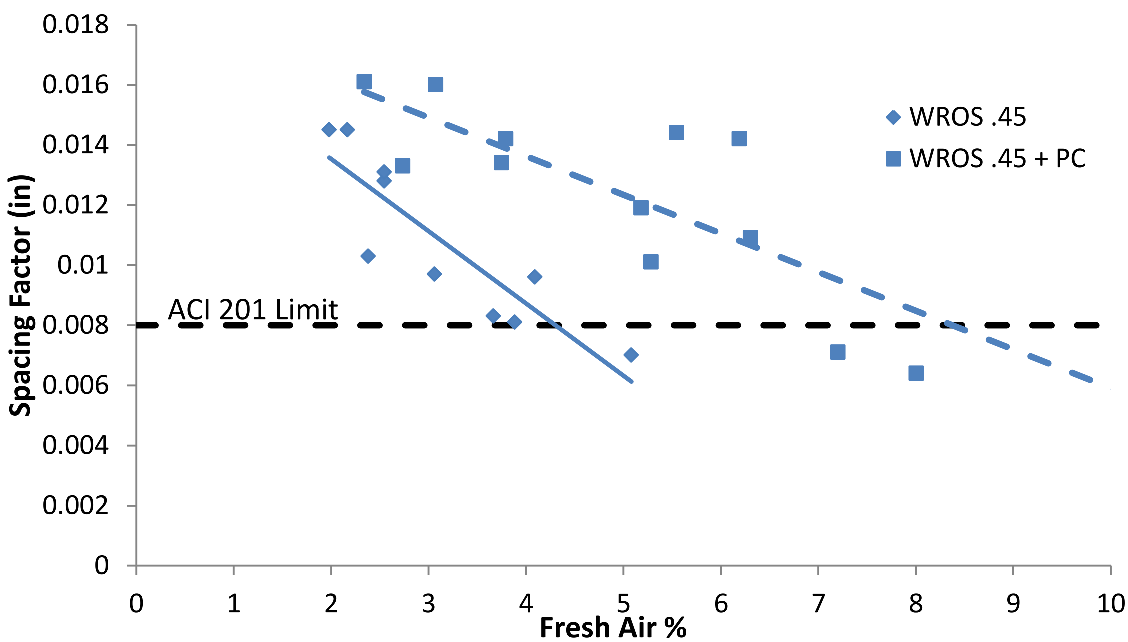


Figure 2.5 Air-void distribution with and without a superplasticizer

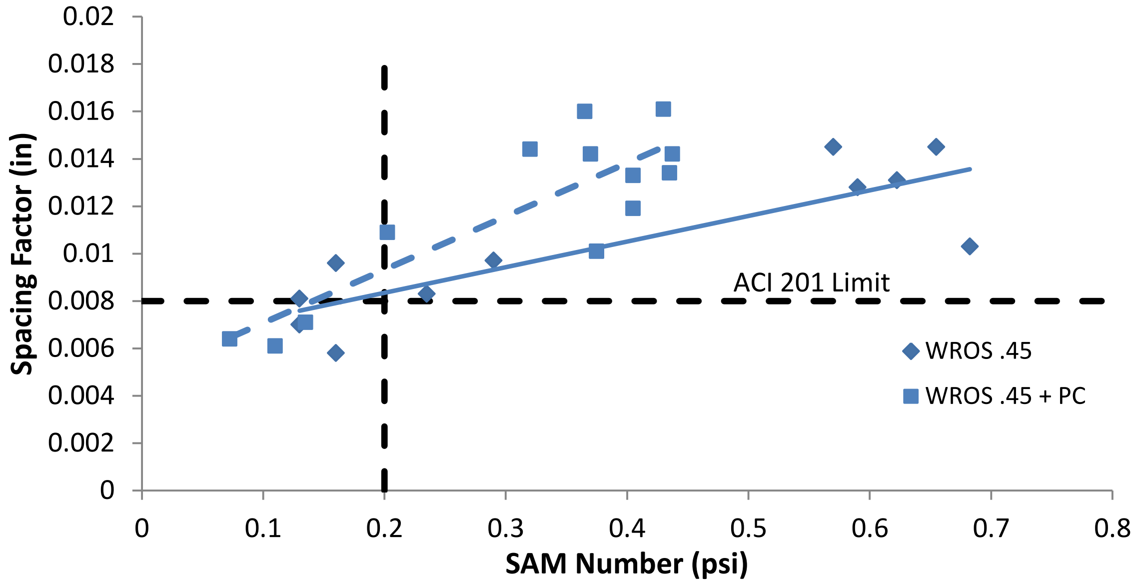


Figure 2.6 SAM number correlations to spacing factor

SAM results compared to hardened air-void parameters

The summary of all SAM test results with the hardened air-void analysis are shown in Appendix A, Table A-1. The slumps range from ½ inch to 10 inches. The graphs comparing the hardened air-void parameters versus the SAM number is shown in Figure 2.7 thru Figure 2.10. The suggested limits, per ACI 201, is a spacing factor less than or equal to 0.008 inches and a specific surface greater than 600 in^{-1}. In these plots, the ACI 201 limits are shown with a dashed line. Freeman (2012) has shown that the number of chords with a diameter smaller than 200 µm has a correlation with freeze-thaw durability. If a sample has greater than 6 chords/in that are smaller than 200 µm, Freeman determined the air-void system was satisfactory. This is shown in Figure 2.10.

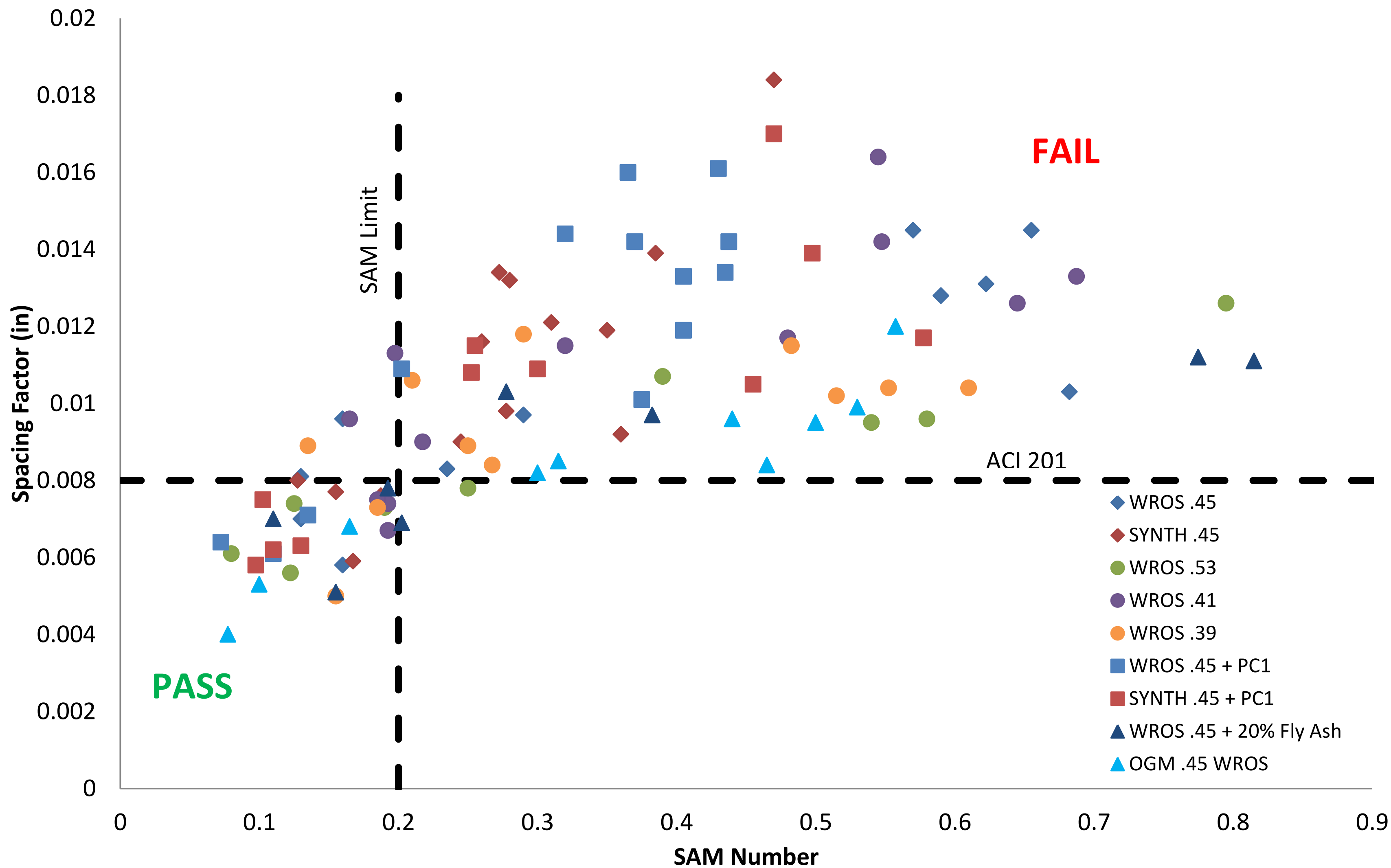


Figure 2.7 SAM number compared to Spacing Factor

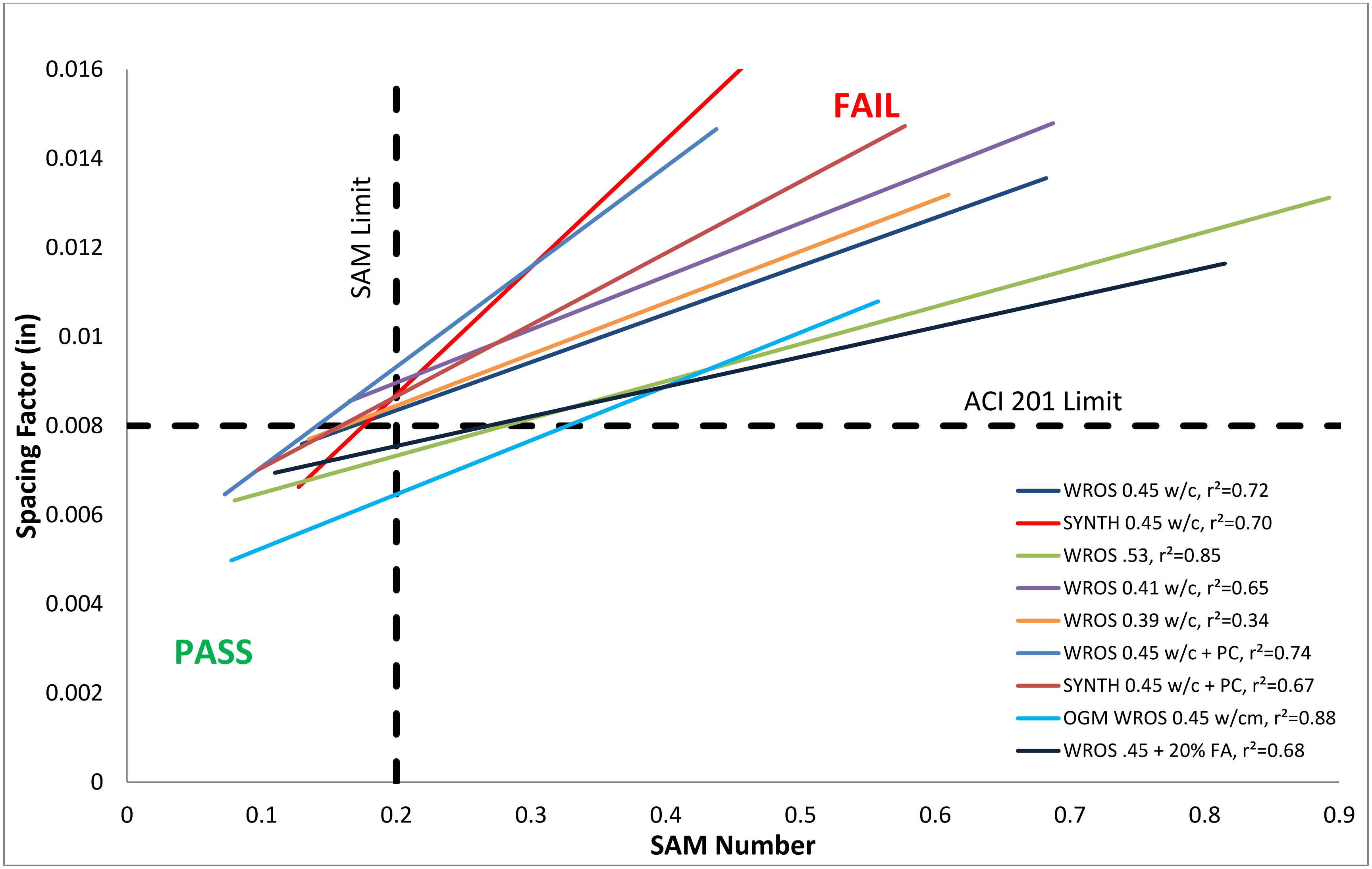


Figure 2.8 SAM number compared to spacing factor with linear trendlines

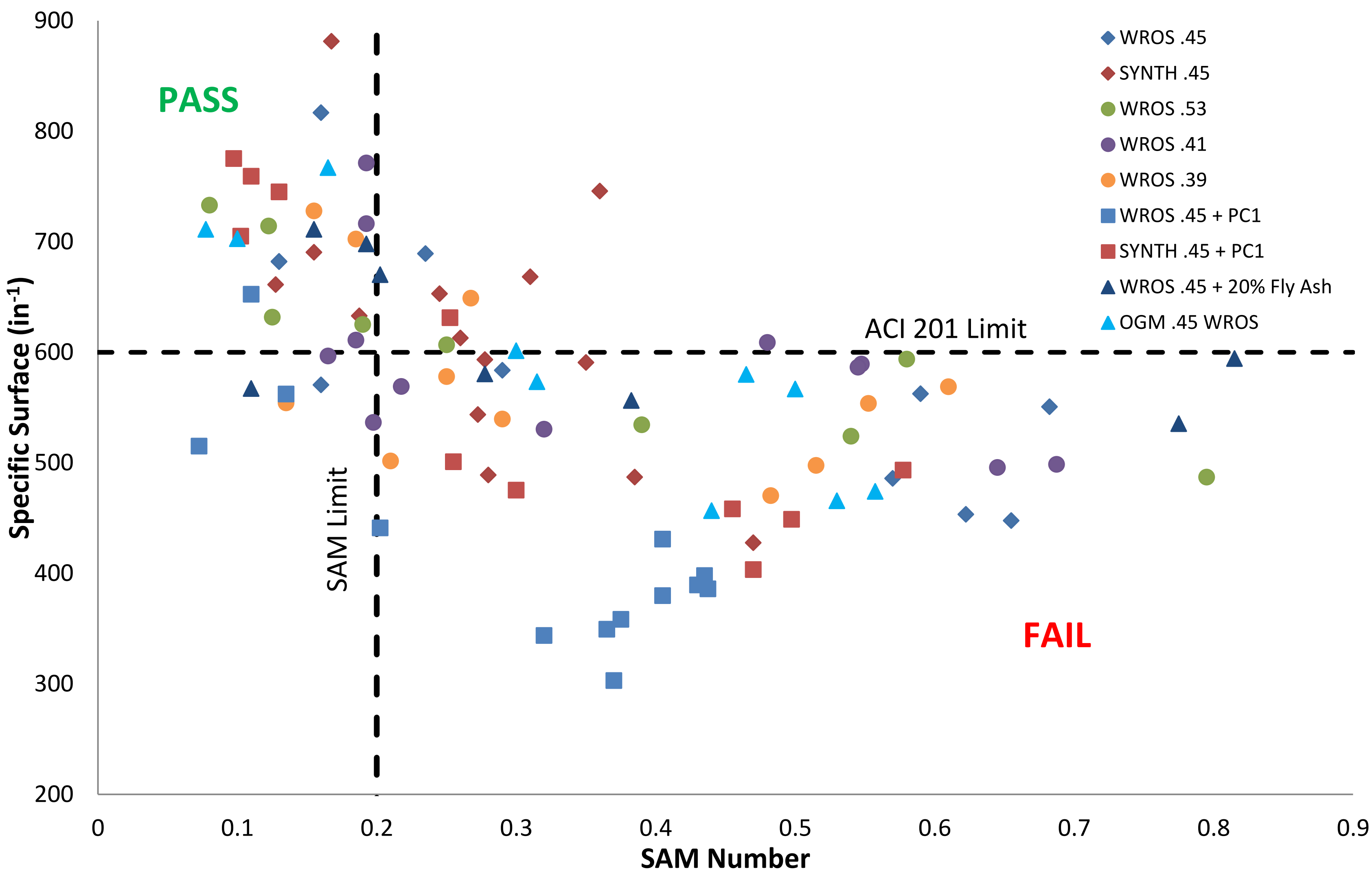


Figure 2.9 SAM number compared to Specific Surface

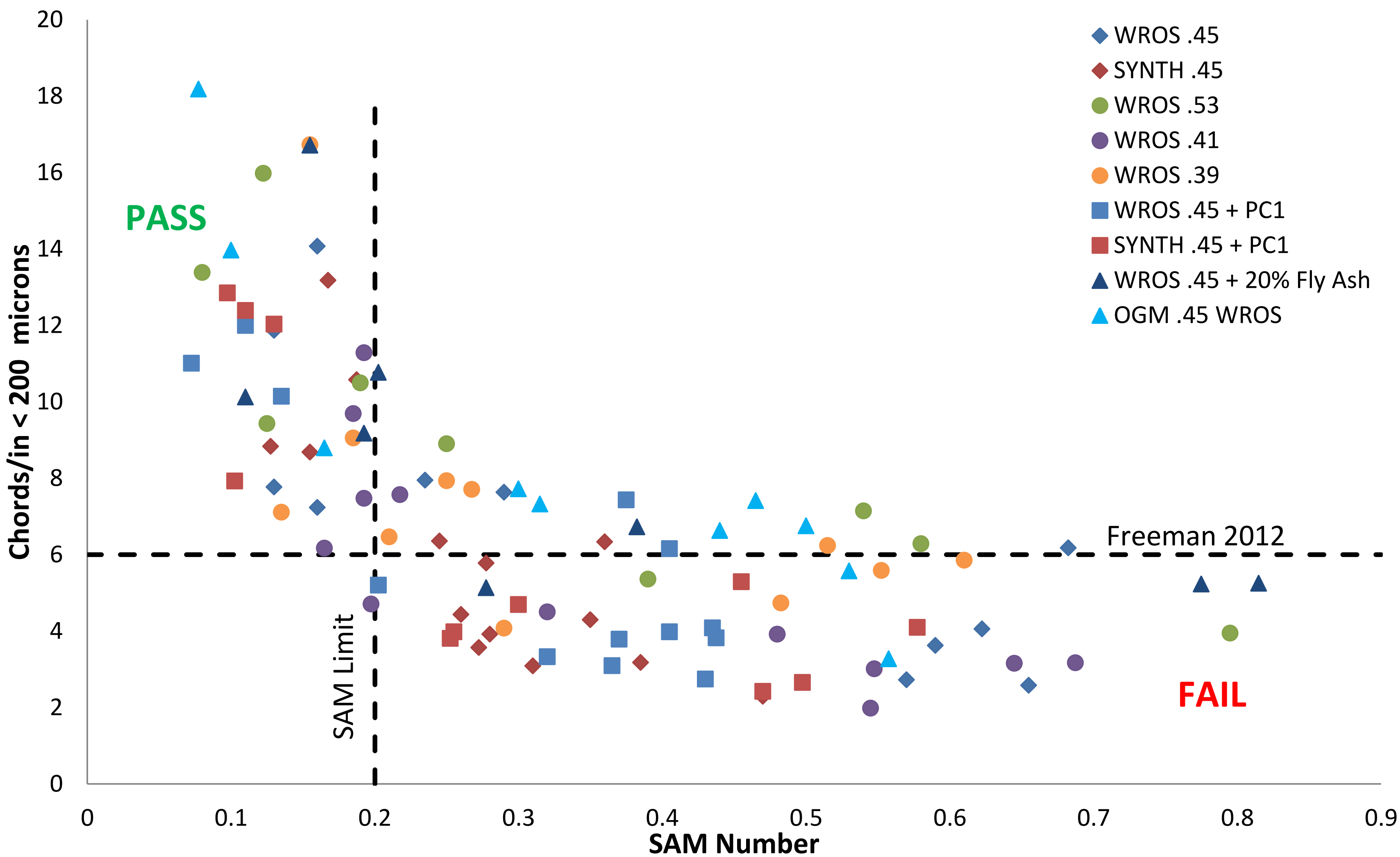


Figure 2.10 SAM number compared to chords per inch smaller than 200 microns.

SAM Test Method Variance

The difference between the results from two SAM meters is shown graphically in Figure 2.11, 2.12, and 2.13. The difference between the measurements does show a Gaussian distribution. The average difference is -0.0055 psi, with a standard deviation of 0.069 psi.

For SAM numbers smaller than 0.30 psi, another analysis was done to show the average difference and standard deviation. The difference for this is shown in Figure 2.12, and it shows an average difference of 0.0017 psi and a standard deviation of 0.048 psi. An analysis was also done where SAM testing was done with a calibration device and water in the bottom chamber. This was done to remove the variability of the concrete and just investigate the repeatability of the method. This data shows a Gaussian distribution, with an average difference of .005 psi and a standard deviation of 0.021 psi. These results are shown in Table 2.6 and all of the distributions are plotted together in Figure 2.13.

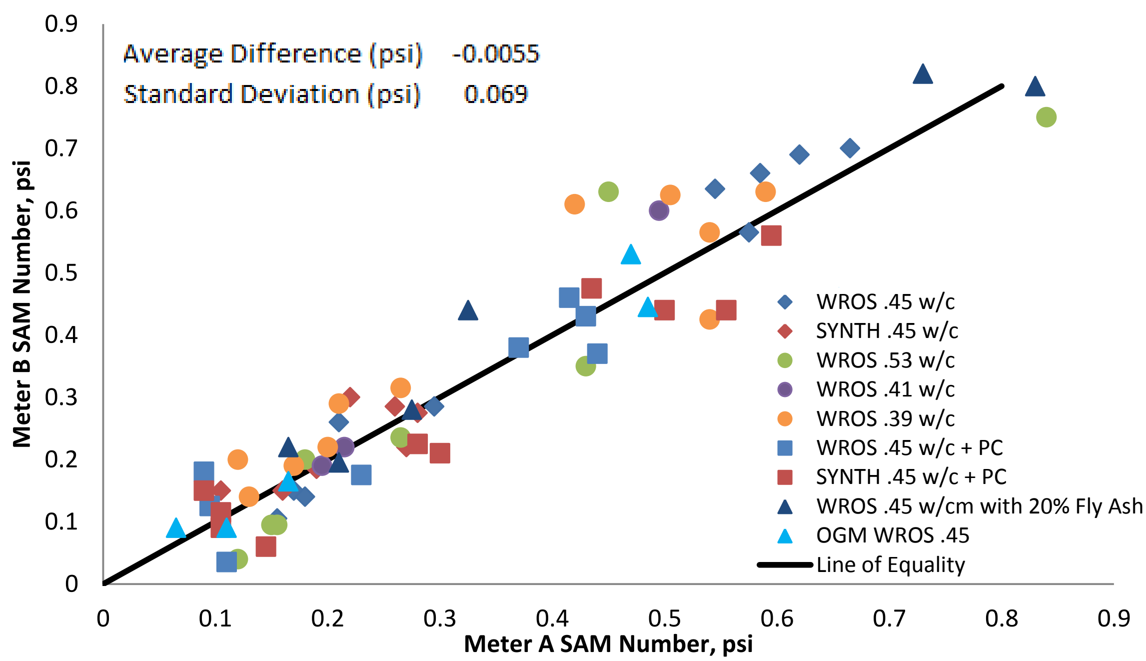


Figure 2.11 SAM number differences between multiple meters

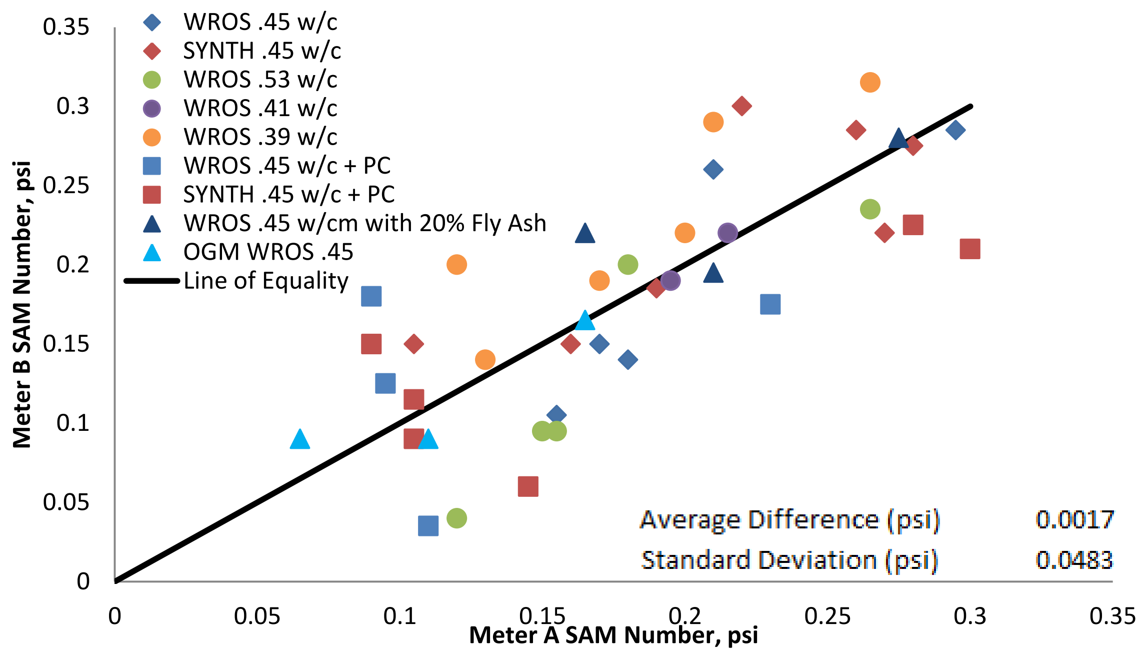


Figure 2.12 Small SAM number differences

Table 2.6 SAM measurement differences

Sam Number Difference	Frequency		
	All Test	Small SAM Number	Calibration Tests
Average Difference	-0.0055	0.0017	0.005
Minimum Difference	0.00	0.00	0.00
Maximum Difference	.195	.09	.07
Standard Deviation	0.0694	0.0483	0.021

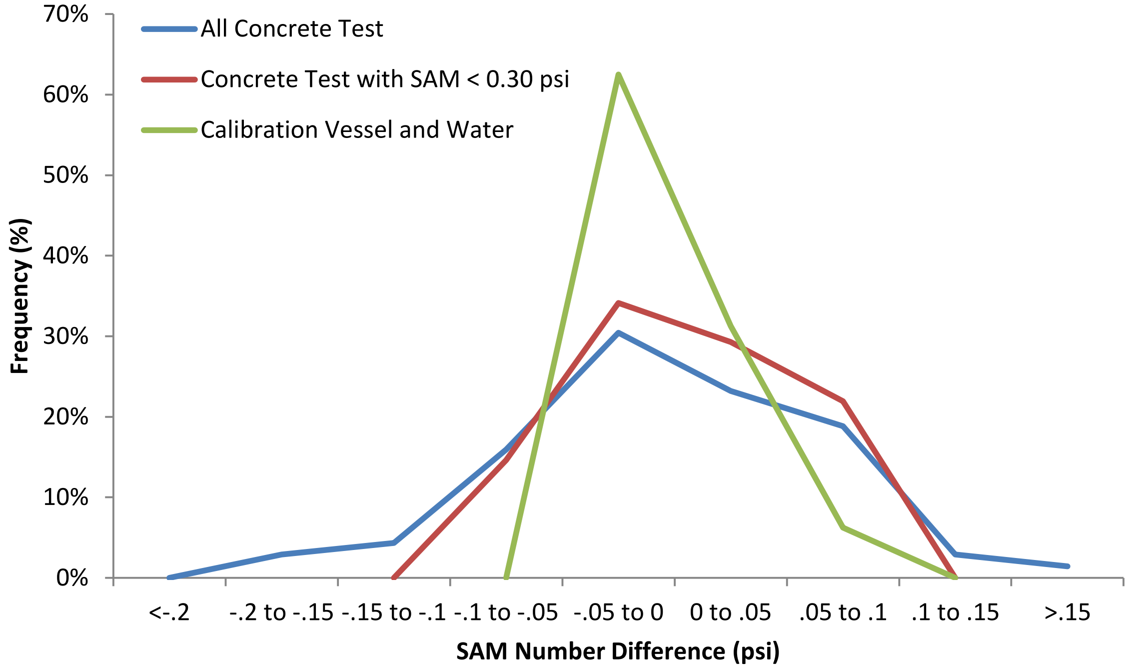


Figure 2.13 SAM Difference Distributions

SAM Versus Other Air Content Measurements

Ley and Tabb (2013) have shown that the traditional ASTM C231 pressure meter air content is very similar to the air content from the SAM, with an average difference of only 0.07% and a standard deviation of 0.308%. This is reasonable since the equations used for both are similar. Because of this, the air content measurements made were air content from super air meter, gravimetric (ASTM C138), and the hardened air-void (ASTM C457). Figures 2.14, 2.15, and 2.16 show the different methods of determining air contents plotted together.

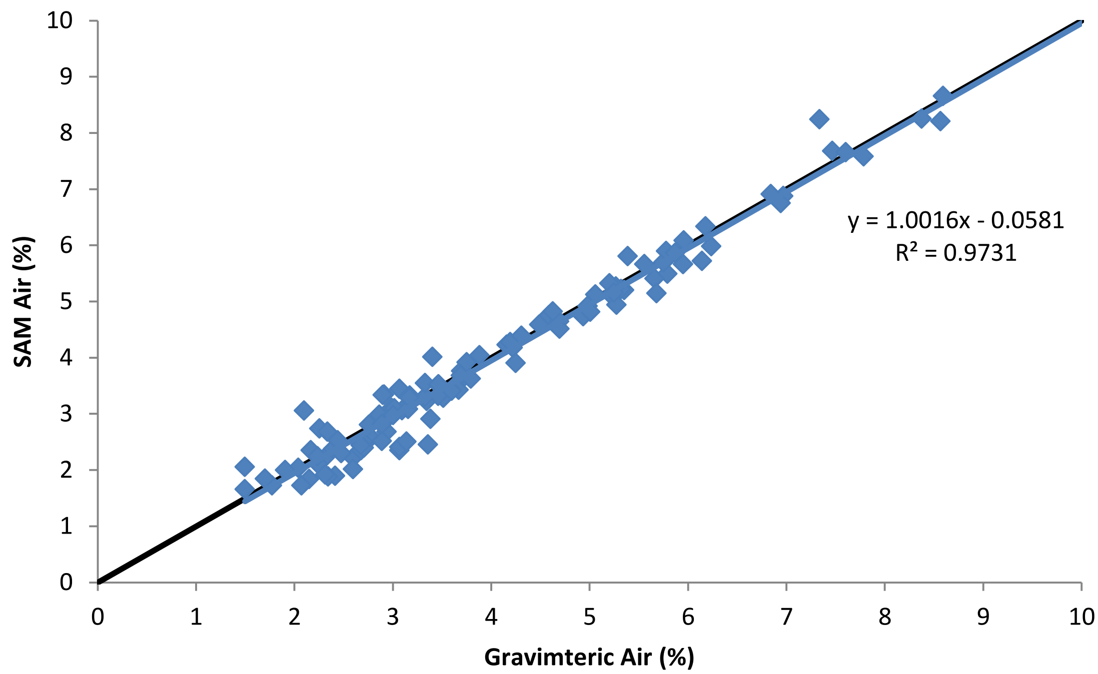


Figure 2.14 Gravimetric and SAM air comparison

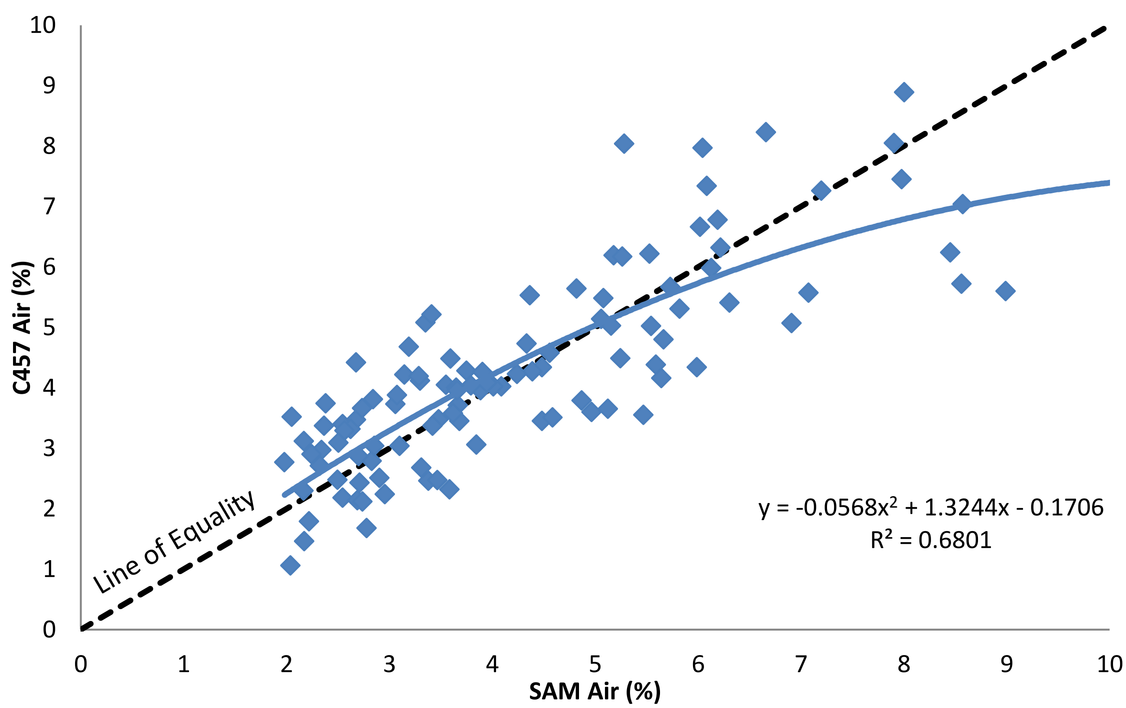


Figure 2.15 Hardened and SAM air comparison

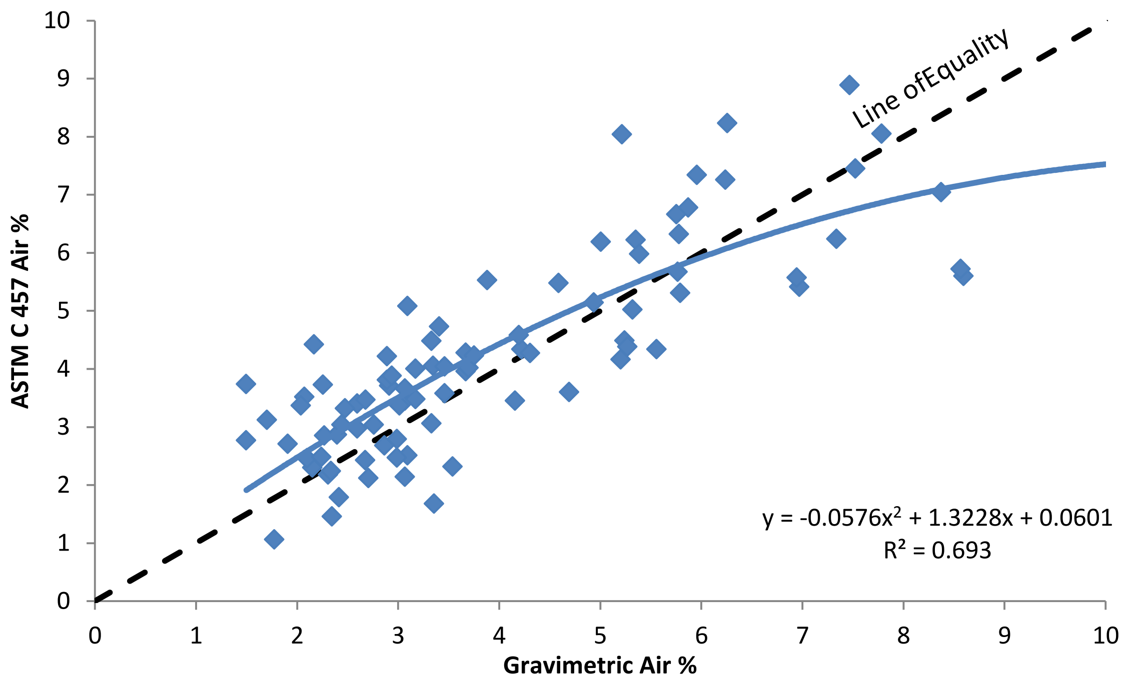


Figure 2.16 Gravimetric and hardened air comparison

The difference in the air contents measured by the SAM is shown graphically in Figure 2.17. Again this suggests a Gaussian distribution with an average difference is -0.0268% and a standard deviation of 0.147%. The difference in the air content measured gravimetrically is shown in Figure 2.18. This data is shown to have an average difference of 0.007% and a standard deviation of 0.37%. When the SAM testing procedure is conducted on only water and a calibration device, the standard deviation becomes 0.104%. Table 2.7 shows the variability of the methods for determining air content used in this research.

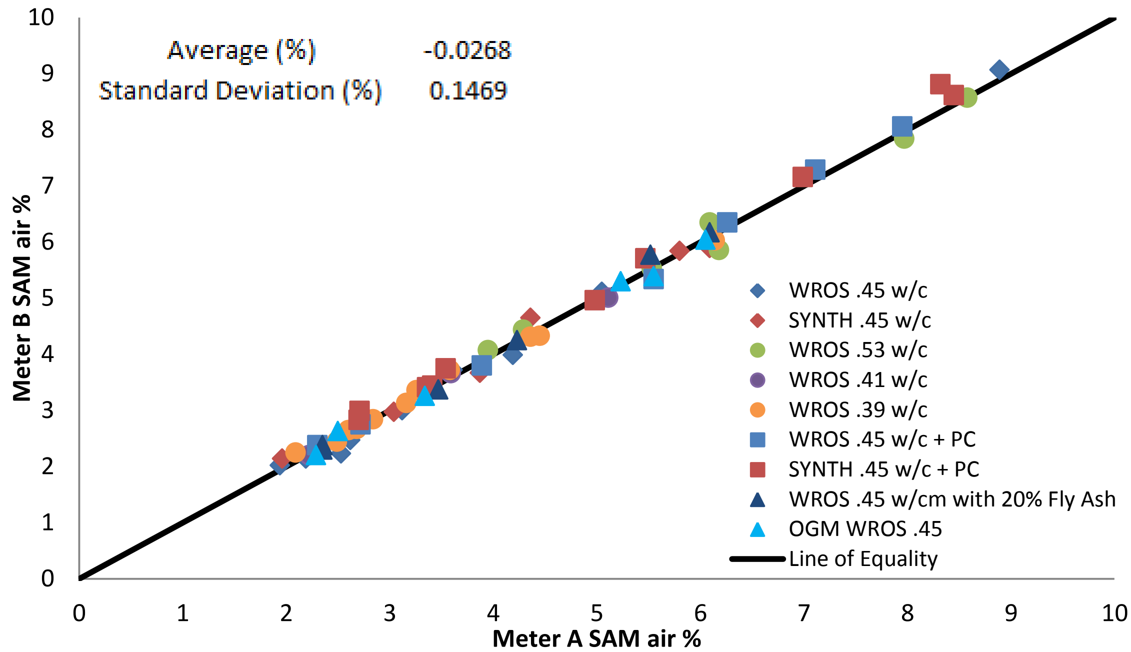


Figure 2.17 SAM air content differences between multiple meters

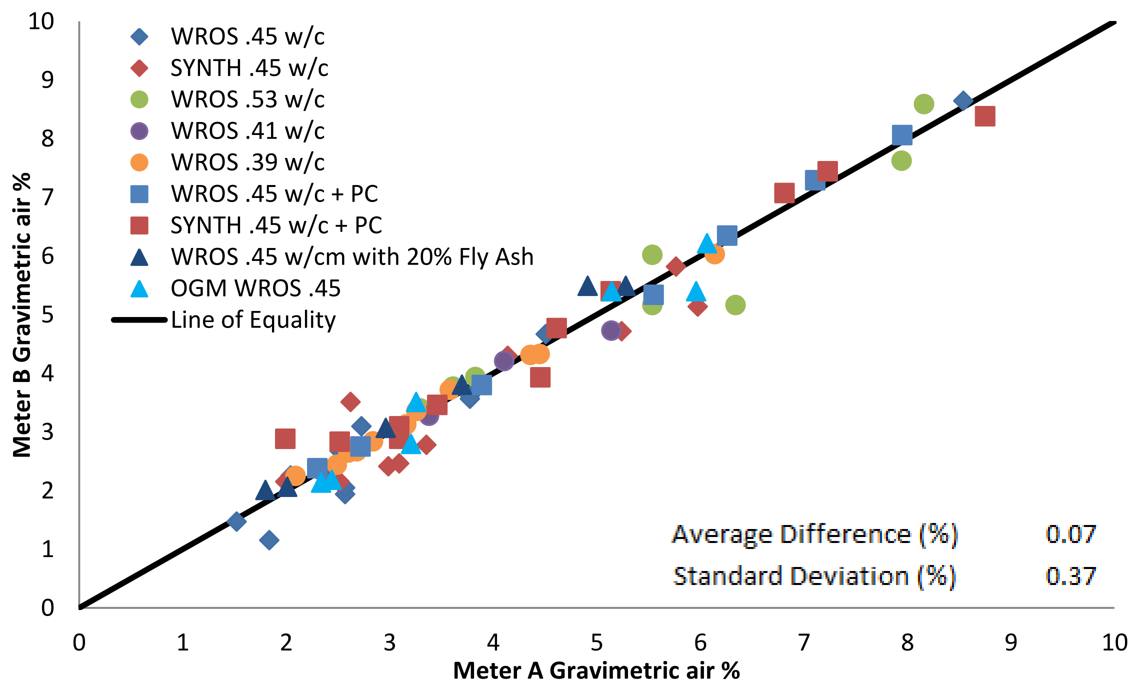


Figure 2.18 Gravimetric air content differences

Table 2.7 Statistical parameters air content measurement methods

	SAM Air%	Gravimetric Air %	Calibration Vessel with water
Standard Deviation	0.147	0.37	0.105
Average Difference	-0.0268	0.07	0.09

Discussion

SAM number and hardened air-void analysis

There was good correlation of the hardened air-void parameters and the SAM number for the mixtures investigated. From the 99 concrete mixtures that were tested, the data suggests that a SAM number of 0.20 psi or lower is needed to achieve the required spacing factor of 0.008 inches suggested by ACI 201. This was chosen by looking at the percent agreement and choosing a conservative value for the SAM number that also showed good agreement between the spacing factor and SAM number. The percent agreement is defined as the percentage of all tests that were in the “passing” region and the “failing” region. The passing region is where the SAM number is 0.20 psi or smaller and the spacing factor is 0.008” or smaller. The failing region is where the SAM number is greater than 0.20 psi and the spacing factor is greater than 0.008”.

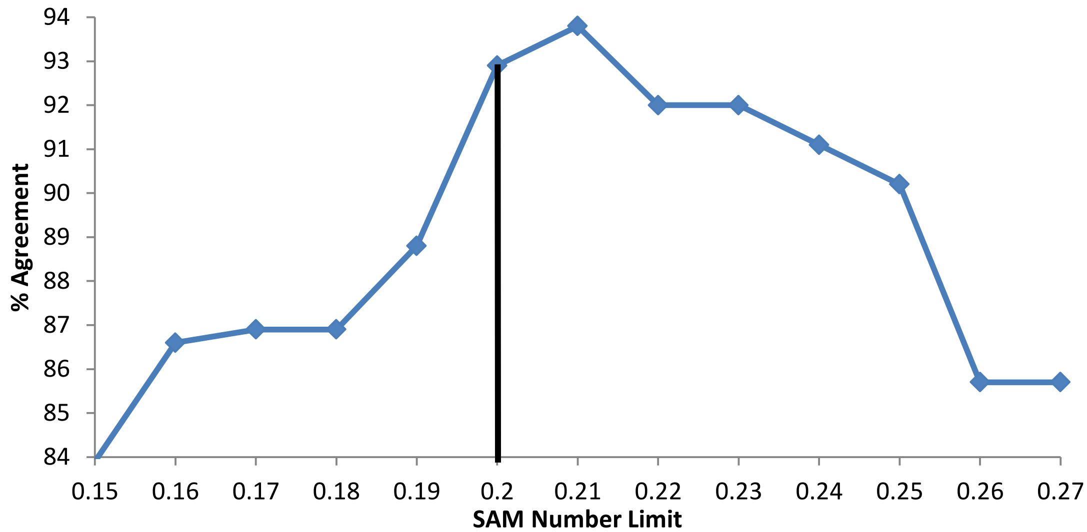


Figure 2.19 SAM number limits

For the 99 concrete mixtures investigated the SAM number of 0.20 psi was shown to correlate with a spacing factor of 0.008 in for 93% of the data investigated. Also, 95% of the data is either correctly predicted to pass/fail the ACI 201 limit or would serve as a conservative estimate of the spacing factor. However, one should note that the percentage of correct estimates will depend on the number of mixtures investigated close to the 0.20 limit. Regardless, for the mixtures investigated the SAM number was shown to be a good estimate of a spacing factor of 0.008 inches in fresh concrete.

The proposed SAM number limit of 0.20 psi also correlates well to the specific surface of the air-void system. ACI 201 requires air-void system in concrete to have a specific surface of 600 in^{-1}. With the SAM limit of 0.20 psi, 82% of the measurements are correctly predicted to pass or fail this limit. However, the SAM testing conservatively predicted that concrete mixtures had an adequate specific surface value, per ACI 201 requirements 93% of the time. This shows that the SAM test method is conservative at times with the specific surface value, but still allows it to accurately measure this parameter.

Freeman (2012) determined that a concrete specimen with a chord frequency (for chords less than 200 microns is size) higher than 6.0 chords/inch, then the concrete is determined to be freeze-thaw durable. For this data and the proposed SAM number limit of 0.20 psi, 77% of the data is correctly predicted to pass or fail this requirement. Also, 99% of the data is either correctly predicted to pass/fail Freeman's limit or would serve as a conservative estimate chord (smaller than 200 microns) frequency. This result also shows that the SAM number closely correlates with the number of voids smaller than 200 microns in the mixture. This is important as the small voids have been shown to be critical for freeze thaw performance.

Test Variability

The SAM number difference distribution is shown in Figure 2.11 suggest that the different meters appear to follow a normal distribution for their difference in SAM number. This data shows the difference between the SAM numbers between the meters is average to be -0.0055 psi with a standard deviation of .069 psi. When the data was investigated with SAM numbers of 0.30 psi and lower than an average difference of 0.0017 psi with a standard deviation of 0.048 psi was found. When the test was performed with water and a calibration device, the standard deviation dropped to.0215 psi. All of these values are shown in Table 2.8. This suggests that about 44% of the variability is from the test method and 56% of the variability is from differences between the concrete. This high variability in the concrete is somewhat surprising as the meters both sampled from the same concrete mixture.

From the evaluations done with two meters only 4.3% of the measurements suggest that one mixture had a passing value and another failing. This further shows the reliability of the prediction by the meters. This suggests that the variability of the SAM test is low enough to be a useful test and not operator dependent with these materials for laboratory mixtures.

Table 2.8 SAM statistical overview

	All Test	SAM Numbers <.30	Calibration Vessel with water Test
Average Difference	-0.0055	0.0017	0.005
Maximum Difference	0.195	0.09	0.06
Standard Deviation	0.0694	0.0483	0.021

The air content difference measured by both meters has a very small variation. Figures 2.17 show the variance of the Super Air contents measured by the SAM. This shows an average difference of 0.0268% with a standard deviation of 0.147%. This suggests an extremely low variability for the air contents for multiple meters. When the SAM test is conducted with only water and a calibration device (no concrete), the variability of the air volume drops even more, with a standard deviation of .104% and an average difference of -0.0268%. This is shown in detail in Table 2.7. This once again suggests that the method has a small variability, with most of the variability of the measured coming from the concrete rather than the method itself.

The gravimetric air contents were also shown to be extremely similar to the measured super air contents, with an average difference between these two methods of -.05% and a standard deviation of .30%. This is also shown in Figure 2.14. This shows that the air contents measured were accurate and repeatable. Table 2.9 shows how the three types of air measurement compare to each other.

Table 2.9 Air content calculation methods differences

Average Difference			
	SAM Air	C 138 Air	C 457 Air
SAM Air	0.0268	0.05	0.32
C 138	0.05	0.07	0.28
C 457	0.32	0.28	X
Standard Deviation			
	Super Air	C 138 Air	C 457 Air
Super Air	0.147	0.30	1.07
C 138	0.30	0.37	1.10
C 457	1.07	1.10	X

Conclusion

This work has outlined an expedited test method that uses a modified version of an ASTM C 231 pressure meter that greatly extends the capabilities of the test method to be able to measure the quality of the air-void system in fresh concrete. The following findings have been made:

- A rapid field test has been shown to accurately predict the air-void distribution of fresh concrete in about eight minutes.
- A SAM number of 0.20 psi correlates well to the ACI 201 suggested limit for the spacing factor and specific surface.
    - 93% of tests were correctly predicted by the SAM for the spacing factor
    - 82% of tests were correctly predicted by the SAM for the specific surface
    - 77% of tests were correctly predicted by the SAM for the chord frequency smaller than 200 microns as suggested by Freeman (2012).

The variability of the test method was also investigated and the following was found:

- The standard deviation between SAM numbers found by two different meters and operators on the same concrete was found to be 0.0694 psi over all tests and 0.483 psi over tests with SAM numbers lower than 0.30 psi. When the same testing was completed with just a calibration vessel and water a much lower standard deviation of 0.0215psi was found.
- This suggests that around 50% of the variability in determining the SAM number comes from the variability of the concrete.
- The standard deviation in the air content measured by two different SAMs was found to be 0.104%. This means it is a very precise test.
- The standard deviation in the gravimetric air content and the fresh air content measured by the SAM was found to be 0.30%. This variability is quite low.

The measurement of the SAM number for these mixtures and with the presented procedures accurately determined the hardened air-void parameters. When the results from two different meters and operators are compared they seem repeatable and independent of the user.

This testing method seems to allow a better determination of the air-void system than the traditional air volume methods used previously. Since this test method can be completed rapidly in the field then it shows promise as a standard testing procedure.

CHAPTER III

MECHANISMS OF THE SEQUENTIAL AIR METER

The Sequential Air Meter (SAM) has been shown to produce a new measurement value, the SAM number, which shows good correlation with the spacing factor as determined by the ASTM C457 hardened air-void parameters. This rapid field testing procedure allows one to determine the quality of the air-void distribution before the concrete is placed. The SAM testing procedure is a sequential pressure testing method that measures the response of a concrete sample to an applied pressure over multiple pressure steps. In the SAM testing method, as the SAM number decreases, the spacing factor of that concrete mixture should also decrease.

The object of this work is to determine the mechanisms behind the SAM. This was done by creating air-entrained cement paste mixtures that are subjected to similar pressures that are seen in the SAM test. The air bubbles in this research were all observed to have a hydration shell around them. Work by Ley, Folliard, and Hover (2009) showed that this shell helped preventing the bubbles from coalescing when they touched and played an important role in resisting air interchange between the bubbles.

The air bubbles in this research were also examined to determine how they were affected by Henry's Law. Henry's Law states that the amount of a gas that dissolves into a solution is directly proportional to the partial pressure of that gas (Benjamin 2002). Henry's law suggests that a saturation of the solution could occur if enough gas dissolves into the solution. A development from Henry's Law, Laplace's Equation, states that the change in pressure from the inside and outside of a curved surface (in this case, an air bubble) is inversely proportional to the radius of the curved surface (Goldman 2009). This suggests that air bubbles would ideally dissolve starting with the smallest if the external pressure is increased. The goal of this work is to determine how air bubbles respond to the applied pressure.

Materials

The cement used in this research satisfied the requirements ASTM C150 type I. The oxide analysis for the cement is shown in Table 3.1. The air entraining admixture (AEA) used in this research was a commercially available Wood Rosin (WROS) that complies with ASTM C260. The mixture proportion used for this mixture type is outlined in Table 3.2.

Table 3.1 ASTM C150 Type I cement oxide analysis

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	Na_2O eq (%)	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	Fe_2O_3 (%)
21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	0.4	56.7	17.8	8.2	7.8	2.6

Table 3.2 Cement paste mixture proportions

w/c ratio	Cement (grams)	Water (grams)
.42	1373.2	576.8

Experimental Methods

Mixing Procedure

All mixtures for this research were prepared according to ASTM C305. The AEA was added before the last mixing step.

Figure 3.1 Elliptical mixer used in this research

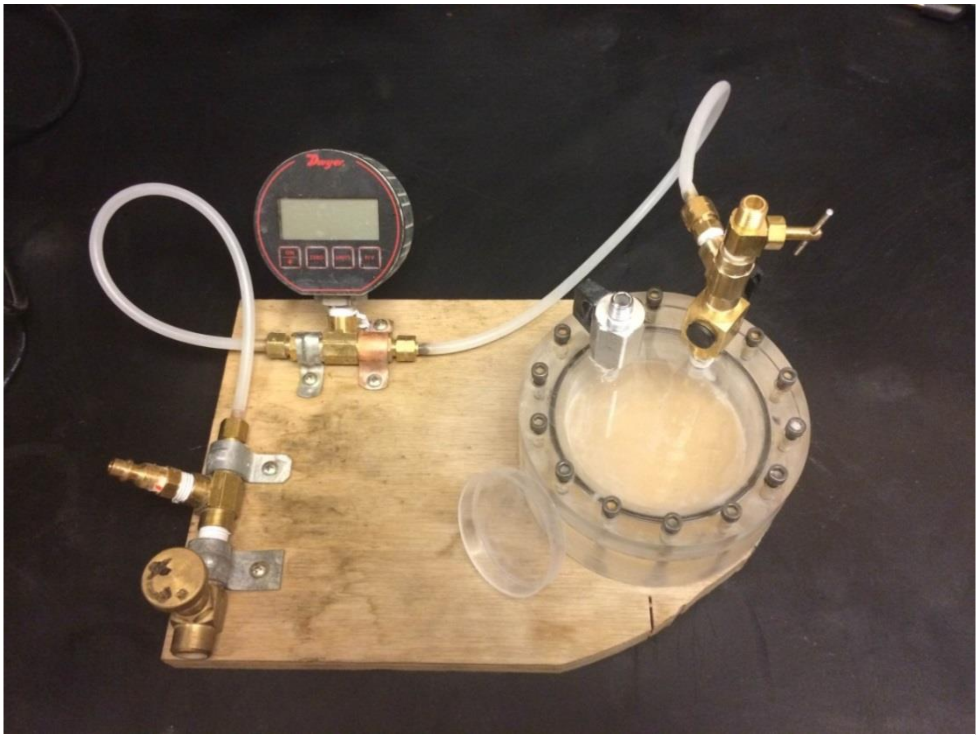
Test Completed

Each cement mixture had a unit weight test performed upon completion of the mixing. This was done in accordance to ASTM C138. The gravimetric air content was determined for every mixture.

Pressure Chamber and Sample Preparation

The pressure chamber used in this research allows the user to microscopically inspect the entrained air bubbles in a cement paste mixture. A picture of the pressure meter is shown in

Figure 3.2. The pressure chamber is made of acrylic glass to allow the user to see through the glass and at the air bubbles.



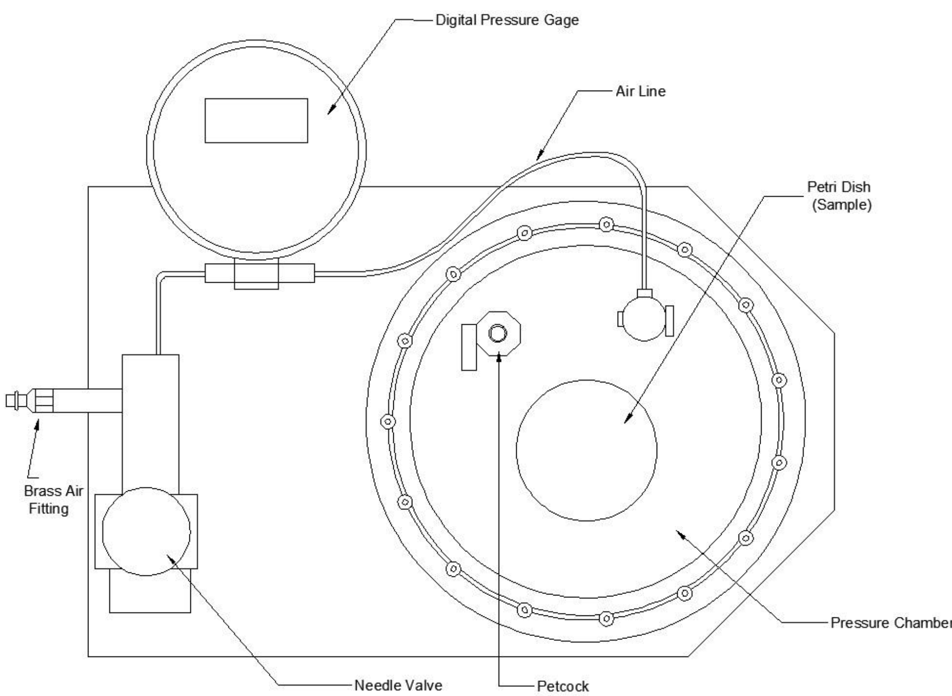


Figure 3.2 Pressure Chamber with petri dish

A cement paste sample is first prepared for the pressure chamber by placing the paste into a small petri dish. The sample is then consolidated by lightly tapping the bottom of the sample on a flat surface. The sample is then placed into the pressure chamber and the chamber was then filled with water and the lid is then securely attached to the chamber. Now the chamber is filled the rest of the way with water through the top valve. The top valve is then closed.

Air is used to pressurize the fluid in the system via the brass fitting, with the amount of air entering the system being controlled with the use of a needle valve. The closing of the needle valve causes the pressure in the chamber to increase, while opening the valve causes a decrease in the chamber pressure. The pressure is measured with a digital pressure gage that has a 0.01 psi accuracy.

Testing Procedure

After completing the unit weight test for the cement paste, a sample was placed into a small petri dish. The cement paste in the petri dish was then consolidated by lightly tapping the bottom of the petri dish against a flat surface. The dish is then placed into the chamber and water is added, eliminating all trapped air, and then sealed. The sample is then placed under a microscope and allowed to rest for approximately 15 minutes. Over time the bubbles in the air entrained cement paste escaped and floated to the surface of the pressure chamber where they were observed with an imaging system.

The imaging system used was a high resolution digital camera connected to AxioVision AC from Carl Zeiss that was attached to a stereo microscope. The stereo microscope allowed an image magnification of up to 500X. This software allows the user to count the number of pixels between two designated locations on the image. The software then converts the number of pixels to units of length via a magnification specific calibration. Accuracy of the measuring system had been checked and calibrated with glass slide standards. This imaging system allowed the researcher to accurately determine the diameter of the air bubbles.

After the rest period, a collection of bubbles was investigated. A picture was taken of the bubbles at atmospheric pressure. The pressure was then increased gradually in increments of 5 psi and a picture was taken at each increment until 35 psi. Now the air pressure was released from the chamber and then another picture was taken at atmospheric pressure. A pressure of 35 psi was chosen because it is a maximum pressure typically observed when a passing SAM number is measured. A summary of the test procedure is shown in Table 3.3.

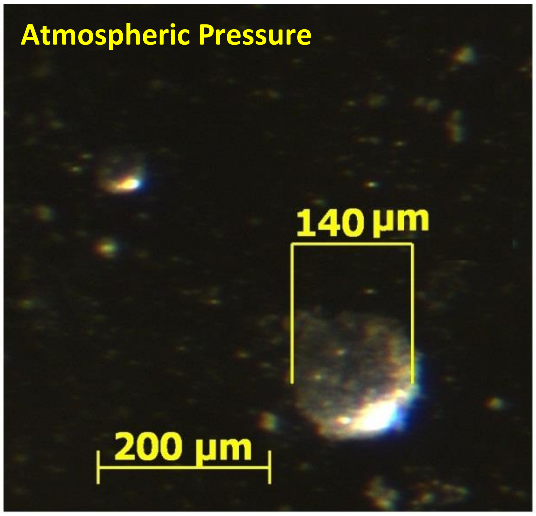
Table 3.3 Pressure Chamber testing procedure

Step	Action
1	Place petri dish with cement paste into pressure chamber and secure the lid of the chamber
2	Fill chamber with water, removing all large air
3	Seal the chamber, and allow 15 minutes for the sample to rest
4	Select location to observe
5	Take a picture of the selected location at atmospheric pressure
6	Pressurize the chamber to 5 psi, then take a picture
7	Repeat step 5 with 10, 15, 20, 25, 30, and 35 psi
8	Release the pressure in the chamber to atmospheric, then take a picture
9	Repeat steps 5 through 8.

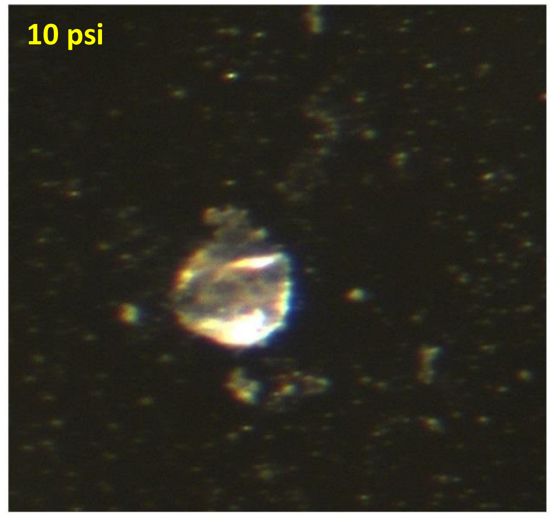
Results and Discussion

Bubble Dissolution

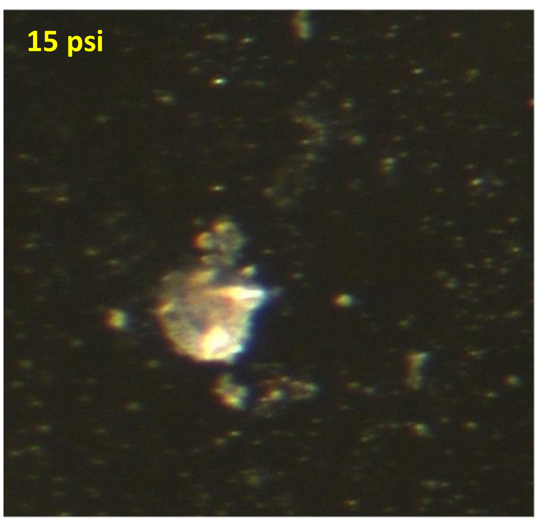
Upon completion of each test, the captured images were analyzed to determine how the air bubbles changed. It was determined that if there was not any change in the air bubble while the pressure kept increasing, the air bubble was determined to have dissolved into the solution. An example of this is shown in Figure 3.3. This was a useful method for determining if the air bubble had dissolved due to the bubble shell sometimes obscuring the view of the air bubble.



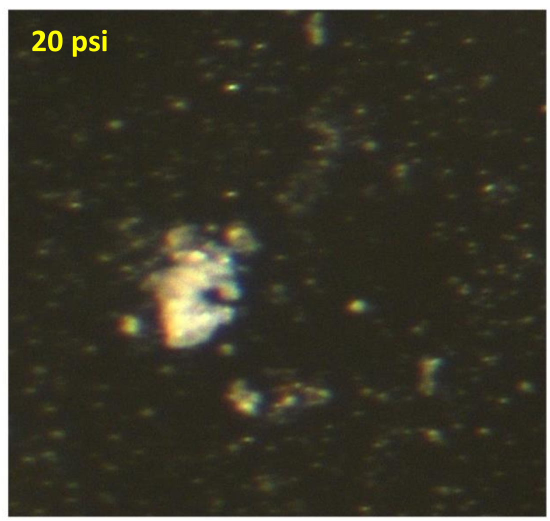
(A)



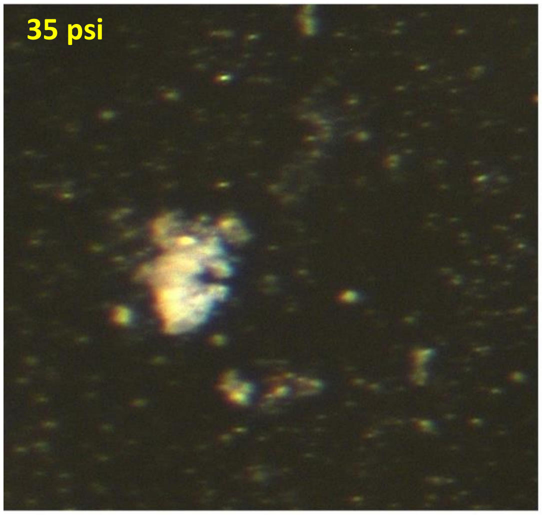
(B)



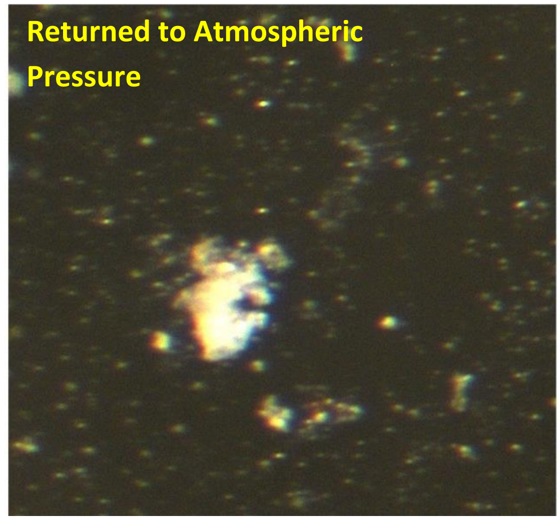
(C)



(D)



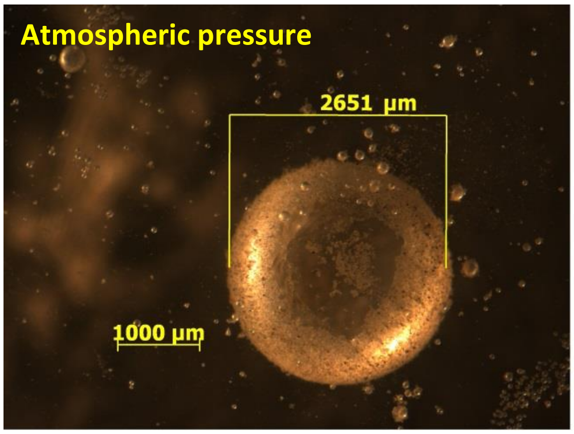
(E)

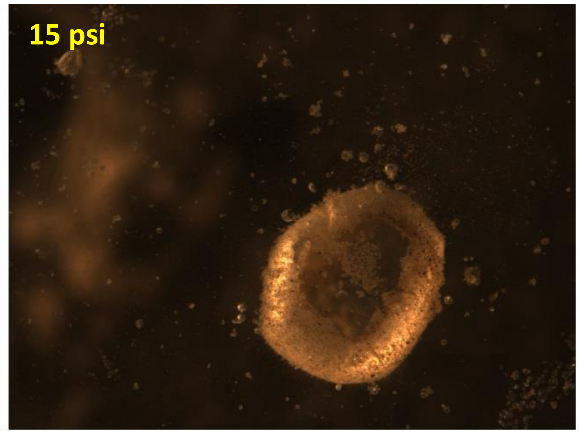


(F)

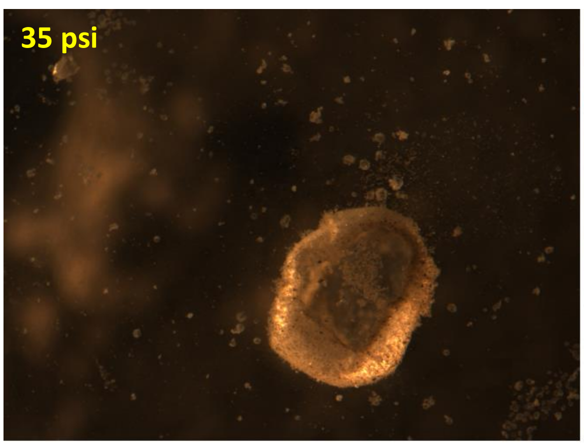
Figure 3.3 Air bubble that is shown to dissolve in D. Notice the air bubble not changing from images C to E.

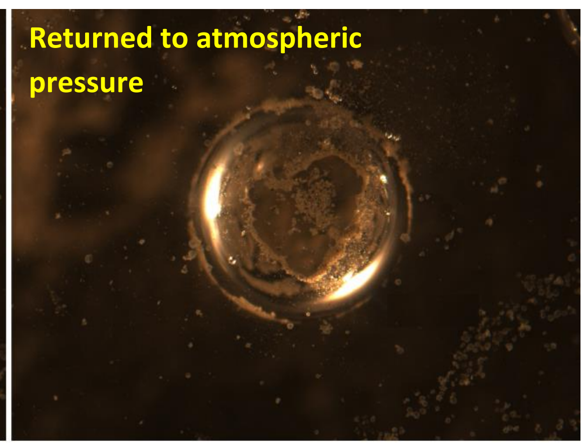
Figure 3.3 shows a typical set of data at (A) atmospheric pressure, (B) an applied pressure of 10 psi, (C) an applied pressure of 15 psi, (D) an applied pressure of 20 psi, and (E) an applied pressure of 35 psi, (F) and then when the sample has been returned to atmospheric pressure. This air bubble is shown to dissolve into the solution before the maximum pressure is reached. This can be determined by examining Figure 3.3 (D) and (E), as there is not any difference from the images and only the bubble shell remains. Therefore, this 140 µm diameter air bubble is shown to have dissolved at the 20 psi pressure increment. Also in Figure 3.3 (F), when the air bubble dissolved, it did not come out of solution when the pressure was release back to atmospheric pressure. Figure 3.4 shows a larger air bubble at (A) atmospheric pressure, (B) an applied pressure of 15 psi, (C) an applied pressure of 35 psi, and (D) then when the sample has been returned to atmospheric pressure. This figure illustrates how an air bubble appears when it does not go into solution under the maximum applied pressure of 35 psi. After inspections the image, one can determine that the air bubble did not go into solution because there is a noticeable increase in bubble size as the bubble is returned to atmospheric pressure as shown in images (C) and (D) in Figure 3.4.





(A) (B)





(C) (D)

Figure 3.4 A large entrained Air bubble that doesn't dissolve in the solution and its opaque hydration shells at (A) atmospheric pressure, (B) 15 psi, (C) 35 psi, and (D) at atmospheric pressure after full pressurization

This research analyzed 115 air bubbles from mixtures with an average air content of 3.15% and 127 air bubbles from mixtures with an average air content of 10.4%. At each pressure step the bubbles were investigated on a dissolved/did not dissolve basis. The results for the dissolution pressure of the air bubbles are shown in Figure 3.5. This shows results for the low air mixtures and the high air mixtures, with the dissolution pressure being measured every 5 psi.

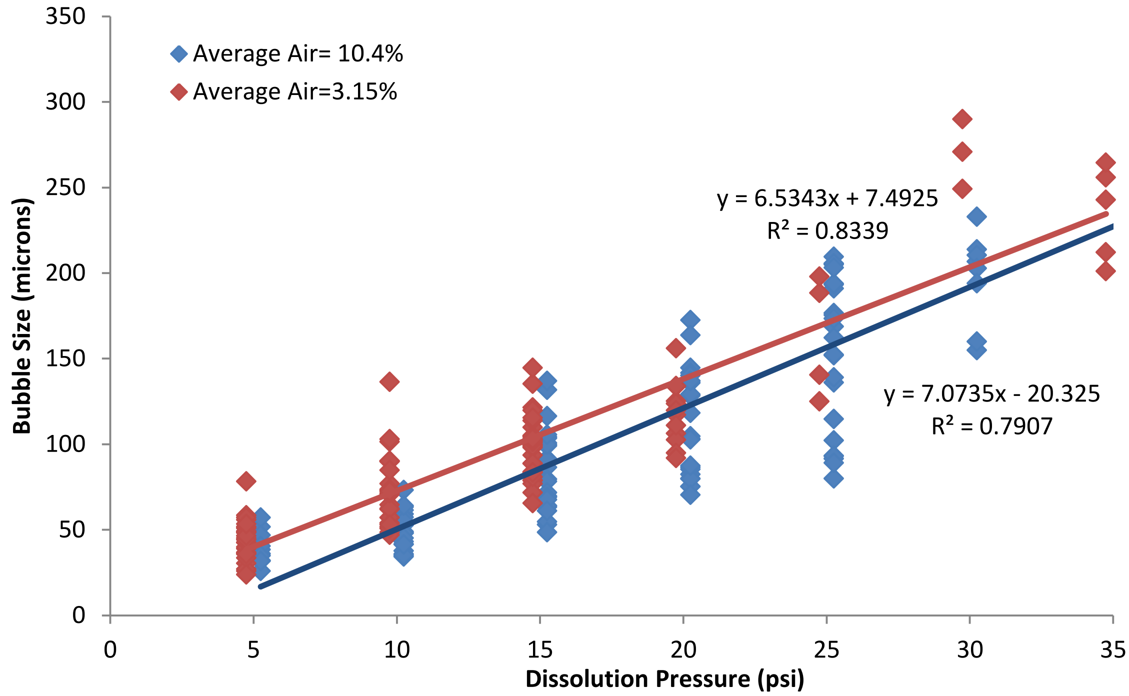


Figure 3.5 – Bubble dissolution data

The way that air bubbles dissolve in water with an applied pressure is shown to approximately follow a linear line. This is shown in Figure 3.5. Also, once the air bubbles are driven into the solution, they do not come out of the solution quickly once the pressure had been released. Laplace-Young Equation states that smaller air bubbles have a higher internal pressure, making them easier to dissolve into the solution. This would mean that smaller air bubbles should dissolved into solution at a lower pressure than a larger air bubble. Therefore, Figure 3.5 would suggest that when the air bubbles are subjected to an applied pressure, the air bubbles follow Henry's Law and dissolve into the solution. This is shown to be true regardless of the air content of the sample, as the low air samples and the high air samples follow a similar linear response.

This would suggest that the process of air bubbles being driven into the solution by an applied pressure does not depend on the volume of air in the paste mixture.

Clustered Air Bubbles

The expected response of air bubbles changed when the air bubbles were clustered together. Clustered air bubbles that were of a similar size to dispersed bubbles did not follow the same dissolution pressures as shown in Figure 3.5. To show this phenomenon, entrained air bubbles that were clustered together (average spacing less than 30 microns) were measured to show how the bubbles changed with an increase in applied pressure. This average spacing was developed by measuring the distance between each bubble. This distance was measured from the outer diameter of each bubble. Figure 3.6 shows clustered and non-clustered air bubbles react under pressure. Notice how the non-clustered air bubbles (shown in the left column) dissolve into solution by 35 psi of applied pressure, and they do not come out of the solution once the pressure had been released. While the clustered air bubbles (right column) do not dissolve, despite the size range of the bubbles being similar. This phenomenon is further shown in Figure 3.7 as the diameter versus pressure for several bubbles are shown. Notice in this figure that the air bubbles do not dissolve into solution when they are predicted to by Figure 3.5, as shown by the black line. These figures show how clustered air bubbles, with the vast majority of them having a diameter less than 250 microns, react to an applied pressure. This shows that the reaction of air bubbles to an applied pressure changes when air bubbles become closer together.

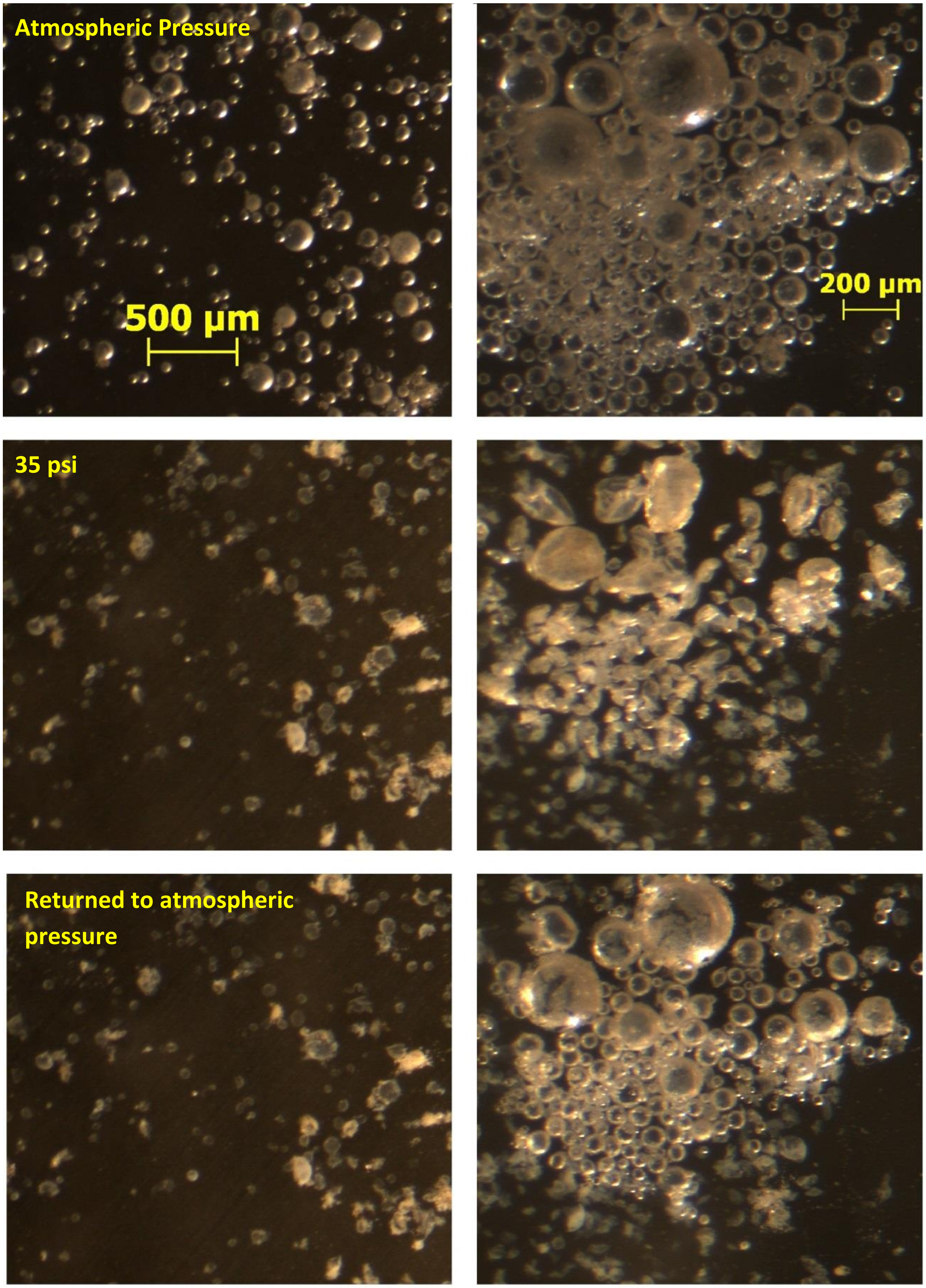


Figure 3.6 Clustered Air Bubbles (right column) shown to be reacting differently under pressure than non-clustered bubbles (left column). The pressures shown are: atmospheric (top), 35 psi (middle), and returned to atmospheric (bottom).

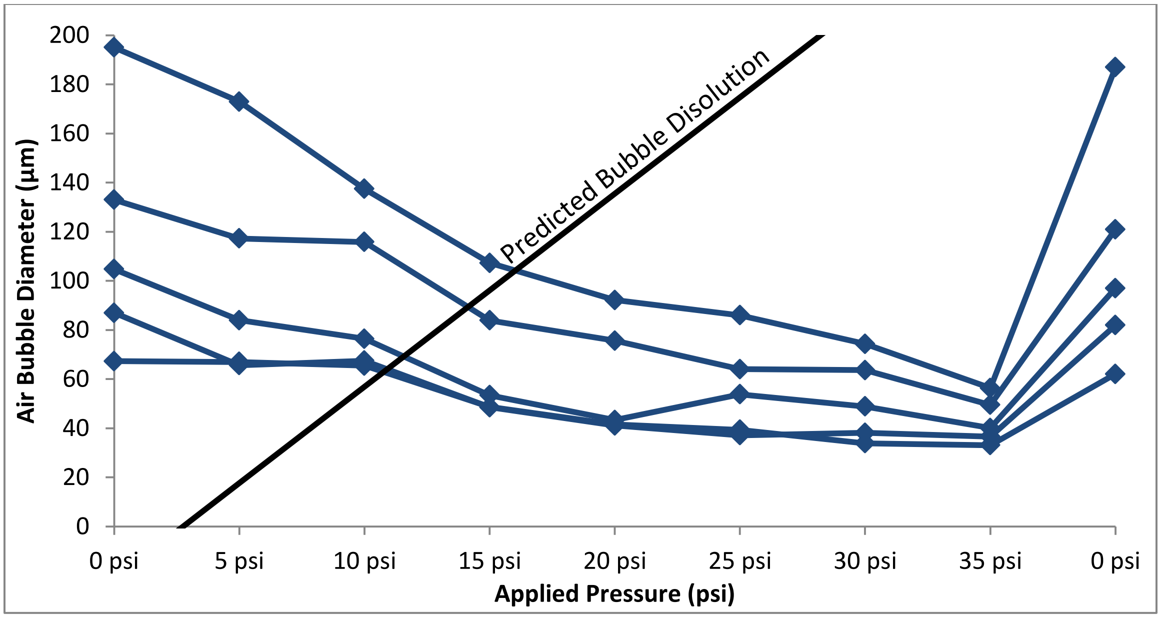


Figure 3.7 Bubble diameters changing with the applied pressure for clustered air bubbles

This phenomenon is illustrated again in Figure 3.8. These figures show how the behavior of air bubbles changed when the air bubbles were far apart (left column) and when they were clustered together (right column). Air bubbles in this figure are of a similar size, with the only difference being the spacing between the air bubbles. Notice how the air bubbles in the right column are not driven into the solution, while they do dissolve under pressure in the left column. These two figures show how the reaction of air bubbles change when they are clustered together. When an air bubble dissolves then it is replaced by an “X”. However, in the right column the “air bubbles” do not dissolve. Instead, most of the air bubbles approximately return to their original size after releasing the pressure.

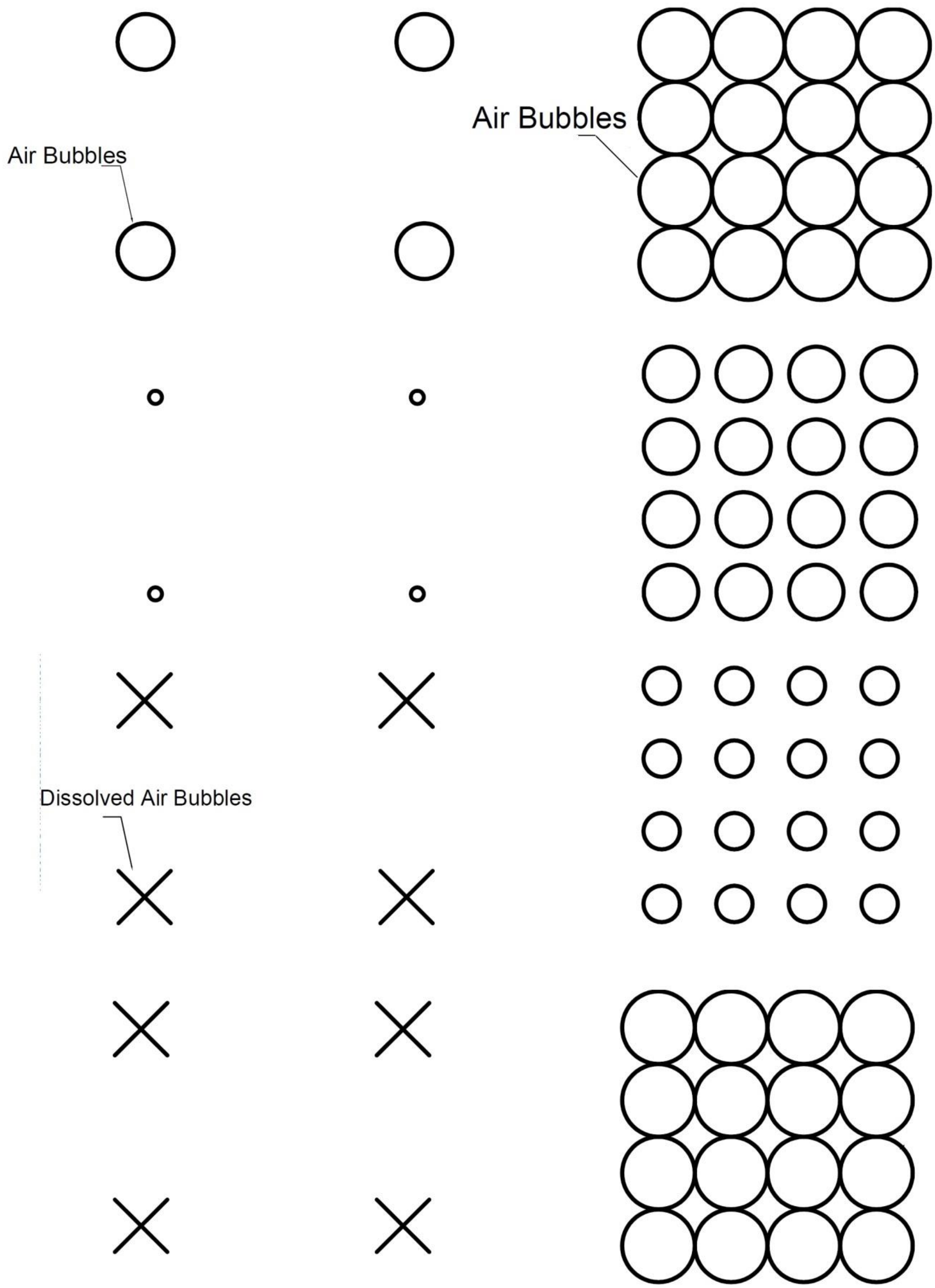


Figure 3.8 Illustrated non-clustered air bubbles (left column) and clustered air bubbles (right column) at various pressures.

When air bubbles were close together, the behavior of the bubbles under pressure changed dramatically. This is shown in Figures 3.6, 3.7, and 3.8. Figure 3.7 shows that when air bubbles have a similar size, but have different spacing between the bubbles, the bubbles do not dissolve at similar pressures. This suggests that when air bubbles become more clustered together, the solution around the air bubbles could create areas of localized super saturation of air. This super saturation is created by amounts of air being driven into the solution locally. This phenomenon could cause air bubbles to not dissolve into the solution at the expected pressures predicted in Figure 3.5. With the "sphere of influence" being smaller (or overlapping) for air bubbles that are close together, this leads to less solution locally, causing this solution to become super saturated upon sufficient pressurization. This type of behavior would follow Henry's Law for a super saturated solution for the clustered air bubbles, and a under saturated solution for non-clustered air bubbles.

Sphere of Influence

T.C Powers used the term "sphere of influence" in 1949 to describe the volume around an air bubble in hardened paste to investigate the ability of the bubble to protect the paste from freezing damage (1949). Powers used this theoretical value to help determine the spacing factor, which is defined as half of the average distance between the average sized air-void. This research used the same term to describe the region around air bubbles as well in the water and fresh cement paste. This research used the average size and spacing of the air bubbles to create a similar "spacing factor" for the bubbles in water, cement paste, or concrete. The volume of water inside the sphere of influence will change dramatically when one compares similar the sphere in paste and concrete when compared to water. Because you are adding particles within the water then this will cause the sphere of influence to "grow" in size. This is shown in Figure

3.9. This change in volume is caused by the lack of solids inside this sphere of influence for the cement paste test (as there was only water surrounding the air bubbles).

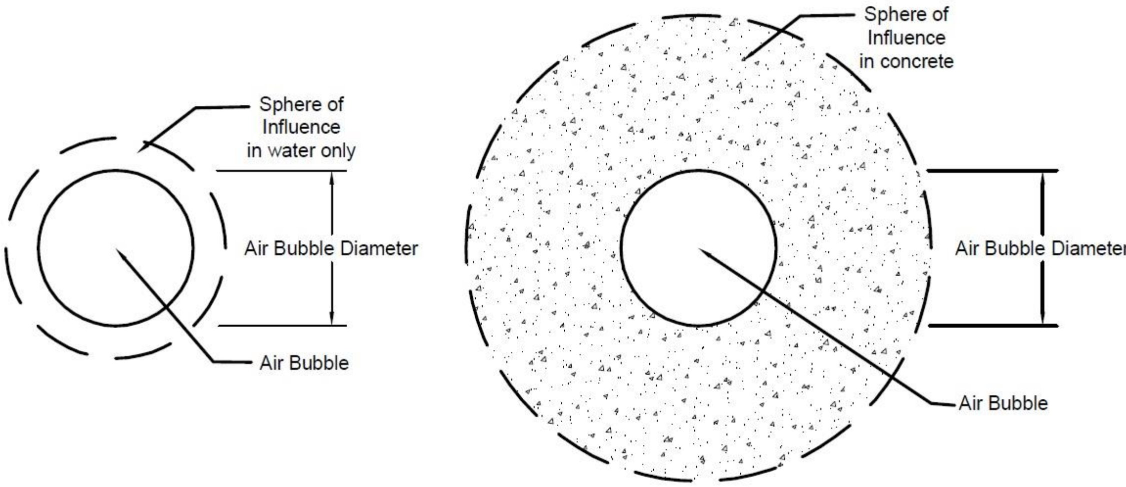


Figure 3.9 (A) the sphere of influence around an air bubble surrounded by only water and (B) Sphere of influence around an air bubble in concrete

The results from the bubbles in water can now be compared to actual SAM test (with concrete) by compare their sphere of influence. This sphere of influence is calculated using the average bubble diameter and the spacing factor obtained through ASTM C457 testing.

Calculations of the Sphere of Influence

This size of the sphere of influence can be calculated using the air bubble diameter and the bubbles spacing. This type of calculation is shown in Equation 3.1. For this calculated volume, one can determine the amount of solution surrounding an air bubble. This is possible by multiplying the sphere of influence volume by the volume percentage of water in a particular concrete mixture. This calculation is shown in Equation 3.2.

$$Volume = Volume_{air\ bubble\ diameter\ plus\ the\ spacing\ factor} - Volume_{air\ bubble}$$

Equation 3.1 Volume of the sphere of influence

$$Volume_{\ water} = (Volume_{sphere\ of\ influence}) \times \%Water\ volume\ in\ mixture$$

Equation 3.2 Volume of water in the sphere of influence

Table 3.4 shows the application of Equations 3.1 and 3.2. This table shows all of the SAM test values and their corresponding ASTM C 457 results. All of the test data is separated by the mixture type, and then sorted by the SAM number. The SAM number and the fresh air content were determined using the SAM testing procedure. The average bubble size and the spacing factor were determined from ASTM C 457 analysis.

Table 3.4 Water Volume in the sphere of influence

Mix ID	SAM Number	Fresh Air %	Average Chord Length (µm)	Average Bubble Size (µm)	Spacing Factor (µm)	Water Volume in Sphere of Influence (μm^3)
.45 WROS	0.15	5.1	150	225	178	4.82
	0.16	9.0	124	187	147	2.75
	0.24	3.7	224	335	211	11.20
	0.29	3.1	175	263	246	10.19
	0.58	2.2	208	312	368	25.49
	0.62	2.5	224	335	333	23.30
.45 SYNTH	0.47	2.2	239	358	467	46.22
	0.31	2.8	152	229	307	12.70
	0.26	3.0	165	248	249	9.60
	0.19	5.8	160	240	193	6.03
	0.17	5.3	114	171	150	2.52
.53 WROS	0.12	7.9	142	213	142	3.71
	0.19	6.0	165	248	185	6.95
	0.39	4.0	191	286	272	15.79
	0.80	2.7	208	312	320	23.42
.41 WROS	0.19	4.5	132	198	188	4.05
	0.19	5.1	142	213	170	3.80
	0.22	3.6	178	267	229	8.35
	0.32	3.1	191	286	292	13.82
	0.55	2.0	173	259	417	23.70
	0.55	2.2	173	259	361	17.97

.39 WROS	0.16	6.1	140	210	127	2.24
	0.19	4.4	145	217	185	4.26
	0.25	3.2	175	263	226	7.65
	0.27	4.9	157	236	213	6.02
	0.48	2.8	216	324	292	15.48
	0.57	2.5	302	453	483	56.34
.45 WROS + PC	0.07	8.0	198	297	163	6.35
	0.14	7.2	180	271	180	6.43
	0.20	6.3	231	347	277	17.96
	0.38	5.3	284	427	257	21.59
	0.43	2.3	262	392	409	40.64
	0.44	3.8	264	396	361	33.23
.45 SYNTH + PC	0.10	8.5	132	198	147	2.99
	0.11	7.1	135	202	157	3.42
	0.26	5.0	203	305	292	16.49
	0.30	4.6	213	320	277	16.09
	0.50	2.9	226	339	353	26.18

Table 3.5 shows similar calculations done with data from the air entrained cement paste air bubbles. This table uses Equation 3.1. These calculated values used the values that were calculated from the clustered and non-clustered air bubbles. The average spacing and the average bubble size were the taken from largest valuesfrom the clustered air bubbles, and the smallest values from the non-clustered air bubbles. With this, a max and minimum was determined. With these types of tests, the complete volume inside the sphere of influence is water.

Table 3.5 Water volume in the sphere of Influence for cement paste mixtures

	Maximum for the Clustered air bubbles	Minimum for the Non-clustered bubbles
Bubble Size (microns)	166.5	177.4
Bubble Spacing (microns)	29.8	158.3
Water volume in “sphere of influence” ($x10^{-6}um^3$)	5.47	14.0

The values for the water volume in the sphere of influence were then compared to the SAM number for each concrete mixture. Figure 3.10 shows the SAM number compared to the water volume in the sphere of influence. This figure shows the average volumes of water in the sphere of influence for the clustered air bubbles and the non-clustered air bubbles contained in Table 3.5 as dashed marks.

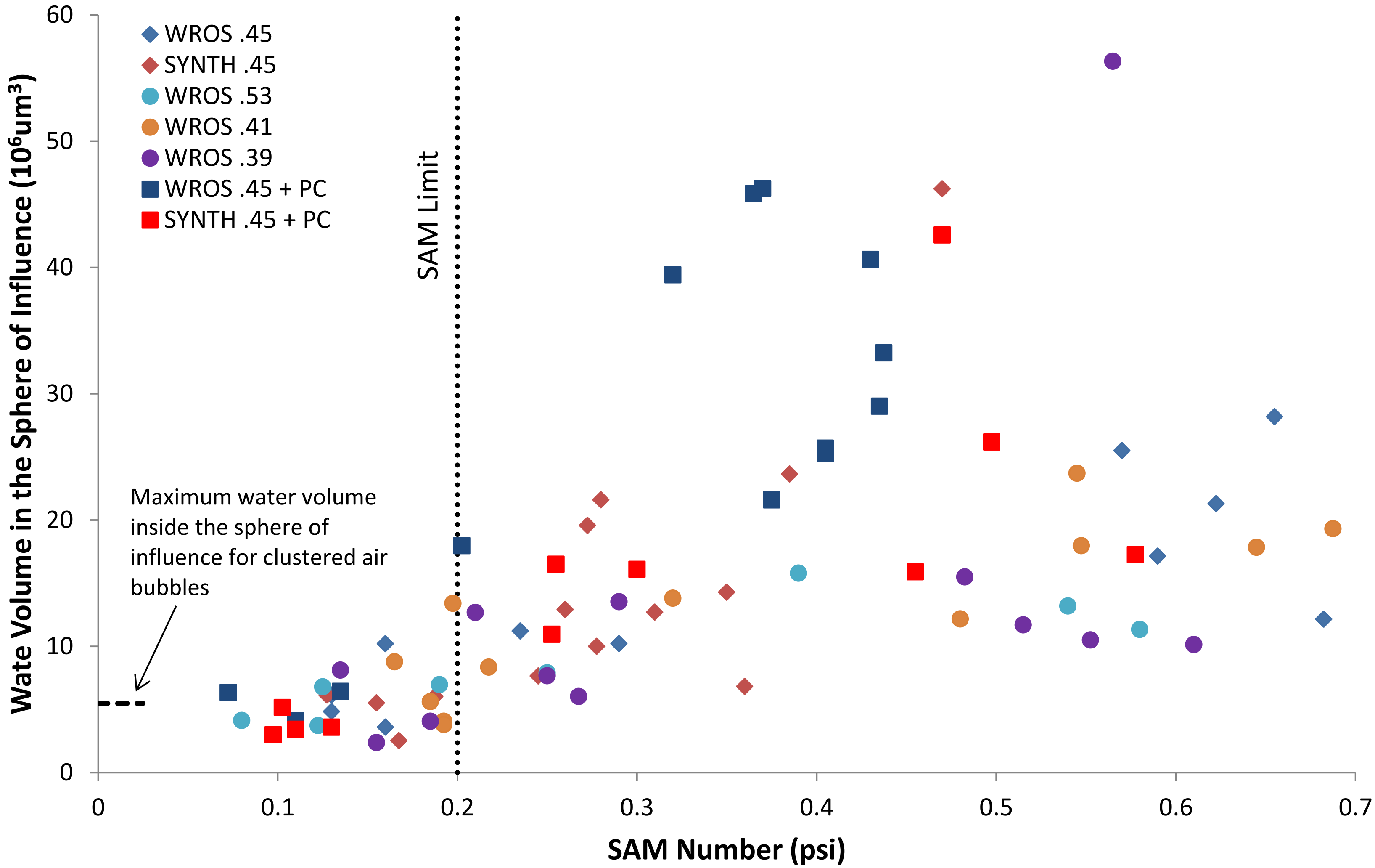


Figure 3.10 SAM number compared to water volume inside an air bubble's sphere of influence

In concrete, the spacing required to reach localized super saturation would be considerably larger than that of the water test. This is due to a significantly larger amount of water in these tests. However, if the volume of solution (water) in an air bubble's sphere of influence is similar to that of concrete, a similar reaction could occur. This would mean that the water volume contain inside the sphere of influence, for the escaped air bubbles and for the actual concrete tests, could be the same, but their total volumes can be different. This would cause the concrete tests to have a much larger total volume inside the sphere of influence due to the concrete having non-solution particles in it. This type of suggestion is supported by Figure 3.10. In the Super Air Meter (SAM) test, concrete mixtures that have a passing SAM number (lower than 0.20 psi) tend to have a spacing factor at or below 0.008 inches. Data from tests conducted with the SAM are shown in Table 3.4. This table shows that as the spacing factor of the air bubbles decreases, the volume of water inside an air bubbles sphere of influence also decreases. When the average spacing from the clustered bubble test results and the amount of water inside the sphere of influence are considered, one can then relate concrete test data to this air entrained cement bubble data by the volume of water contained in an air bubble's sphere of influence. The calculated values from Table 3.5 are values for the volume of water that can be contained within the sphere of influence of an air bubble. These values show different water volumes where air bubbles do and do not dissolve into a solution. This is shown as a dashed line in Figure 3.10.

All of this data suggests that having air bubbles close together changes the reaction of an air bubble system to an applied pressure. This data suggests that these changes occur due to changes in the water volume contained inside the sphere of influence of the air bubbles. Therefore, this process could be a mechanism of the SAM.

Conclusion

This work outlined a possible mechanism for the Super Air Meter (SAM). The following conclusions can be made:

- This research has shown that when air bubbles that escaped from cement paste are subjected to an applied pressure, they follow Henry's Law and Boyle's Law. That is to say that the air bubbles decrease in size as the pressure increases (Boyle's Law). And at a critical pressure, the air bubble would then dissolve into the solution (Henry's Law).
- However, once the air bubbles become clustered together, the reaction of the bubbles to the applied pressure changes.
    - The air bubbles then tend to not dissolve into the surrounding solution.
    - This phenomenon depends on the spacing of the air bubbles.
- Water volume contained in an air bubble's sphere of influence shows that as the SAM number decreases, the average volume of water inside a bubble's sphere of influence also decreases.
    - The volume of water inside an air bubble's sphere of influence in a passing SAM test is comparable to what was found in the clustered air bubble test.

As air bubbles get closer together they appear to be less likely to dissolve into the solution. This would mean that the pressure differentials encountered in the SAM test would be lower for samples that have more air bubbles that are clustered, which would explain why the SAM testing method and its SAM number correlates the best with a samples spacing factor. Therefore, this could be a possible mechanism for the SAM.

CHAPTER IV

CONCLUSION

This thesis is composed of two studies that looked into the performance of the super air meter (SAM). The first looks at the application of a fresh concrete test that allows one to rapidly predict the air-void distribution of concrete. This utilized the (SAM) and could be conducted in a matter minutes. This research consisted of mixtures that contained varying amounts of two air entraining admixtures (AEAs) with and without a polycarboxylate superplasticizer (PC). These mixtures were designed to determine the reliability and variability of the SAM. The second study focused on the mechanism behind the SAM. To accomplish this, air entrained cement paste was examined under a stereomicroscope while being subjected to an applied pressure.

It was found that the hardened air-void parameters obtained from ASTM C 457 correlated well to the SAM number. This research has shown a SAM number of 0.020 psi or less can satisfies the ACI 201 suggested limit for the spacing factor. The reliability of the SAM was determined to be 93% for the test examined in this research. The SAM also was shown to have a low variability, which allows the testing method to be repeatable. This makes the SAM an accurate predictor of the air-void system in fresh concrete and a valuable asset that should be used for the field testing of concrete.

The mechanism for the SAM found in the research consisted air bubbles that were clustered together followed Henry's Law. Air bubbles that were clustered together did not dissolve at the same pressures as the bubbles that were not clustered, even though these bubbles were of a similar size. This shows that the spacing of the air bubbles is important to how they react under pressure. Furthermore, with the spacing of the air bubbles being closely tied to the ASTM C 457 spacing factor (arguably the most important air-void parameter), this shows why the SAM number is lower for concretes with a lower spacing factor and higher for concretes with a higher spacing factor.

Further testing could be done to determine if there is a correlation with the freeze-thaw durability of a concrete and the SAM number. This could allow one to directly measure a value in the field that correlates to the freeze-thaw performance of a concrete in minutes as opposed to months.

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APPENDICES

Appendix A: SAM Testing Results

Table A-1 shows the SAM test results for the researched mixes as well as the hardened air-void parameters obtained through ASTM C457. This data shows the SAM test results, the gravimetric air content and the unit weight (ASTM C138), the slump (ASTM C143), and the hardened air-void parameters (ASTM C457). The table is organized by the mixture type, and then again by the SAM number.

Table A-1 SAM results and Hardened air-void parameters

Mixture	**SAM Number**	Spacing Factor (in)	Slump (in)	SAM Air (%)	ASTM C138 (%)	ASTM C 457Air (%)	Specific Surface (in-1)	Void Freq. (in-1)	Chords/in <200um
WROS .45 w/c	**0.13**	0.0081	3	3.9	3.67	3.96	682	6.75	7.77
	0.13	0.007	3.5	5.1	4.59	5.48	682	9.35	11.87
	0.16	0.0058	4.5	9.0	8.59	5.6	817	11.43	14.07
	0.16	0.0096	2.5	4.1	3.70	4.02	570	5.73	7.23
	0.23	0.0083	3.5	3.7	2.91	3.71	689	6.40	7.95
	0.29	0.0097	3	3.1	2.26	3.73	584	5.44	7.63
	0.57	0.0145	2.5	2.2	2.15	2.3	486	2.80	2.73
	0.59	0.0128	2.5	2.5	2.31	2.18	563	3.06	3.62
	0.62	0.0131	1.75	2.5	2.60	3.4	453	3.85	4.05
	0.65	0.0145	3	2.0	1.50	2.77	448	3.11	2.58
	0.68	0.0103	3.25	2.4	1.50	3.74	551	5.15	6.18

SYNTH .45 w/c	**0.13**	0.008	3	4.5	4.22	4.34	661	7.18	8.83
	0.15	0.0077	3	6.0	5.56	4.34	690	7.48	8.68
	0.17	0.0059	4.25	5.2	5.24	4.49	881	9.90	13.18
	0.19	0.0076	3	5.8	5.79	5.31	633	8.40	10.58
	0.25	0.009	3.5	3.7	3.07	3.45	653	5.63	6.36
	0.26	0.0116	3.5	3.0	2.33	2.24	613	3.43	4.43
	0.27	0.0134	3.125	2.7	3.07	2.14	544	2.91	3.57
	0.28	0.0098	2.625	2.1	2.07	3.52	593	5.22	5.78
	0.28	0.0132	2.75	2.8	2.99	2.79	489	3.41	3.92
	0.31	0.0121	4.5	2.8	3.36	1.68	668	2.81	3.08
	0.35	0.0119	3.25	3.6	3.54	2.32	591	3.42	4.29
	0.36	0.0092	3.5	3.4	2.10	2.46	746	4.58	6.34
	0.38	0.0139	3.25	2.9	3.09	2.51	487	3.05	3.18
	0.47	0.0184	3.25	2.2	2.41	1.79	428	1.92	2.29
WROS .53 w/c	**0.08**	0.0061	8.5	8.6	8.37	7.04	733	12.90	13.39
	0.12	0.0056	9	7.9	7.79	8.05	714	14.38	15.98
	0.13	0.0074	9	6.2	5.78	6.32	632	9.98	9.43
	0.19	0.0073	9	6.0	5.75	6.66	625	10.41	10.49
	0.25	0.0078	8.5	5.5	5.35	6.22	607	9.43	8.90
	0.39	0.0107	8	4.0	3.69	4.02	534	5.37	5.36
	0.54	0.0095	9	4.4	3.88	5.53	524	7.24	7.15
	0.58	0.0096	9	3.6	3.35	4.05	594	6.01	6.28
	0.79	0.0126	8.5	2.7	2.68	3.47	487	4.22	3.95
WROS .41 w/c	**0.16**	0.0096	1.5	3.5	3.17	3.48	597	5.19	6.17
	0.19	0.0075	2	5.7	5.76	5.67	611	8.66	9.69
	0.19	0.0074	1.75	4.5	4.16	3.45	771	6.66	7.47
	0.19	0.0067	1.5	5.1	4.94	5.14	716	9.21	11.28
	0.20	0.0113	1.75	3.8	3.33	3.06	537	4.10	4.70
	0.22	0.009	2	3.6	3.33	4.48	569	6.37	7.57
	0.32	0.0115	1.5	3.1	2.76	3.04	530	4.03	4.50
	0.48	0.0117	1.75	2.7	2.71	2.12	609	3.23	3.92
	0.55	0.0164	2.125	2.0	1.77	1.06	586	1.55	1.98
	0.55	0.0142	1.75	2.2	2.34	1.46	589	2.16	3.01
	0.65	0.0126	1.125	2.7	2.40	2.87	496	3.56	3.16
	0.69	0.0133	1.125	2.5	2.24	2.48	498	3.09	3.17
WROS .39 w/c	**0.13**	0.0089	0.5	4.3	3.40	4.73	554	6.56	7.11
	0.16	0.005	0.75	6.1	5.96	7.34	728	13.36	16.73
	0.19	0.0073	0.75	4.4	4.31	4.27	702	7.49	9.05
	0.21	0.0106	0.75	3.7	3.17	4	502	5.02	6.46
	0.25	0.0089	0.5	3.1	2.89	4.22	578	6.09	7.94

	0.29	0.0118	1.25	3.3	2.86	2.68	540	3.62	4.07
	0.48	0.0115	0.75	2.8	2.89	3.81	470	4.48	4.74
	0.51	0.0102	1	2.7	2.17	4.42	498	5.49	6.24
	0.55	0.0104	0.75	2.6	2.48	3.32	554	4.60	5.59
	0.57	0.019	0.75	2.5	2.27	2.85	337	2.40	1.94
	0.61	0.0104	1	2.2	1.70	3.12	569	4.43	5.85
WROS .45 w/c + PC	**0.07**	0.0064	10	8.0	7.47	8.89	515	11.45	11.01
	0.11	0.0061	9	10.5	10.14	7.32	652	11.95	12.00
	0.13	0.0071	9.5	7.2	6.24	7.26	562	10.21	10.15
	0.20	0.0109	9.5	6.3	6.97	5.41	441	5.97	5.20
	0.32	0.0144	9.5	5.5	5.32	5.02	344	4.32	3.33
	0.37	0.016	9	3.1	2.94	3.88	349	3.39	3.09
	0.37	0.0142	9.25	6.2	5.87	6.78	303	5.14	3.79
	0.38	0.0101	9.25	5.3	5.22	8.04	358	7.20	7.43
	0.41	0.0133	8.5	2.7	3.07	3.66	431	3.94	3.98
	0.41	0.0119	9.5	5.2	5.01	6.19	380	5.87	6.16
	0.43	0.0161	9.75	2.3	2.60	2.97	389	2.89	2.75
	0.43	0.0134	9	3.8	3.67	4.28	398	4.26	4.08
	0.44	0.0142	9.5	3.8	3.46	4.04	386	3.89	3.82
SYNTH .45 w/c + PC	**0.10**	0.0058	8.5	8.5	7.34	6.24	775	12.09	12.85
	0.10	0.0075	9.25	5.6	5.27	4.38	705	7.73	7.93
	0.11	0.0062	9	7.1	6.94	5.57	759	10.58	12.39
	0.13	0.0063	8.5	8.6	8.57	5.72	745	10.65	12.03
	0.25	0.0108	9	3.5	2.99	2.47	631	3.91	3.81
	0.25	0.0115	8.25	5.0	4.69	3.6	501	4.50	3.98
	0.30	0.0109	9	4.6	4.19	4.58	475	5.44	4.69
	0.45	0.0105	9	3.4	3.09	5.08	458	5.82	5.29
	0.47	0.017	9.25	2.7	2.67	2.43	403	2.45	2.42
	0.50	0.0139	8.5	2.9	2.44	3.04	449	3.41	2.65
	0.58	0.0117	8.5	3.6	3.46	3.58	493	4.42	4.09
WROS .45 w/cm with 20% Fly Ash	**0.11**	0.007	7	8.0	7.52	7.45	567	10.56	10.12
	0.16	0.0051	6.5	6.7	6.26	8.23	711	14.64	16.71
	0.19	0.0078	7.5	5.6	5.20	4.16	698	7.25	9.18
	0.20	0.0069	6.755	6.1	5.39	5.98	670	10.02	10.77
	0.28	0.0103	6.5	3.4	3.01	3.37	580	4.89	5.14
	0.38	0.0097	5	4.2	3.75	4.23	556	5.88	6.73
	0.77	0.0112	6.5	2.4	2.04	3.37	535	4.50	5.23
	0.82	0.0111	5.5	2.3	1.91	2.71	594	4.02	5.25

OGM WROS .45	**0.08**	0.004	1.5	6.0	6.14	7.97	711	14.17	18.18
	0.10	0.0053	1.5	5.3	5.27	6.17	703	10.83	13.97
	0.16	0.0068	2	5.5	5.68	3.55	767	6.81	8.79
	0.30	0.0082	2	3.7	3.13	3.96	601	5.96	7.72
	0.31	0.0085	2	4.0	3.88	4.08	573	5.85	7.32
	0.44	0.0096	2	3.4	3.05	5.21	457	5.95	6.63
	0.46	0.0084	2	3.3	3.00	4.12	580	5.98	7.41
	0.50	0.0095	1.5	2.6	2.24	3.29	567	4.66	6.75
	0.53	0.0099	1.5	3.2	3.38	4.68	466	5.45	5.57
	0.56	0.012	2	2.2	2.31	2.9	474	3.44	3.27

Table A-2 shows the SAM test results for the researched mixes. Meter A and meter B correspond to separate testing devices that have approximately the same volumes for the top and bottom chambers. Each meter was tested at the same time.

Table A-2: Multiple Meter SAM results

Mixture	SAM Number			Super Air (%)		
	Meter A	Meter B	Difference A - B	Meter A	Meter B	Difference A - B
WROS .45 w/c	0.15	0.11	0.05	5.1	5.1	-0.06
	0.17	0.15	0.02	8.9	9.1	-0.18
	0.18	0.14	0.04	4.2	4.0	0.20
	0.21	0.26	-0.05	3.6	3.7	-0.11
	0.30	0.29	0.01	3.1	3.0	0.12
	0.58	0.56	0.01	2.2	2.1	0.05
	0.54	0.63	-0.09	2.6	2.5	0.15
	0.59	0.66	-0.07	2.6	2.5	0.01
	0.62	0.69	-0.07	1.9	2.0	-0.08
	0.66	0.70	-0.04	2.5	2.2	0.30
SYNTH .45 w/c	0.10	0.15	-0.05	4.4	4.7	-0.29
	0.16	0.15	0.01	6.1	5.9	0.20
	0.19	0.19	0.01	5.8	5.8	-0.04
	0.27	0.22	0.05	3.9	3.7	0.20
	0.22	0.30	-0.08	3.0	3.0	0.07
	0.26	0.28	-0.02	2.7	2.7	-0.05
	0.28	0.27	0.01	2.0	2.1	-0.18

WROS .53 w/c	0.12	0.04	0.08	8.6	8.6	0.01
	0.15	0.09	0.06	8.0	7.8	0.13
	0.16	0.10	0.06	6.1	6.4	-0.26
	0.18	0.20	-0.02	6.2	5.9	0.32
	0.27	0.23	0.03	5.5	5.5	0.00
	0.43	0.35	0.08	4.0	4.1	-0.12
	0.45	0.63	-0.18	4.3	4.4	-0.15
	0.84	0.75	0.09	2.7	2.7	0.01
WROS .41 w/c	0.20	0.19	0.01	5.1	5.0	0.10
	0.22	0.22	0.00	3.6	3.7	-0.07
	0.50	0.60	-0.10	2.2	2.2	0.02
WROS .39 w/c	0.13	0.14	-0.01	4.4	4.3	0.05
	0.12	0.20	-0.08	6.1	6.0	0.11
	0.17	0.19	-0.02	4.5	4.3	0.12
	0.20	0.22	-0.02	3.6	3.7	-0.14
	0.21	0.29	-0.08	3.2	3.1	0.03
	0.27	0.31	-0.05	3.3	3.4	-0.10
	0.54	0.43	0.11	2.8	2.8	0.00
	0.42	0.61	-0.19	2.7	2.7	0.01
	0.54	0.57	-0.03	2.6	2.7	-0.05
	0.51	0.63	-0.12	2.5	2.4	0.05
	0.59	0.63	-0.04	2.1	2.3	-0.16
WROS .45 w/c + PC	0.11	0.04	0.07	8.0	8.1	-0.11
	0.10	0.13	-0.03	10.5	10.5	-0.04
	0.09	0.18	-0.09	7.1	7.3	-0.18
	0.23	0.17	0.06	6.3	6.4	-0.09
	0.37	0.38	-0.01	5.6	5.3	0.21
	0.44	0.37	0.07	2.7	2.8	-0.03
	0.43	0.43	0.00	2.3	2.4	-0.08
	0.41	0.46	-0.04	3.9	3.8	0.09
SYNTH .45 w/c + PC	0.11	0.09	0.02	8.3	8.8	-0.49
	0.15	0.06	0.08	5.5	5.7	-0.24
	0.11	0.12	-0.01	7.0	7.2	-0.17
	0.09	0.15	-0.06	8.5	8.6	-0.17
	0.28	0.22	0.06	3.4	3.4	-0.03
	0.30	0.21	0.09	5.0	5.0	0.02
	0.43	0.48	-0.04	3.4	3.4	-0.05
	0.50	0.44	0.06	2.7	2.8	-0.13
	0.56	0.44	0.11	2.7	3.0	-0.28

	0.59	0.56	0.03	3.5	3.8	-0.21
WROS .45 w/cm with 20% Fly Ash	0.16	0.22	-0.05	5.5	5.8	-0.25
	0.21	0.20	0.01	6.1	6.2	-0.08
	0.27	0.28	-0.01	3.5	3.4	0.10
	0.33	0.44	-0.11	4.2	4.3	-0.02
	0.73	0.82	-0.09	2.4	2.4	-0.03
	0.83	0.80	0.03	2.4	2.3	0.05
OGM WROS .45	0.07	0.09	-0.03	6.1	6.0	0.01
	0.11	0.09	0.02	5.2	5.3	-0.07
	0.16	0.16	0.00	5.6	5.4	0.16
	0.47	0.53	-0.06	2.5	2.6	-0.13
	0.49	0.44	0.04	3.3	3.3	0.08
	0.66	0.46	0.19	2.3	2.2	0.09

Table A-3 shows concrete mixtures that were conducted using “extreme” temperatures. Mixtures were conducted with an average temperature of 93°F (Hot mixtures), 61°F (Cool mixtures), and 47°F (Cold mixtures). Figure A-1 shows the temperature mixtures ASTM C 457 results plotted with a temperature controlled mixture. All of the mixtures in this table and figure have the same mixture design and admixtures.

Table A-3 Extreme temperature mixtures

Mixture	Temp. (F)	SAM Number	Spacing Factor (in)	Specific Surface (in^{-1})	Rapid Air	SAM Air %	Slump (in)
91°F	92	0.39	0.0111	456	3.0	2.9	2.5
	92	0.18	0.0101	602	3.2	3.7	2
	94	0.53	0.0147	441	2.8	2.9	2.5
	93	0.15	0.0072	735	4.4	4.6	2.75
	92	0.23	0.0085	681	3.6	3.3	2.5
	96	0.15	0.0061	741	6.1	5.3	3.25
73°F	73	0.68	0.0103	551	3.7	2.4	3.25
	73	0.29	0.0097	584	3.7	3.1	3
	73	0.16	0.0096	570	4.0	4.1	2.5
	73	0.13	0.007	682	5.5	5.1	3.5

	73	0.57	0.0145	486	2.3	2.2	2.5
	73	0.65	0.0145	448	2.8	2.0	3
	73	0.23	0.0083	689	3.7	3.7	3.5
	73	0.13	0.0081	682	4.0	3.9	3
	73	0.59	0.0128	563	2.2	2.5	2.5
	73	0.62	0.0131	453	3.4	2.5	1.75
	73	0.16	0.0058	817	5.6	9.0	4.5
61°F	61	0.09	0.006	884	4.3	5.2	3.75
	62	0.69	0.0089	749	2.6	2.5	3
	61	0.14	0.0068	754	4.7	4.1	2.75
	60	0.18	0.0103	558	3.7	3.1	2.5
	61	0.17	0.0071	693	5.1	3.7	1.75
47°F	49	0.15	0.0068	711	5.4	4.0	3.75
	47	0.24	0.0087	633	4.0	2.7	3.5
	54	0.13	0.0068	751	4.8	5.4	3.5
	42	0.73	0.0112	597	2.6	2.0	5.5
	42	0.14	0.0057	744	6.8	5.0	5

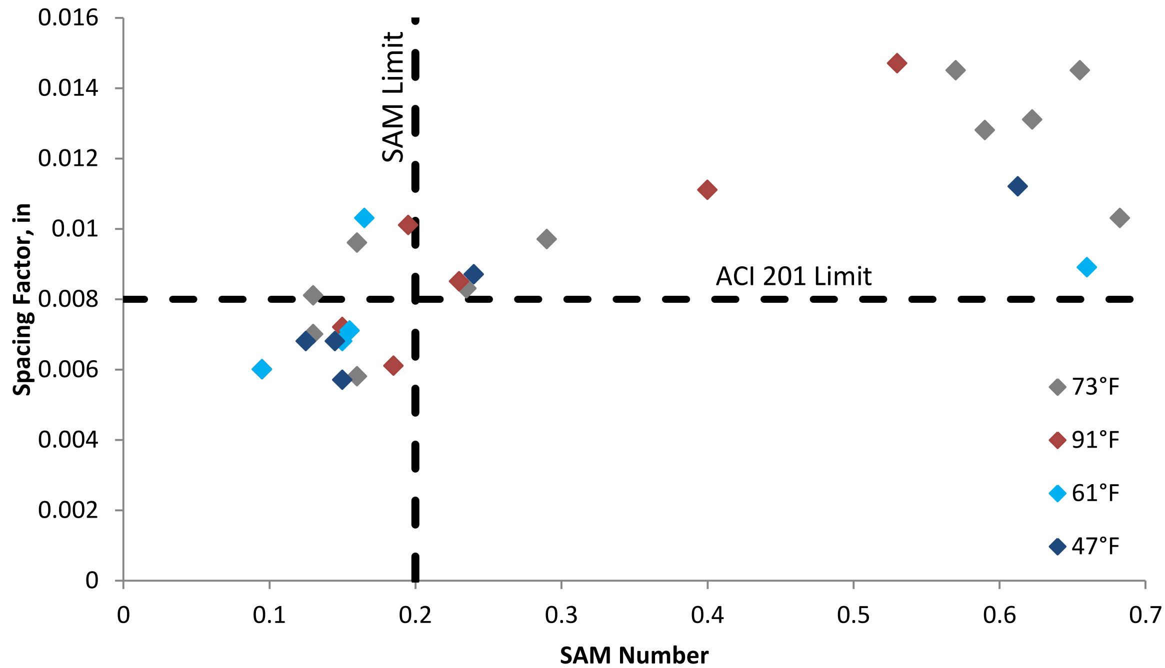

Figure A-1 Temperature mixture ASTM C 457 results compared to the SAM number.

Figure A-2 and Table A-4 shows the SAM test results that were conducted on concrete at various job sites.

Table A-4 Field Test Data

Field I.D.	SAM Number	Super SAM	ASTM C457 Air %	Spacing Factor (in)	Specific Surface (in^{-1})	Chord Frequency	Chords/in <200um
Field 1	0.66	3.4	5.2	0.0132	359	4.69	4.19
	0.71	2.5	4.7	0.0114	435	5.1	4.59
	0.67	2.7	4.3	0.012	431	4.6	4.33
	0.75	3.0	4.3	0.0164	313	3.38	1.85
	0.13	9.4	9.7	0.0049	521	12.62	12.05
	0.75	2.9	4.4	0.0119	430	4.68	4.34
	0.58	3.0	4.5	0.0104	484	5.47	5.34
	0.62	3.0	4.6	0.0109	460	5.33	5.25
Field 2	0.19	6.6	9.4	0.0044	631	14.88	15.27
	0.18	4.9	6.0	0.0068	632	9.56	10.81
	0.17	5.7	5.7	0.0063	701	10	11.54
	0.26	5.5	5.2	0.0076	616	7.94	8.4
	0.25	4.9	4.2	0.0092	557	5.85	6.54
	0.16	5.1	5.5	0.0077	588	8.14	8.96
	0.17	7.3	8.4	0.0055	561	11.81	12.32
Field 3	0.24	5.2	2.8	0.0098	626	4.44	5.14
	0.37	6.0	3.4	0.0098	578	4.87	5.06
	0.30	5.9	3.7	0.0099	542	5.06	5
	0.29	5.7	3.2	0.0137	425	3.37	3.01
	0.19	6.8	6.3	0.0062	672	10.52	11.54
	0.24	5.6	5.4	0.0076	602	8.06	8.58
	0.15	6.6	7.5	0.0059	588	10.98	12.74
Field 4	0.32	4.5	3.6	0.0108	503	4.57	4.36
	0.54	4.3	3.6	0.0116	474	4.21	4.11
	0.55	4.3	4.1	0.0087	591	6.04	6.7
	0.32	4.6	3.5	0.0118	469	4.05	4.23
	0.15	4.4	5.4	0.007	644	8.68	9.6
	0.25	4.6	4.8	0.0095	504	6.04	5.74
	0.36	4.1	4.1	0.0101	510	5.18	5.38
	0.67	3.1	2.8	0.0101	618	4.37	4.22
	0.64	3.0	2.7	0.0126	507	3.43	3.33

	0.62	2.9	3.9	0.0119	455	4.48	4.48
	0.44	3.1	3.5	0.0108	431	7.96	4.93
	0.40	3.1	4.2	0.0099	529	5.6	5.95
	0.34	3.0	4.0	0.0151	355	3.56	3.01
	0.58	3.0	3.7	0.0114	486	4.55	4.42
	0.41	3.0	4.0	0.0104	514	5.17	5.08
	0.32	3.0	3.2	0.0109	542	4.36	5.06
	0.37	4.0	4.8	0.0089	539	6.42	6.51
	0.31	3.9	4.6	0.009	543	6.25	7.1
	0.35	4.0	4.0	0.0089	589	5.82	6.79
	0.17	3.9	5.4	0.008	568	7.64	8.16
Field 5	0.15	5.2	5.6	0.0076	550	7.74	7.86
	0.15	6.5	7.0	0.0057	592	10.34	11.08
	0.29	3.6	3.4	0.0084	639	5.41	6.63
	0.10	6.1	7.9	0.0063	467	9.21	8.97
	0.15	5.6	4.9	0.0066	683	8.41	8.72
	0.13	5.9	5.2	0.008	550	7.16	7.66
Field 6	0.35	7.2	5.8	0.0063	610	8.88	9.47
	0.18	6.8	7.0	0.0053	613	10.65	11.05
	0.12	6.7	5.3	0.0069	623	8.22	8.45
	0.13	7.3	5.6	0.0064	623	8.75	8.93
	0.12	7.3	6.7	0.0064	527	8.85	8.23
	0.32	6.7	5.2	0.0071	609	7.98	8.9
	0.18	7.6	7.3	0.0047	651	11.89	13.45
	0.14	6.7	6.7	0.0053	634	10.57	11.07

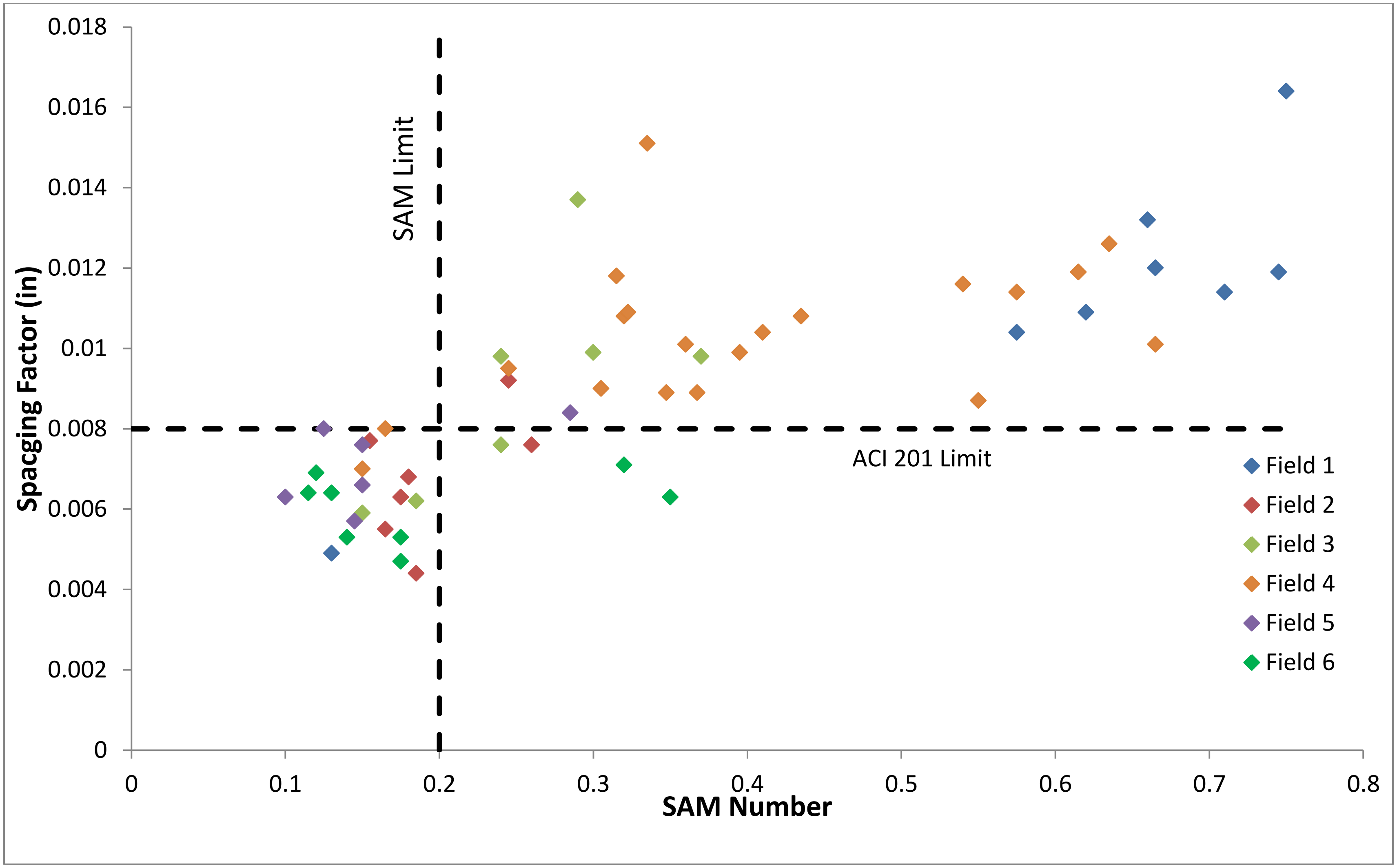

Figure A-2 Field Test Results

VITA

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Master of Science

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