OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

DEVELOPMENT OF A ROBUST FIELD TECHNIQUE TO QUANTIFY THE AIR-VOID DISTRIBUTION IN FRESH CONCRETE

TYLER LEY, PH.D., P.E.
BRANDEN TABB

OTCREOS9.1-31-F

Oklahoma Transportation Center
2601 Liberty Parkway, Suite 110
Midwest City, Oklahoma 73110

Phone: 405.732.6580
Fax: 405.732.6586
www.oktc.org

DISCLAIMER

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
OTCREOS9.1-31-F		

4. Title and Subtitle	5. Report Date
Development of a Robust Field Technique to Quantify the Air-Void Distribution in Fresh Concrete	July 2013
	6. Performing Organization Code
7. Author(s) Tyler Ley and Braden Tabb	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Oklahoma State University School of Civil and Environmental Engineering 207 Engineering South Stillwater, OK 74078	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTRT06-G-0016
12. Sponsoring Organization Name and Address Oklahoma Transportation Center (Fiscal) 201 ATRC Stillwater, OK 74078 (Technical) 2601 Liberty Parkway, Suite 110 Midwest City, Oklahoma 73110	**13. Type of Report and Period Covered** Final Report, Aug. 2009 – Aug. 2013 **14. Sponsoring Agency Code**

15. Supplementary Notes
Project performed in cooperation with the Oklahoma Transportation Center and the University Transportation Center Program

16. Abstract

In order to make concrete frost durable it is common to provide a small and well distributed air void system. Current measuring techniques require weeks to complete on hardened and polished samples of concrete. This report presents the results of a novel test method that uses a higher number of sequential pressures to measure the air void volume and distribution of voids in fresh concrete. The method has been named the Super Air Meter or SAM. Results from the SAM are measured for over 50 concrete mixtures and then compared to hardened air void analysis and conventional measurements of fresh air content. In addition some data is presented from two different operators and two different devices to compare the repeatability of the method. The results are very promising and the data suggests that the test is an inexpensive and useful tool to evaluate the air void quality in fresh concrete.

17. Key Words	18. Distribution Statement
Concrete durability, freeze thaw performance, test methods, fresh properties, Super Air Meter	No restrictions. This publication is available at www.oktc.org and from the NTIS.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	53 + covers	

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
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	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	yd
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	hectares	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	gallons	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 Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

ACKNOWLEDGMENTS

The research team would like to thank the OkTC for funding this project. Many great discussions should also be acknowledged between the authors and Larry Roberts of Roberts Consulting and Dr. Larry Sutter of Michigan Tech. Both gave their time to discussions of this research that was extremely useful. John Jackson of Cardinal Machining should also be acknowledged for their help in creating the restraint cage.

Although the results of Chelsea Harden and Robbie Frazier are not included in this report, their research efforts were also helpful in laying the ground work for these findings.

Development of a Robust Field Technique to Quantify the Air-Void Distribution in Fresh Concrete

Final Report: July, 2013

Tyler Ley, Ph.D., P.E.
Braden Tabb

Oklahoma State University
Civil and Environmental Engineering Department
207 Engineering South
Stillwater, OK 74078

Oklahoma Transportation Center
Tinker Business & Industrial Park
2601 Liberty Parkway, Suite 110
Midwest City, Oklahoma 73110

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Concrete is a durable material that is used for many applications throughout the world due to its flexible use, low cost, and potential for long term durability. One weakness of concrete is that it is susceptible to damage by the tensile stresses that develop when water freezes within the microstructure. To address this surfactants are used to cast a well distributed bubble system into the concrete. Much work has been done to show that the volume of the voids of the smallest size ranges (perhaps smaller than 200 μm) is essential to providing frost durability to the concrete. In order to measure these voids current techniques require the concrete to be cut and polished and then investigated with a stereo microscope. This process can take weeks.

This report will investigate a new method that was developed for this project that determines the quality of an air void system by only testing fresh concrete. This method uses a device called the Super Air Meter or SAM. The device uses sequential pressure responses on the fresh concrete and the measure of the subsequent response. These measured values have been shown to correlate well with the air void system quality in the concrete from traditional hardened air void analysis. In addition the method and device is similar to the traditional ASTM C231 pressure meter and can accurately determine the air content in addition to the quality of the air void system in fresh concrete.

The ability to accurately determine if a fresh concrete mixture has a sufficient quality air void system to resist the environmental effects of frost damage is a large benefit over any existing method. This work will allow for more cost effective and timely construction and laboratory research when frost damage is a critical consideration.

The slow current methods of hardened air void analysis make laboratory studies difficult and tedious. The SAM test will allow researchers and scientists with a focus on frost durability and admixture development to more quickly make new discoveries and gain improved understandings in these areas. This test can also be useful when inspecting construction in which it is necessary for the concrete to have frost durability as the test can be completed quickly and on site. If the results show that the concrete will does not meet the specifications then the contractor can modify the mixture immediately. This is a great benefit as changes can be made before the concrete is hardened in the forms. This will allow for improved quality control over a much larger number of construction projects due to the inexpensive and simple SAM test method.

CHAPTER 1- INTRODUCTION

Concrete is a durable material that is used for many applications throughout the world. The reason concrete is so widely used is because of its flexible use, low cost, and potential for long term durability. One weakness of concrete is that it is susceptible to damage by the tensile stresses that develop when water freezes within the microstructure. On accident it was found that if a well distributed bubble system is cast into the concrete then this can make the concrete durable against freeze thaw damage. Much work has been done to show that it is essential to provide a certain volume of microscopic bubbles in the concrete. In order to obtain these microscopic bubbles it is common to include an air entraining admixture in the mixture. This surfactant allows bubbles to be stabilized during the mixing.

T.C. Powers' findings in 1954 led to the development of the spacing factor, a measurement parameter for hardened air voids that seems to correlate to frost durability[1, 2]. Further work by the Bureau of Reclamation found that a spacing factor of 0.008" and a specific surface of 600 in^{-1} were suitable to provide a sufficient air void system to resist frost damage[3]. ACI 201 now suggests these two limits in air void parameters when concrete is exposed to freeze thaw cycles[4]. Furthermore, in 1956 Paul Klieger determined that minimum air content in the concrete paste to be 18% in order to be consistently frost durable[5]. Klieger's work has led to the current ACI 318 specification for minimum air content in concrete to be bases on maximum nominal aggregate size which is a function of the paste content in a concrete mixture[6].

Measuring the total volume of air in fresh concrete has been the method used for determining the frost durability of a concrete mixture but findings by Freeman (2012) and Felice (2012) have shown that total volume of air is not an accurate measure of a concretes ability to resist frost damage[7, 8]. Freeman has investigated the use of polycarboxylates superplasticizers in modern air entrained concretes and found that these mixtures lost a significant quantity of air over time while unconsolidated. Hardened air void analysis showed that the introduction of a recommended dose of polycarboxylate coarsens, and therefore lowers the quality of the air void system. Frost durability was not achieved despite the fact that the air contents volume was near the ACI 318 recommended value.

The goal of this work is to determine a method for predicting the quality of an air void system in fresh concrete. Previous research by Pigeon and Pleau (1995) and Ley (2007) has shown that as the volume of air increases the average spacing between voids, or the spacing factor, will decrease. This fact will be utilized to help determine a method that can predict air void system quality[9, 10].

This report will investigate a method developed at Oklahoma State University that determines the quality of an air void system by only testing fresh concrete. This method uses a device called the Super Air Meter or SAM. The device measures the response of concrete to several sequential pressures of fresh concrete. This response has been shown to correlate well with the air void system quality in the concrete. In addition the method and device is similar to the traditional ASTM C231 pressure meter and can accurately determine the air content in addition to the quality of the air void system in fresh concrete[11].

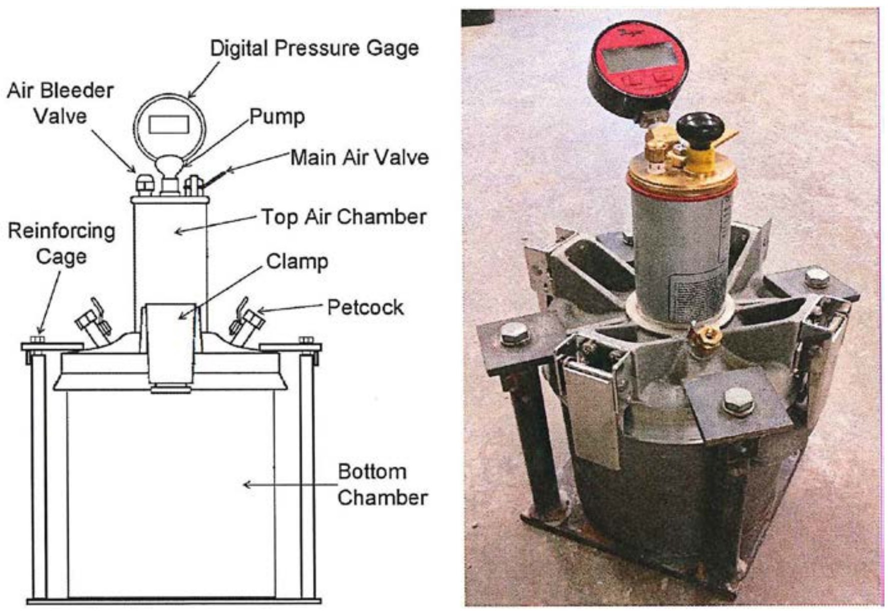
The ability to accurately determine if a fresh concrete mixture has a sufficient quality air void system to resist the environmental effects of frost damage is a large benefit over any existing method. This work will allow for more cost effective and timely construction and laboratory research when frost damage is a critical consideration.

Currently, the ASTM C 457 Hardened Air Void Analysis is used to determine if a frost critical concrete has a sufficient quality air void system[12]. The problem with using hardened air void analysis is that results can take weeks to obtain while the SAM test method takes only minutes. The slow process that is hardened air void analysis is a cause for sluggish laboratory studies in which large data sets can be difficult and tedious to produce. The SAM test will allow researchers and scientists with a focus on frost durability and admixture development to more quickly make new discoveries and gain improved understandings in these areas. This test can also be useful when inspecting construction in which it is necessary for the concrete to have frost durability as the test can be completed quickly and on site. If the results show that the concrete will does not meet the specifications then the contractor can modify the mixture immediately. This is a great benefit as changes can be made before the concrete is hardened in the forms. This will allow for improved quality control over a much larger number of construction projects due to the inexpensive and simple SAM test method.

CHAPTER 2 - EXPERIMENTAL METHODS

Testing Procedure

The Super Air Meter (SAM) consists of a traditional ASTM C231 pressure meter that uses a digital pressure gage instead of the traditional dial gage. The digital pressure gage used for testing has a range from 0.0 psi to 100.0 psi with a 0.1 psi accuracy throughout its range. In addition, a secondary restraint cage allows the SAM to hold up to 75 psi of over pressure. This restraint cage uses bolts and steel plates to clamp the lid. The bolts were tightened with a ratchet evenly so that the lid would be secured uniformly over the bottom chamber. An overview of the device is shown in Figure 1.



(a) (b)

Figure 1: (a) Shows a diagram of the SAM used for testing (b) Shows an image of a SAM with its reinforcing cage.

The SAM test method is outlined in Table 1. The testing procedure is the same as described in ASTM C231 with a few modifications. After the bottom chamber is filled with consolidated concrete, the test is continued by tightly securing the lid on top of the bottom chamber. Water is then added through the petcock valves until the bottom chamber is full. The top chamber is then pressurized to 14.5 psi ± 0.1 psi and allowed to stabilize for 10 seconds. This delay is needed to let the compressed air in the top chamber cool to room temperature. The lever is then pressed to equalize the pressure between the top chamber and the bottom chamber. The lever is held down for 10 seconds to allow the pressure in the top chamber to equalize with the pressure in the bottom chamber. During this time the bottom chamber is sharply hit with a rubber mallet around its sides. It is important that the lever be held down until the pressure in the top chamber stops changing. It was found that 10 seconds was typically long enough for this to occur. The equilibrium pressure is recorded. Now, ***without opening the petcocks or releasing air from the bottom chamber or top chamber*** the top chamber is pressurized to 30 psi ± 0.1 psi and allowed to stabilize. Again, the lever is pressed to allow the top chamber and bottom chamber to reach an equilibrium pressure. The resulting pressure is again recorded. This process is repeated for a top chamber pressure of 45 psi ± 0.1 psi, 60 psi ± 0.1 psi, and 75 psi ± 0.1 psi. After the equilibrium pressure from the 75 psi pressure step was recorded, the petcocks were opened and the lever is pressed to return all the pressures from the bottom chamber and the top chamber back to atmospheric pressure. The lever was held down for 10 seconds, during which, the bottom chamber is smartly hit with a rubber mallet 10 times around its sides. The same sample of concrete was then tested in the same manner stated above. It is possible to run a third set of pressures to compare to the second. If all of the equilibrium pressures from the second and third sets were within a reasonable tolerance of 0.3 psi then the testing was stopped.

Table 1: Summary of the SAM test method.

Step	Action
1	Place concrete in bottom chamber per ASTM C231
2	Securely place lid
3	Add water through petcocks
4	Pressurize top chamber to 14.5 ± 0.1 psi
5	Press lever and record equilibrium pressure, P_{2a}
6	Pressurize top chamber to 30 ± 0.1 psi
7	Press lever and record equilibrium pressure, P_{2b}
8	Pressurize top chamber to 45 ± 0.1 psi
9	Press lever and record equilibrium pressure, P_{2c}
10	Pressurize top chamber to 60 ± 0.1 psi
11	Press lever and record equilibrium pressure, P_{2d}
12	Pressurize top chamber to 75 ± 0.1 psi
13	Press lever and record equilibrium pressure, P_{2e}
14	Return pressure in bottom chamber and top chamber back to atmospheric pressure.
15	Repeat 3 thru 14 an additional time for equilibrium pressures P_{2f} thru P_{2j}

Table 2: Variables used in the SAM test method calculations.

Initial Pressure	Equilibrium Pressure		
	Set 1	Set 2	Set 3
14.5 psi	P_{2a}	P_{2f}	P_{2k}
30 psi	P_{2b}	P_{2g}	P_{2l}
45 psi	P_{2c}	P_{2h}	P_{2m}
60 psi	P_{2d}	P_{2i}	P_{2n}
75 psi	P_{2e}	P_{2j}	P_{2o}

Calculating Air Content

The air volume can be calculated by applying Boyle's Law to the air in the top chamber and the air in the concrete sample. Equation 1 shows Boyle's Law applied to the top chamber where P_{C1} and P_{C2} are the pressures of air in the top chamber before and after equalizing the system and V_{C1} and V_{C2} are the volumes of air from the top chamber before and after equalizing the system. P_{C1} and P_{C2} are given by the gage reading and shown in Figure 2 (a) and (b). V_{C1} is a constant given by the dimension of the top chamber. Equation 1 is used to determine V_{C2}. Figures 2 (a) and (b) are modeled after diagrams in Hover's work (1988)[13].

Equation 1: $$PC1VC1 = PC2VC2$$

The change in volume before and after equalizing the system is equal and opposite for the top chamber air and the bottom chamber air as shown in Equation 2. Boyle's Law is applied to the air in the bottom chamber as shown in Equation 3 where P_{a1} and P_{a2} are the pressures of air in the bottom chamber before and after equalizing the system and V_{a1} and V_{a2} are the volumes of air from the bottom chamber before and after equalizing the system. P_{a1} is assumed to be atmospheric pressure and P_{a2} is equal to P_{C2} and shown in Figure 2 (a) and (b). Equations 2 and 3 are simultaneously solved to determine V_{a1} and V_{a2}.

Equation 2: $$\Delta V = VC2 - VC1 = Va1 - Va2$$

Equation 3: $$Pa1Va1 = Pa2Va2$$

Equation 4 gives the theoretical air content in the bottom chamber where V_{bowl} is the total volume of the bottom chamber.

Equation 4: $$Air\% = \frac{Va1}{Vbowl} * 100$$

These calculations are comparable to those done by a traditional ASTM C231 Type B pressure meter. The SAM was calibrated by finding the performance of the meter with three different air volumes in the bottom bowl. This was done by using a commercially available device for calibrating ASTM C231 meters that provides a void that is 5% of the volume of the bottom chamber, assuming that the chamber is 0.25 ft^3. With this technique a calibration could be run with nothing but water in the bottom bowl to simulate 0% air content, one device for 5% air content, and two devices for 10%. Because the SAM uses a digital gage this allows a more complicated calibration procedure to be used for the testing. An overview of the procedure is shown in Table 3.

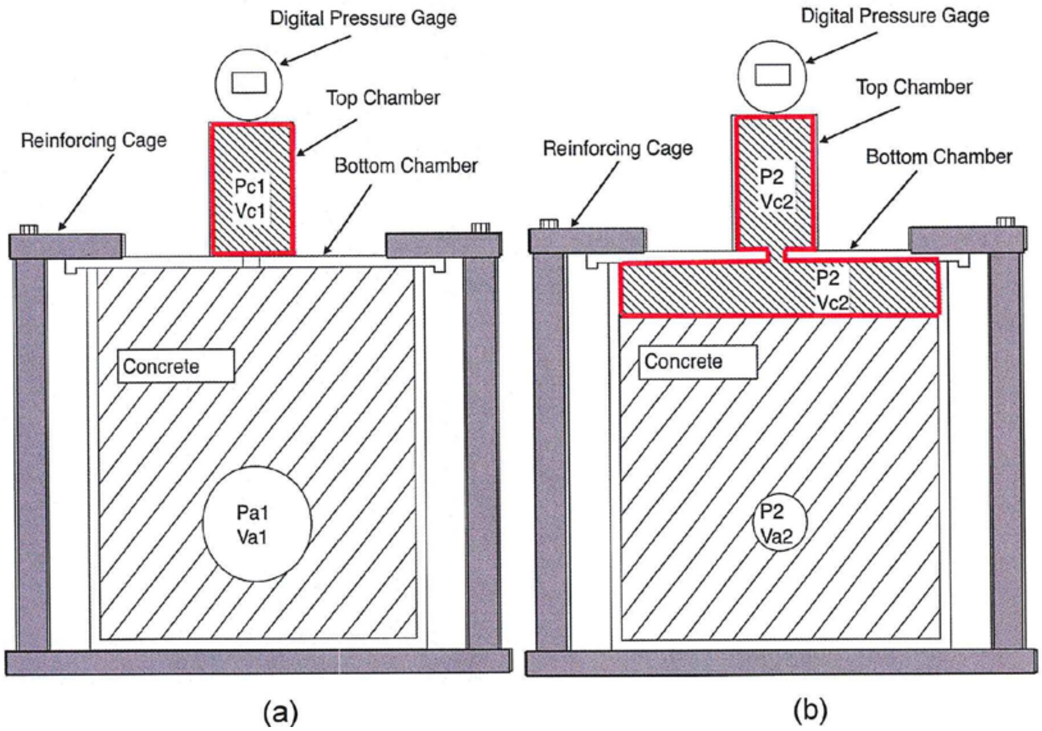


Figure 2: (a) SAM before equalizing the system and (b) SAM after equalizing the system.

Table 3: Summary of the SAM calibration method.

Step	Action
1	Fill bottom chamber with room temperature water
2	Securely place lid
3	Add water through petcocks
4	Pressurize top chamber to 14.5 ± 0.1 psi
5	Press lever and record equilibrium pressure, P_2
6	Return the SAM device back to atmospheric pressure
7	Repeat steps 3 thru 6 two more times
8	Remove the lid and place a calibration device in the water
9	Repeat steps 2 thru 7
10	Remove the lid and place a second calibration device in the water
11	Repeat steps 2 thru 7

SAM Number

The difference between the first and second set of equilibrium pressures from the 75 psi pressure step is called the SAM number and is shown by Equation 5 using variables in Table 2. Figure 3 shows three examples of the pressure difference at all five pressure steps. The SAM number will be compared to the parameters from the ASTM C 457 hardened air-void analysis. Using a hand pump the concrete samples were pressurized in the sequential manner so that high equilibrium pressures could be applied to the concrete in the bottom bowl in a controlled manner. The sequence of equilibrium pressure steps also added a quality control check to the data. SAM numbers for these pressures ranged from 0.0 psi to about 1.8 psi.

Equation 5:

$$SAM\ \ Number = \left[Avg\left(P2set2, P2set3 \right) - P2set1 \right] 75\, pressure\ step$$

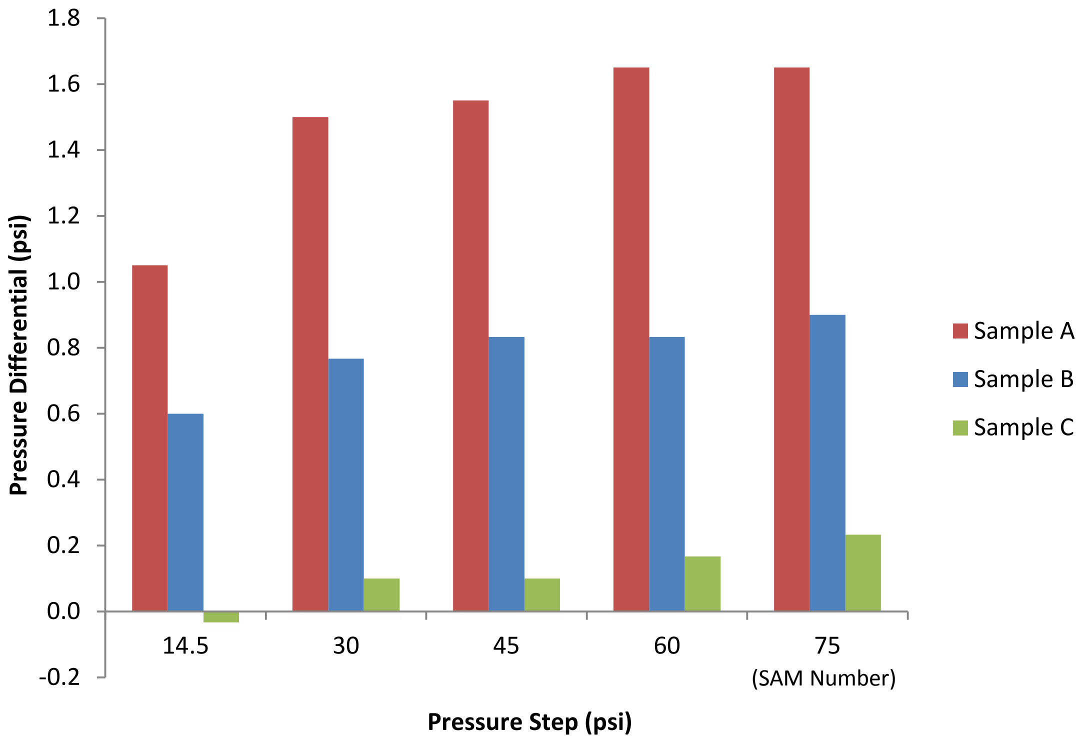


Figure 3: Pressure differential between 1st and 2nd set of equilibrium pressures at each pressure step for three different samples.

Quality Control

Quality control checks were used to ensure the test was completed correctly. The first check considered the difference between the second and third set of equilibrium pressures. If any of the differences were greater than 0.2 psi then a fourth set of equilibrium pressures were obtained in hopes to reduce the standard deviation. If a fourth set was obtained then the average of the second, third, and fourth sets were used. If any one of these values differed from the average of the other two by 0.4 psi or more then the test data was too variable to consider accurate and was not used. In summary, if the standard deviation of the second, third, and possibly fourth sets of equilibrium pressures is greater than 0.21 psi then the test data was too variable to consider accurate. The second check considers the difference in equilibrium pressures at the 14.5 psi pressure step and the 75 psi pressure step. If the difference at 75 psi or the SAM number is less than the difference at the 14.5 psi pressure step by more than 0.2 psi then the test data was considered inaccurate. These checks were used to ensure that the collected data was consistent. These observations were made by completing a large number of SAM tests. It was observed that when the SAM test was performed inconsistently it would cause the equilibrium pressures to be different or less consistent than data sets from SAM tests that were performed consistent with the procedures.

Two SAM devices were investigated to better determine the repeatability of the test method. The volumes of the chambers of both SAM's were measured to be very similar to each other. These results are compared in this document.

CHAPTER 3 – MATERIALS

All concrete mixtures used a Type I cement meeting the requirements of ASTM C150 with the oxide analysis shown in Table 4[14]. The coarse aggregate is a locally available crushed limestone with a maximum nominal aggregate size of ¾ in. Both the coarse and fine aggregates met the Standard Specification of Concrete Aggregates (ASTM C33) and are used in commercial concrete[15]. The admixtures described in Table 5 met the requirements set by ASTM C260 and C494[16, 17]. The wood rosin (WROS) and synthetic (SYNTH) air entraining admixtures (AEA) were chosen as they represent two popular AEAs used commercially. Three mixture designs were investigated as shown in Table 6. The cement content was held constant while varying the w/cm. Each of the AEAs was investigated with and without the use of a polycarboxylate (PC) superplasticizer. When a PC was used it was used at a dosage of 5.0 oz/cwt. To investigate the impact of changes in w/cm, paste content, and workability a WROS air entraining agent was investigated at a 0.41 and 0.53 w/cm. The higher w/cm mixtures were designed to have a similar slump as the mixtures with a w/cm of 0.45 and a PC. The dosage of AEA was modified to achieve different air contents for each mixture.

Table 4: The oxide analysis of the cement used in the study (%).

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 5: Admixtures used in the study.

Short Hand	Description	Application
WROS	Wood Rosin	Air Entraining Agent
SYNTH	Synthetic chemical combination	Air Entraining Agent
PC	Polycarboxylate	Superplasticizer

Table 6: Mixture proportions with SSD aggregates.

w/c ratio	Cement (lb/yd³)	Paste Content (%)	Coarse (lb/yd³)	Fine (lb/yd³)	Water (lb/yd³)
0.41	611	29	1900	1217	250
0.45	611	30	1850	1203	275
0.53	611	33	1775	1150	324

Mixing procedures

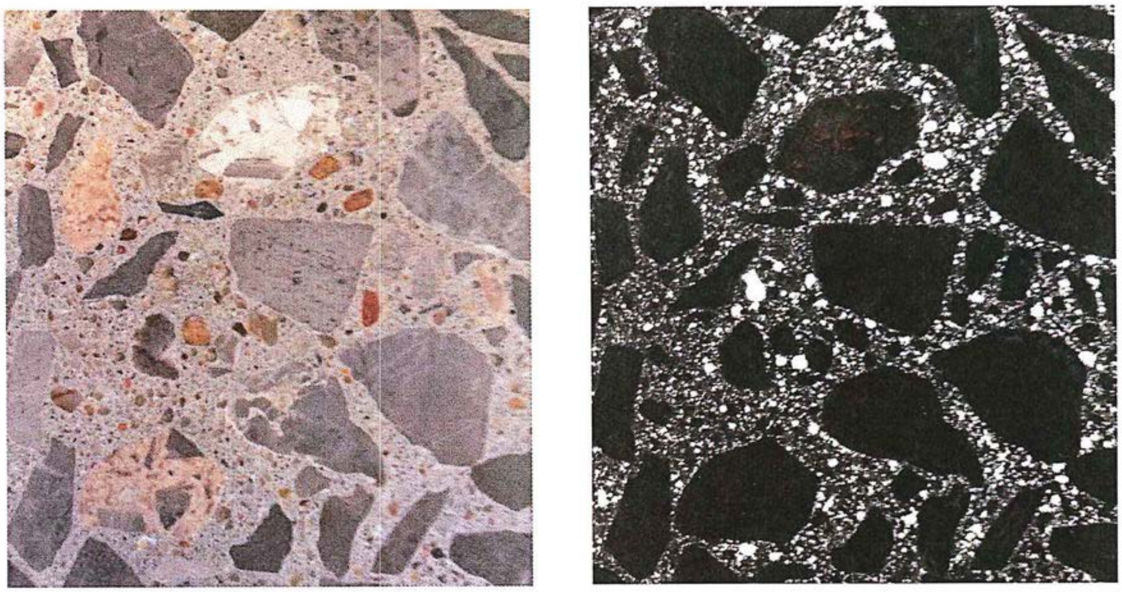
Aggregate was added to a drum mixer along with about half of the mixing water and mixed for 3 minutes. This allows the aggregate to become well mixed and achieves an SSD condition. The remaining mixing water and cement was added to the drum mixer. The combination of aggregate, water, and cement was mixed for 3 minutes. The mixer was then scraped for a period of 2 minutes to ensure a consistent mixture of the concrete. The admixtures were then added. When used, the PC was added first and allowed to mix for 10 to 15 seconds before the AEA was added. The concrete was then mixed for an additional 3 minutes to complete the mixing process.

Quality Control Tests

Immediately after the mixing process was complete the concrete mixture was sampled for two unit weight tests and for a hardened air void analysis. The hardened air void analysis sample was then set aside and covered with wet burlap for 24 hours. The two unit weight samples were obtained using the method described in ASTM C231. After measuring the two unit weight samples, fresh air content with the traditional pressure meter (ASTM C231), slump (ASTM C143), and a SAM test were performed[18].

Hardened Air

Each hardened air sample was saw cut into a ¾” thick section by an 18” diameter saw. Then a four parts acetone to one part lacquer mixture was applied to the testing surface to help preserve the exposed void walls. The hardened sample was then lapped using an 18” diameter lapper with a magnetically bonded diamond grit surface. The lapping increased with continued fineness until a high quality finish was observed on the paste and aggregate portions of the sample under a stereomicroscope. The sample was then placed in a bath of acetone for approximately 10 min. to dissolve the remaining hardened lacquer from the voids. After the sample has dried, black ink was applied to the testing surface using a permanent marker and allowed to dry for 2 to 3 hours. Then a second solid layer was applied using perpendicular strokes and allowed to dry for 8 hours. The voids were then filled with a barium sulfate powder. This fine white powder was chosen because of its high color contrast with the black ink of the permanent marker and the particle size is less than 4 x 10^{-5} in. The voids were filled by pressing two layers of powder into the entire testing surface using a rubber stopper and striking off the excess after each layer. The aggregates were then colored black to avoid accounting for the voids in aggregates. This technique has been shown to be sufficient and described in detail by Ley (2007). After all the air voids are white and all other parts of the sample are colored black the air void parameters are then measured using the Rapid Air 457 from Concrete Experts, Inc. Figure 4 (a) and (b) shows samples that have been satisfactorily lapped. Figure 4 (a) shows a sample before the coloring process and Figure 4 (b) shows the same sample after. The RapidAir 457 machine uses a linear traverse method for analysis with a camera and detects the contrast between the white air voids and black aggregates or paste. A threshold of 185 was used for all hardened air void analyses. The paste content was a required input for the analysis and was determined from the batch weights for the mixture design. The air void parameters reported in this paper exclude chord sizes less than 0.0012 in unless stated otherwise. These chord sizes are not easily visible to the human eye therefore the results from the Rapid Air 457 machine can be compared to previous ASTM C457 results. Other researchers have used this same practice[10, 19-21].



(a) (b)

Figure 4: (a) Satisfactorily lapped sample (b) The same sample after the coloring process and ready for scanning.

CHAPTER 4 - RESULTS

Three typical data sets from a Super Air Meter test can be seen in Tables 7, 8, and 9 where the SAM number is shown in italics. These tables show the equilibrium pressures from each pressure step and the average equilibrium pressure of the second, third, and fourth sets. The right most columns show the pressure differential between the averaged sets and the first set and is shown graphically in Figure 3. These three samples represent SAM tests that were performed on WROS 0.45 w/cm concrete samples that contained a poor (A), mediocre (B), and good (C) air void system as defined by the spacing factor in ASTM C 457. The corresponding hardened air void analysis results are shown in Table 10. The -200 μm chords/in is the frequency of chords from the analysis that are smaller than 200 μm in size. A graphical representation of the SAM test performed on the three concrete samples is shown in Figures 5, 6, and 7 where the solid line represents the equilibrium pressure between the top and bottom chambers and the two dashed lines represent the pressures in the top and bottom chamber separately while they are sealed from one another. The points in which the dashed lines are equal represent equilibrium pressures between the two chambers.

Table 7: Sample A data set obtained from SAM test on a 2.2% WROS air entrained concrete with a 0.45 w/cm.

Initial Pressure (psi)	Equilibrium Pressure (psi)					Avg. - Set 1 (psi)
	Set 1	Set 2	Set 3	Set 4	Avg (2,3,4)	
14.5	10.1	11.2	11.1	-	11.15	1.05
30.0	23.7	25.2	25.2	-	25.20	1.50
45.0	38.0	39.6	39.5	-	39.55	1.55
60.0	52.5	54.2	54.1	-	54.15	1.65
75.0	67.1	68.8	68.7	-	68.75	*1.65*

Table 8: Sample B data set obtained from SAM test on a 3.2% WROS air entrained concrete with a 0.45 w/cm.

Initial Pressure (psi)	Equilibrium Pressure (psi)					Avg. - Set 1 (psi)
	Set 1	Set 2	Set 3	Set 4	Avg (2,3,4)	
14.5	9.1	9.6	9.9	9.6	9.70	0.60
30.0	21.9	22.5	22.9	22.6	22.67	0.77
45.0	35.8	36.5	36.8	36.6	36.63	0.83
60.0	50.1	50.8	51.2	50.8	50.93	0.83
75.0	64.6	65.4	65.7	65.4	65.50	*0.90*

Table 9: Sample C data set obtained from SAM test on a 5.8% WROS air entrained concrete with a 0.45 w/cm.

Initial Pressure (psi)	Equilibrium Pressure (psi)					Avg. - Set 1 (psi)
	Set 1	Set 2	Set 3	Set 4	Avg (2,3,4)	
14.5	7.0	7.0	7.0	6.9	6.97	-0.03
30.0	17.9	18.1	18.0	17.9	18.00	0.10
45.0	30.6	30.7	30.7	30.7	30.70	0.10
60.0	44.1	44.3	44.3	44.2	44.27	0.17
75.0	58.2	58.5	58.4	58.4	58.43	*0.23*

Table 10: Hardened air parameters and SAM number for Samples A, B, and C.

Sample	A	B	C
SAM No.	1.65	0.90	0.23
C231 Air (%)	2.2	3.2	5.8
Hardened Air (%)	3.35	2.63	6.01
Specific Surface (in-1)	420	694	768
Spacing Factor (in)	0.0125	0.0084	0.0048
Void Freq. (in-1)	3.52	4.55	11.54
Avg. Chord Length (in)	0.0095	0.0057	0.0052
Paste to Air Ratio	6.58	8.38	3.67
-200 µm Chords/in	3.50	5.73	13.66

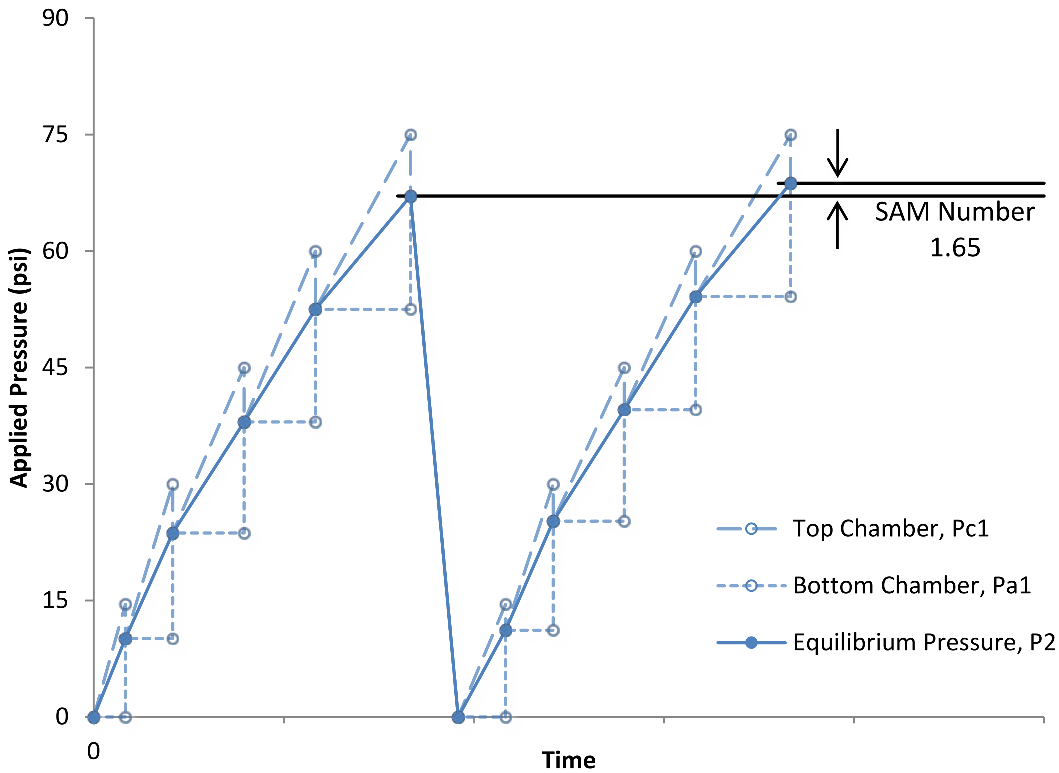


Figure 5: Pressure stages of Sample A SAM test.

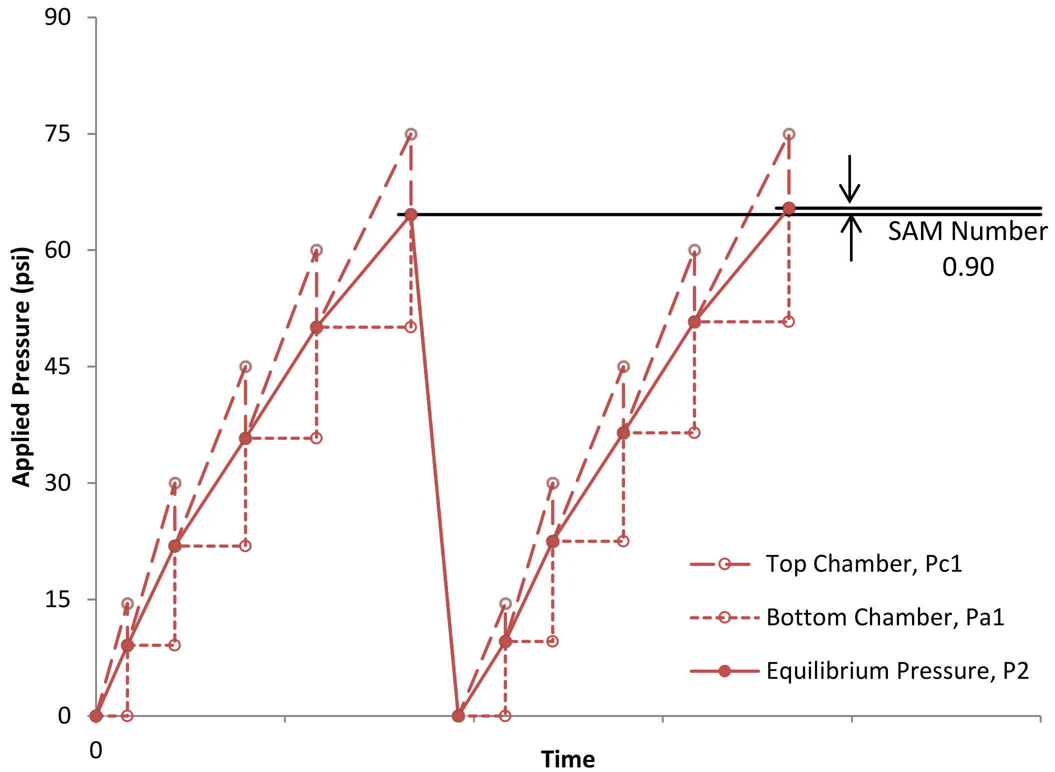


Figure 6: Pressure stages of Sample B SAM test.

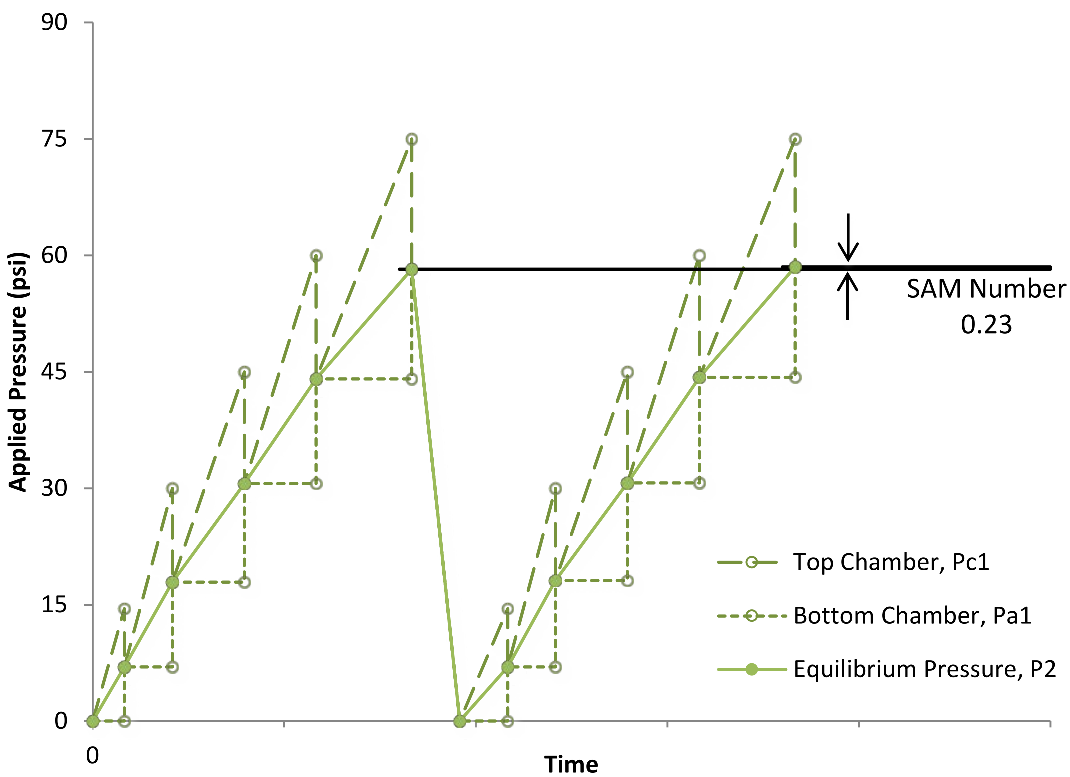


Figure 7: Pressure stages of Sample C SAM test.

Table 11 shows a summary of the results from each SAM test, traditional pressure meter test (ASTM C231), gravimetric air content (ASTM C138)[22], slump test (ASTM C143), and hardened air void analysis (ASTM C457). The slump test was not run for every mixture. The mixtures with a 0.45 w/cm without a PC had a slump of 1¾" to 4" while the 0.45 w/cm mixtures with a PC had a slump of 8½" to 10". A slump of 6" to 8¼" was observed for the 0.53 w/cm mixtures and the 0.41 w/cm mixtures had a lower slump of ¼" to 1". Table 11 is organized by mixture type and then by ascending SAM number. The three methods of calculating air content are shown as Super air content, calculated from the SAM test data, the traditional ASTM C231 pressure meter air content, and the ASTM C457 hardened air content. The air contents are compared to the C231 air contents in Figures 8, 9, and 10. Other hardened air parameters such as the spacing factor and specific surface are shown in Table 11. The spacing factor increases and the specific surface decreases as the SAM number increases. The -200 µm chord frequency and total chord frequency both decrease as the SAM number increases. Graphs of the hardened air void parameters are plotted against SAM number in Figures 11 thru 17.

Table 11: Fresh and Hardened measurements from mixtures investigated.

Mixture	C143 Slump (in)	SAM No. (psi)	SAM Air (%)	C231 Air (%)	C138 Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in-1)	-200 µm Chord/in	Total Chord/in
WROS 0.45 w/cm	2.5	0.00	5.51	5.9	6.94	5.11	0.0070	614	8.48	10.25
	2.5	0.15	6.15	6.1	7.46	5.71	0.0054	714	11.44	13.10
	-	0.23	5.82	5.8	6.97	6.01	0.0048	768	13.66	15.66
	2.25	0.50	4.58	5.1	5.88	5.25	0.0067	626	8.84	10.78
	2.75	0.50	3.34	3.7	4.71	3.19	0.0073	735	6.98	8.11
	2.75	0.73	3.34	3.6	4.40	3.20	0.0116	460	3.56	4.72
	-	0.90	3.14	3.2	4.16	2.63	0.0084	694	5.73	6.48
	2.75	1.10	3.14	3.0	4.08	2.71	0.0115	502	3.43	4.33
	-	1.23	2.17	2.1	2.94	2.74	0.0102	564	4.39	5.42
	2.25	1.27	3.14	3.5	4.53	2.99	0.0122	454	3.02	4.22
	2.25	1.35	2.25	2.3	3.62	3.35	0.0125	420	3.50	4.74
	1.75	1.77	2.18	2.3	3.51	2.49	0.0132	455	3.07	3.82
WROS + PC 0.45 w/cm	-	0.33	9.64	9.8	11.10	9.74	0.0051	445	9.80	13.45
	8.75	0.93	7.47	8.0	9.10	7.66	0.0093	309	4.01	6.95
	9.25	1.07	3.89	3.6	5.13	3.49	0.0166	310	2.04	3.31
	-	1.07	4.01	4.0	5.54	2.86	0.0116	487	3.67	4.77
	8.5	1.13	4.13	4.0	5.41	4.81	0.0120	372	3.79	5.55
	9.25	1.17	4.39	5.0	5.67	4.48	0.0095	483	5.27	6.96
	8.75	1.20	5.22	5.5	5.93	5.35	0.0107	385	4.07	6.15
	-	1.20	5.51	6.0	7.05	4.46	0.0129	356	3.45	4.94
	9.25	1.33	6.68	7.4	8.40	5.67	0.0092	423	5.66	7.80
	8.5	1.33	3.34	3.6	4.48	3.19	0.0161	334	1.80	3.13
	9.25	1.60	4.79	5.2	6.74	3.86	0.0153	323	2.70	4.06
SYNTH 0.45 w/cm	-	0.35	5.82	5.9	6.74	5.37	0.0048	855	14.39	15.96
	-	0.40	4.13	4.3	5.41	4.36	0.0073	636	8.42	9.65
	2.0	0.40	5.51	5.8	6.87	6.23	0.0048	741	13.77	16.03
	3.5	0.55	2.76	2.6	4.09	2.85	0.0109	518	4.19	5.01
	-	0.95	1.75	1.7	3.02	2.59	0.0137	432	2.83	3.60
	2.0	1.10	1.82	1.9	3.51	2.14	0.0147	438	2.00	2.86
	2.0	1.15	1.89	2.0	3.77	1.74	0.0154	459	2.00	2.60

Mixture	C143 Slump (in)	SAM No. (psi)	SAM Air (%)	C231 Air (%)	C138 Air (%)	Hard Air (%)	Spacing Factor (in)	Specific Surface (in-1)	-200 µm Chord/in	Total Chord/in
SYNTH + PC 0.45 w/cm	10.0	0.10	8.48	8.5	9.36	7.50	0.0053	552	8.84	12.07
	-	0.17	10.9	10.0	11.18	7.64	0.0045	648	12.07	14.98
	10.0	0.20	8.21	8.5	9.16	7.37	0.0064	467	7.32	10.35
	-	0.70	6.15	6.0	7.62	5.95	0.0063	584	7.87	10.28
	9.5	0.87	7.24	7.2	8.29	6.82	0.0079	409	6.43	9.10
	9.5	0.90	5.27	6.0	6.89	5.63	0.0116	337	3.96	5.89
	8.0	1.03	4.39	3.9	5.77	3.51	0.0150	342	2.66	3.97
	8.0	1.15	2.85	2.8	4.03	3.59	0.0147	346	2.24	3.66
	8.0	1.15	2.66	2.5	3.80	3.30	0.0145	363	2.73	3.94
	9.5	1.30	5.22	4.9	5.98	4.96	0.0100	439	4.81	6.59
	-	1.50	4.79	4.6	6.58	6.10	0.0114	318	4.47	6.45
WROS 0.53 w/cm	8.0	0.20	9.33	9.5	9.63	9.91	0.0037	651	16.01	19.79
	8.0	0.30	9.33	8.8	10.27	8.76	0.0039	698	15.89	18.89
	8.25	0.30	7.26	7.4	7.43	6.82	0.0060	591	9.11	11.92
	7.0	0.43	5.51	5.3	6.19	4.58	0.0109	437	4.58	6.24
	7.0	0.77	5.08	4.9	5.87	4.00	0.0103	489	4.13	5.73
	7.0	0.80	4.79	4.6	5.74	5.41	0.0095	462	5.90	8.06
	6.0	1.45	2.76	2.7	4.33	3.01	0.0164	351	2.03	3.12
WROS 0.41 w/cm	1.0	0.10	4.76	5.0	6.74	4.11	0.0072	655	8.15	9.26
	1.0	0.50	3.67	3.6	5.05	3.33	0.0099	529	4.59	5.72
	1.0	0.53	3.45	3.4	4.71	2.91	0.0147	377	2.36	3.32
	0.25	0.75	1.89	2.0	3.39	2.46	0.0141	423	2.65	3.38
	0.25	1.10	2.10	2.1	3.84	2.61	0.0178	326	1.76	2.64

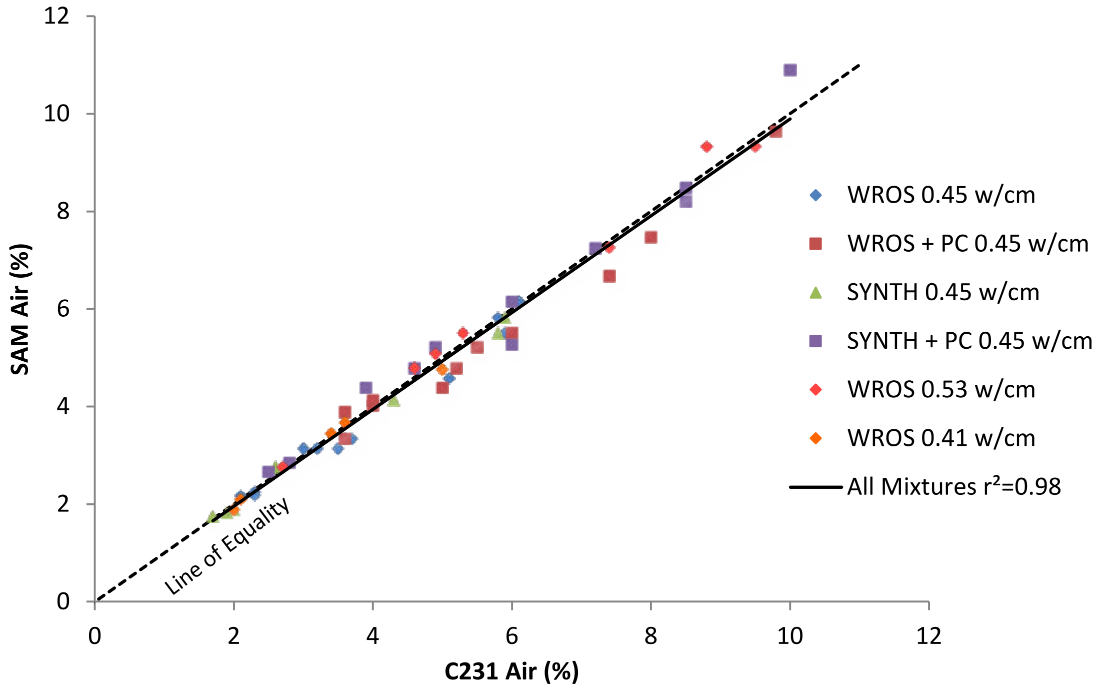


Figure 8: A comparison of air content measurements from the SAM and the traditional C231 pressure meter.

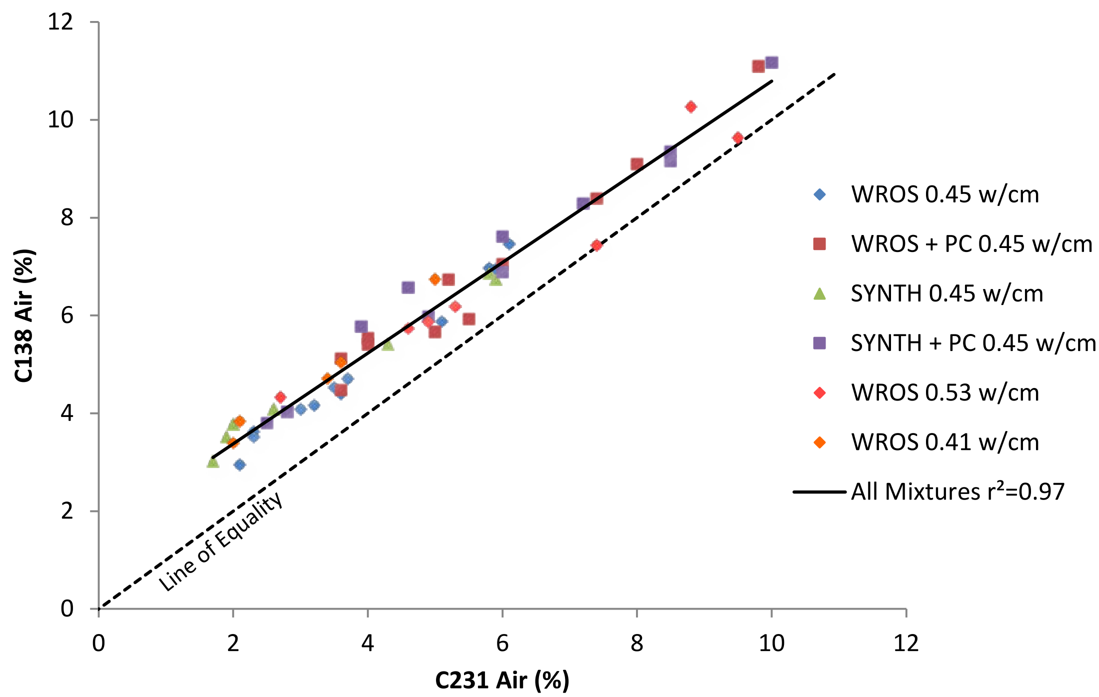


Figure 9: A comparison of air content measurements from the gravimetric method and the traditional C231 pressure meter.

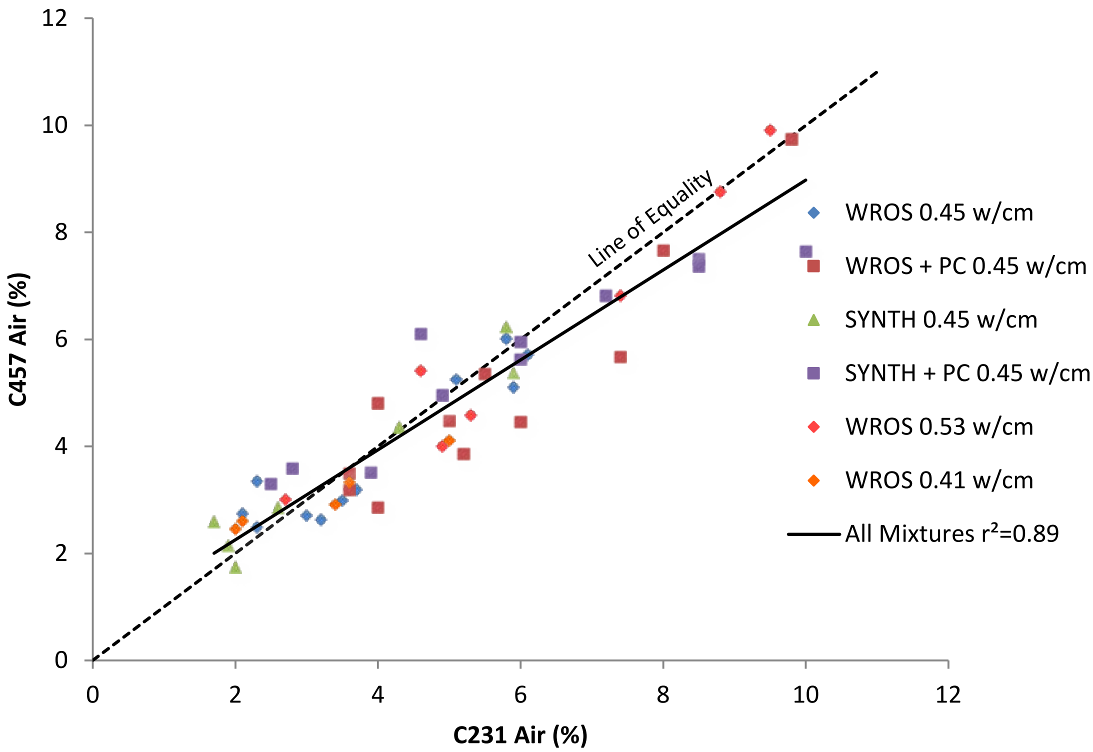


Figure 10: A comparison of air content measurements from the hardened air void analysis and the traditional C231 pressure meter.

Comparison to Hardened Parameters

Figure 11 shows the SAM number versus the hardened spacing factor determined by ASTM C457 for each of the mixtures. Figure 12 shows quadratic trend lines of the spacing factor data shown in Figure 11 and four statistical parameters for each of the mixtures investigated is shown in Table 12. There were not enough data points for the WROS 0.41 w/cm mixture to be statistically analyzed in the same manner as the other mixtures. The specific surface (in^{-1}) of each mixture is compared to the SAM number in Figure 13. The quadratic trend lines are shown in Figure 14 and the four statistical parameters for each mixture are shown in Table 13. The ACI 201 limit for frost durable concrete is suggested to have a specific surface of 600 in^{-1}. This limit is shown on Figures 13 and 14 as a dashed line.

Another hardened parameter analyzed is the number of chords per inch. Figure 15 compares this measurement to the SAM number for each mixture. Freeman (2012) found that the frequency of chords that are less than 200 μm in size is a hardened air void parameter that correlated well with air void system quality. The -200 μm chords frequency is compared to the SAM number in Figures 16 and 17. The quadratic trend lines for this data are shown in Figure 17 and the statistical parameters for each mixture was shown in Table 14. Freeman (2012) has shown that concrete that contains at least 6.0 chords that are less than 200 μm per traverse inch is sufficient to resist frost damage. This limit is shown in Figures 16 and 17 as a dashed line.

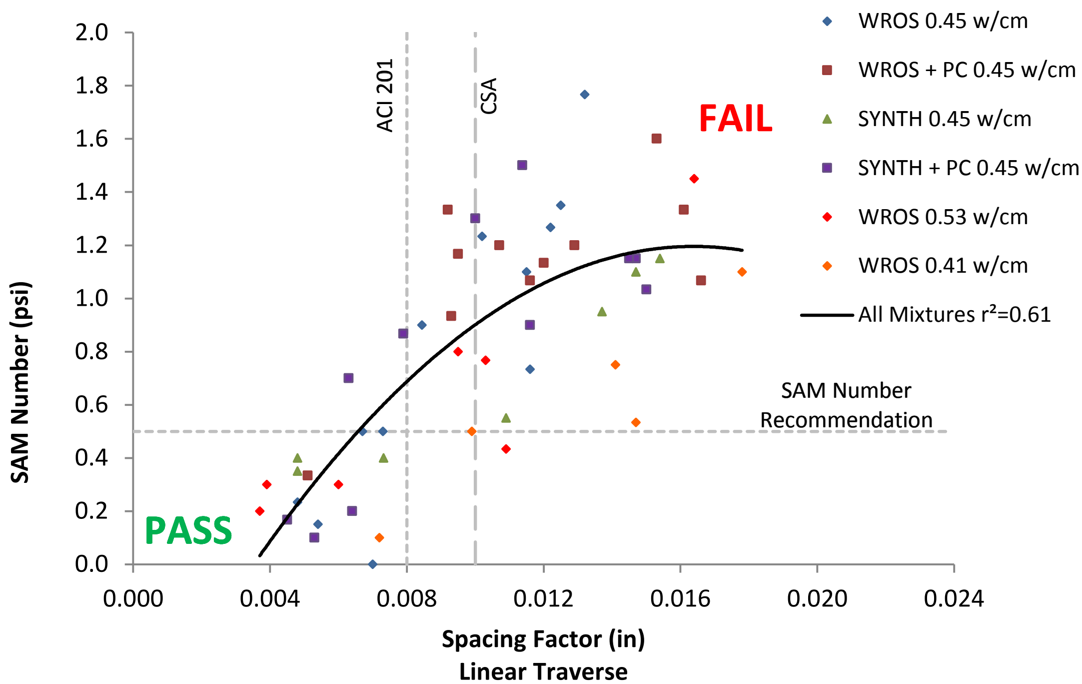


Figure 11: A comparison of hardened spacing factor and the SAM number[4, 23].

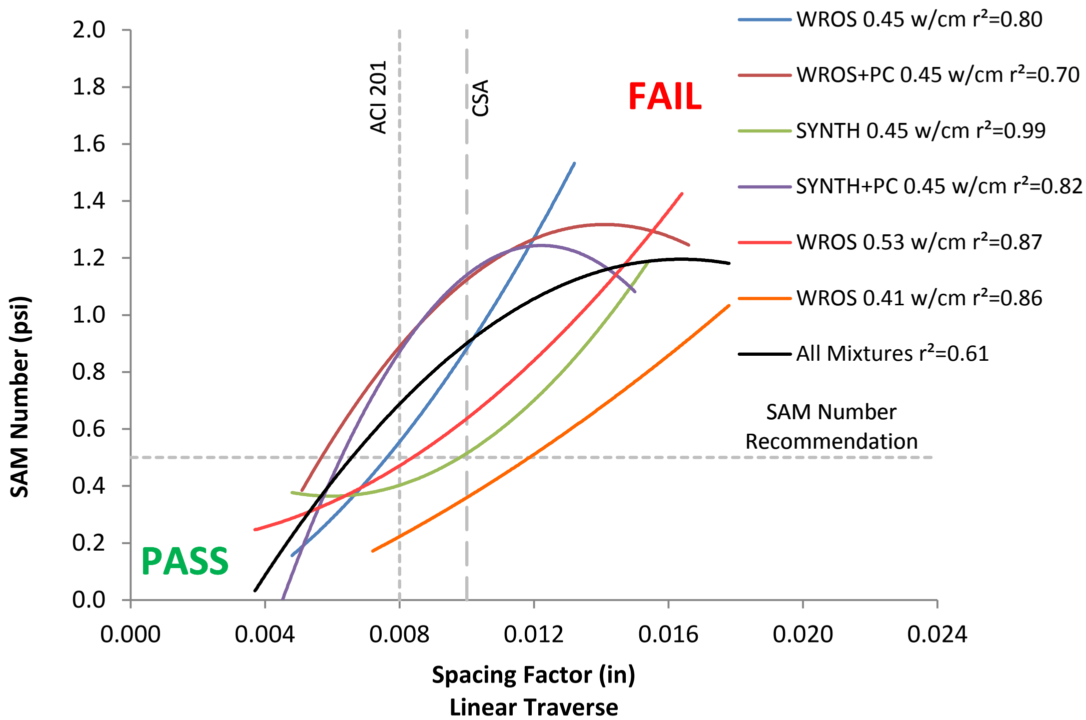


Figure 12: A comparison of hardened spacing factor versus the SAM number with quadratic trend lines.

Table 12: Quadratic model of spacing factor versus the SAM Number.

Mixture	Statistical Parameter			
	r^2	Adjusted r^2	Akaike information criterion	σ
All Mixtures	0.61	0.60	23.62	0.29
WROS 0.45 w/cm	0.83	0.79	3.79	0.23
WROS+PC 0.45 w/cm*	0.70	0.63	-0.54	0.19
SYTNH 0.45 w/cm	0.99	0.99	-20.97	0.04
SYNTH+PC 0.45 w/cm	0.82	0.78	3.10	0.23
WROS 0.53 w/cm	0.87	0.81	0.73	0.19
WROS 0.41 w/cm	0.86	-	-	-

*There was limited data for this trendline.

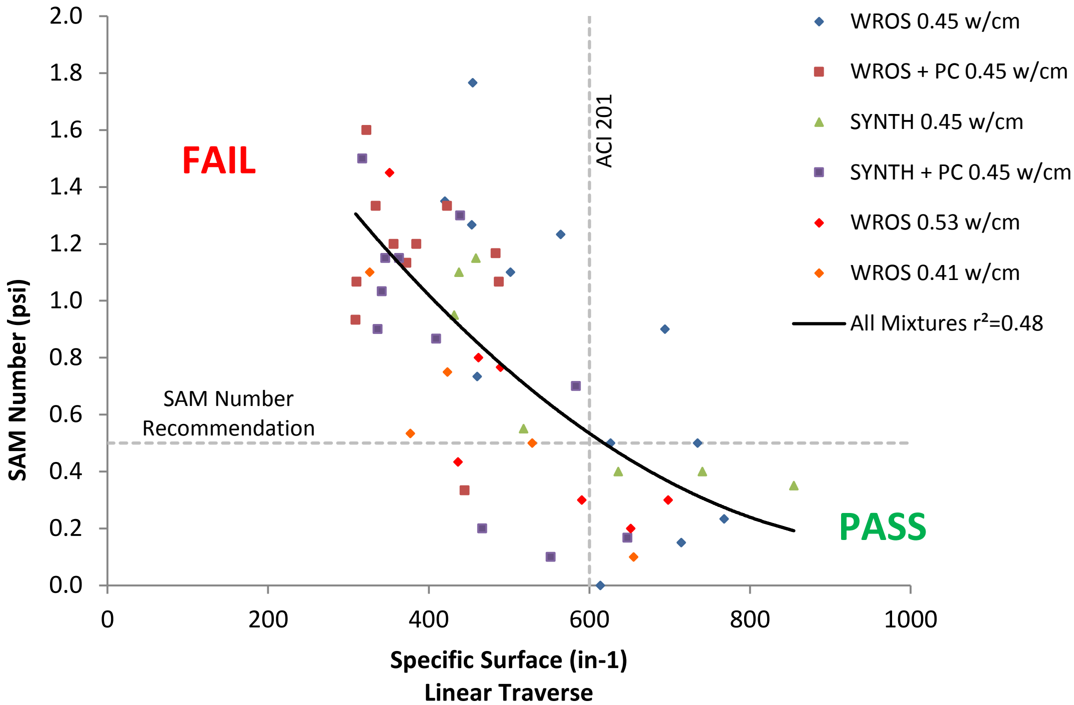


Figure 13: A comparison of hardened specific surface and the SAM number.

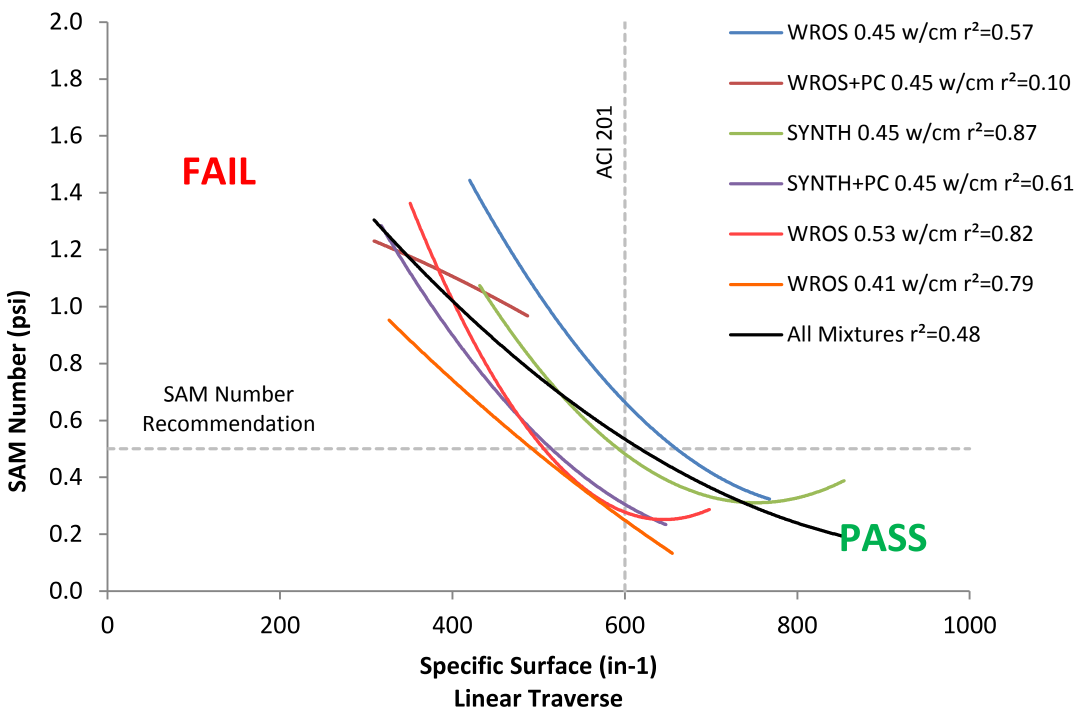


Figure 14: A comparison of the hardened specific surface and the SAM number with quadratic trend lines.

Table 13: Quadratic model of specific surface versus the SAM Number.

Mixture	Statistical Parameter			
	r^2	Adjusted r^2	Akaike information criterion	σ
All Mixtures	0.48	0.46	38.85	0.33
WROS 0.45 w/cm	0.57	0.48	16.42	0.40
WROS+PC 0.45 w/cm*	0.10	-0.13	11.74	0.34
SYTNH 0.45 w/cm	0.87	0.81	-2.15	0.16
SYNTH+PC 0.45 w/cm	0.61	0.52	11.57	0.33
WROS 0.53 w/cm	0.82	0.73	3.30	0.23
WROS 0.41 w/cm*	0.79	-	-	-

*There was limited data for this trendline.

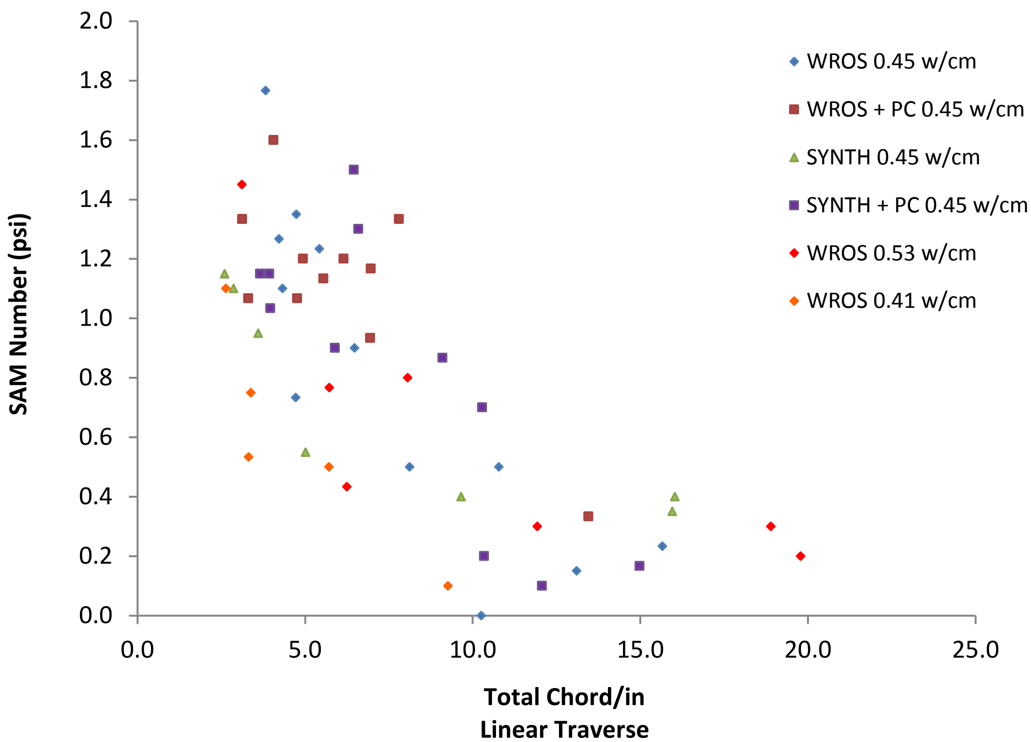


Figure 15: A comparison of the frequency of total chords versus the SAM number.

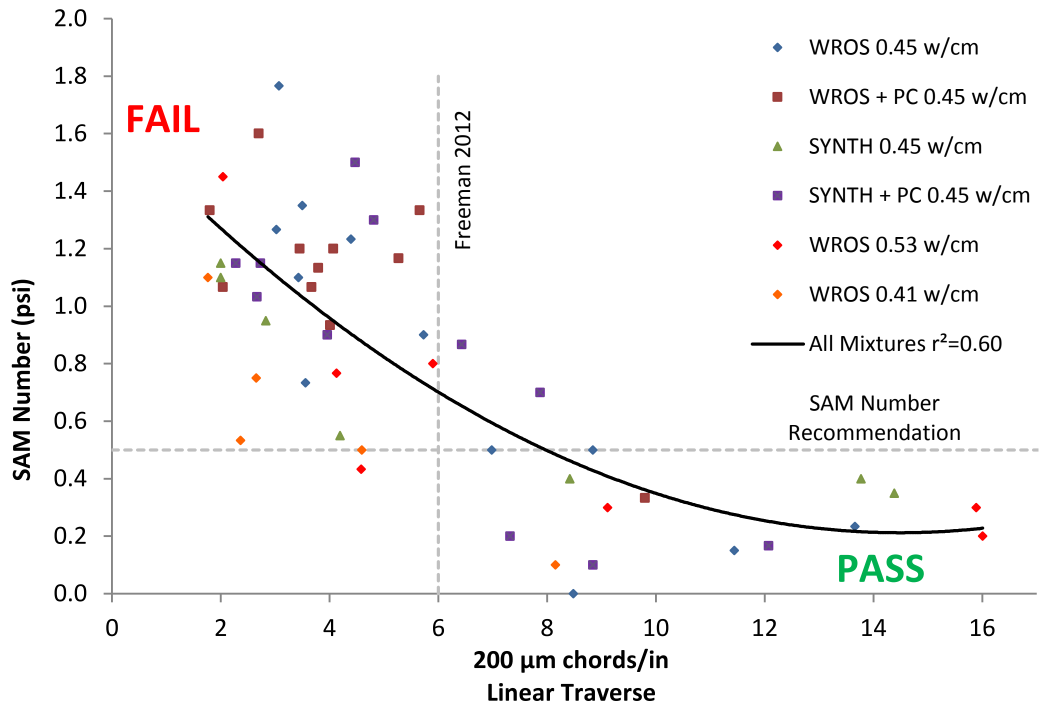


Figure 16: A comparison of the frequency of -200 µm chords versus the SAM number.

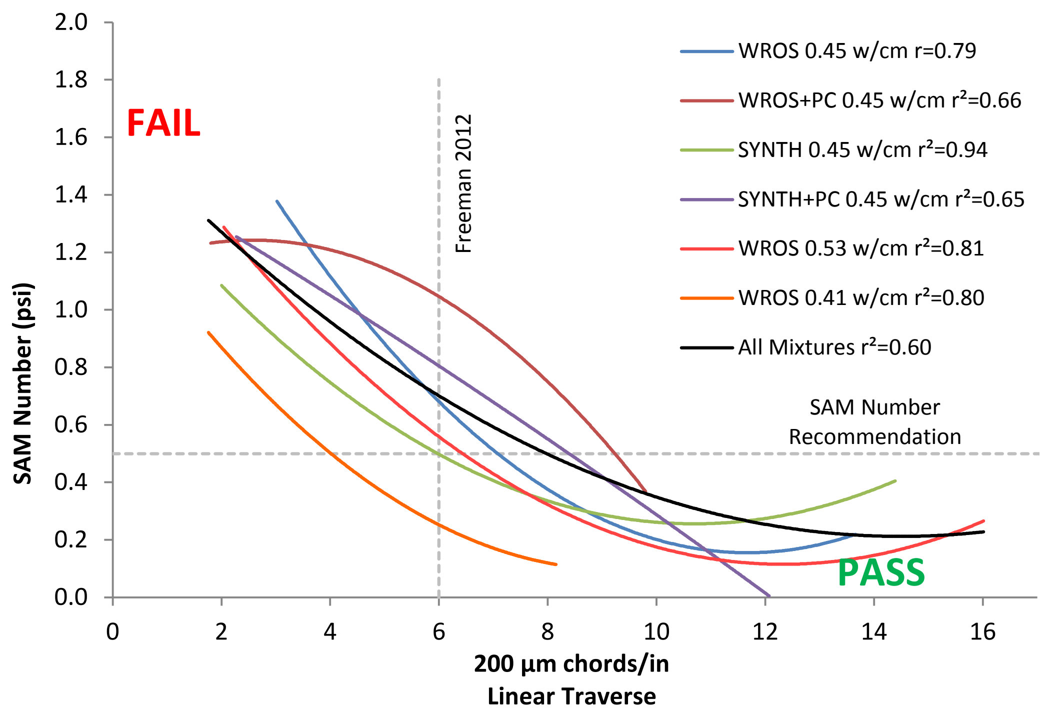


Figure 17: A comparison of the frequency of -200 µm chords versus the SAM number with quadratic trend lines.

Table 14: Quadratic model of the frequency of -200 μm chords versus the SAM Number.

Mixture	Statistical Parameter			
	r^2	Adjusted r^2	Akaike information criterion	σ
All Mixtures	0.60	0.58	25.82	0.29
WROS 0.45 w/cm	0.79	0.74	6.12	0.26
WROS+PC 0.45 w/cm*	0.66	0.57	1.01	0.21
SYTNH 0.45 w/cm	0.94	0.91	-7.32	0.11
SYNTH+PC 0.45 w/cm	0.65	0.56	10.56	0.32
WROS 0.53 w/cm	0.81	0.72	3.56	0.23
WROS 0.41 w/cm*	0.80	-	-	-

*There was limited data for this trendline.

Statistical Analysis

A statistical analysis was used to determine the best model that describes the relationship between the SAM and the individual hardened air parameters. The statistical parameters coefficient of determination, adjusted coefficient of determination, standard deviation, and Akaike information criterion were considered in determining the best model for the data collected. The model with an r^2 and Adjusted r^2 value nearest to 1.0 and an AIC with the lowest algebraic value and a σ value nearest to 0.0 were chosen to represent the data. Where the SAM number is compared to spacing factor the model chosen to represent the “All Mixtures” data set was a quadratic model. The comparisons of SAM number to specific surface and -200 μm chord frequency were similarly analyzed and the model chosen to represent both of these data sets was a quadratic model. The results from this analysis are included in the appendix of this document.

Multiple SAM Testing

Table 15 shows testing results from two similar SAMs on WROS 0.45 w/cm mixture tested simultaneously. Two dosages of AEA were tested; the first mixture contained a small dosage of WROS and the second mixture contained a larger dosage.

For each dosage two SAMs were used and each SAM was tested on two samples of concrete.

Table 15: A comparison of two SAMs and two opperators completed on the same mixtures with WROS AEA and 0.45 w/cm.

Sample	SAM Air (%)			
	Meter A	Meter B	Abs. Diff.	% Diff.
1a	1.92	2.14	0.22	10.8
1b	1.85	2.06	0.21	10.7
2a	7.51	7.51	0.00	0.0
2b	6.53	6.90	0.37	5.5

Sample	SAM Number (psi)			
	Meter A	Meter B	Abs. Diff.	% Diff.
1a	1.00	0.90	0.10	10.5
1b	0.95	1.15	0.20	19.0
2a	0.35	0.20	0.15	54.5
2b	-0.25	-0.10	0.15	85.7

Both SAMs resulted in similar SAM air content for the tests while the SAM numbers for each test differed at most by only 0.20 psi between both meters.

CHAPTER 5 - DISCUSSION

Each of the three hardened air parameter analyzed shows an increase in air void system quality as the SAM number decreases. The statistical analysis best fit model of the three hardened air void parameter for all mixtures were individually chosen to represent the corresponding hardened parameter. A quadratic trend line was used to fit the spacing factor, specific surface, and voids -200μm as it performed the best in the statistical analysis. This model was a nice balance of complexity and accuracy.

Spacing Factor

The data showed that a SAM number of 0.50 psi is recommended to achieve the spacing factor limit set by ACI 201 of 0.008”. For each mixture type, except the 0.45 WROS + PC mixture, data points were well distributed over a typical range of spacing factors. If the ACI 201 spacing factor limit of 0.008” and the corresponding SAM number of 0.50 psi is used then only 6.4% of the data points fall in a region in which they either pass the SAM test but fail the ACI 201 spacing factor limit, or fail the SAM test but pass the ACI 201 spacing factor limit. This also provides a safety factor for the measurement. The positive agreement between this model and the data suggests that the SAM number is an accurate measure of the spacing factor of the concrete and therefore a good indication of the quality of the air void distribution.

Most mixture trend lines in Figure 12 are similar in shape and position. One exception is the WROS 0.41 w/cm mixture. The trend line for this mixture is shifted downward by approximately 0.35 psi on the y-axis when compared to the other mixtures. This suggests that a lower SAM number may be necessary for a 0.41 w/cm mixture compared to the 0.45 and 0.53 w/cm mixtures. This difference is likely due to the low slump of the mixture and therefore the higher plastic yield stress of the mixture. It is possible that the overpressure supplied by the meter is not able to as effectively compress the air voids in the mixture. Despite the trend line being offset from the others the data was still well behaved. This is encouraging and further work is needed to better understand the performance of these mixtures.

Specific Surface

A SAM number of 0.30 psi is required to achieve a specific surface of 600 in^{-1} for most mixtures. However the mixture containing only AEA and a 0.45 w/cm required a SAM number of 0.70 psi. If the values of 0.30 psi and 600 in^{-1} are used as limits then 19.1% of the data points fall in a region in which they either pass the SAM test but fail the ACI 201 limit or fail the SAM test but pass the ACI 201 limit. If the recommended SAM number is adjusted to 0.50 psi then only 12.3% of the data fall in a region in which they either pass the SAM test but fail the ACI 201 limit or fail the SAM test but pass the ACI 201 limit. This adjustment is less conservative with respect to specific surface but using a 0.30 psi limit on the SAM number was found to be too rigorous with respect to spacing factor. In addition it is most common to use the spacing factor to evaluate the frost durability of hardened concrete. The coefficients of determination show more variance in the data when the SAM number is compared to specific surface than spacing factor as seen in Tables 12 and 13. It is not clear why this is occurring.

Chords per Inch

It was determined by Freeman (2012) that when the frequency of -200 μm chords for a hardened concrete sample is greater than 6.0 then that sample contained a sufficient quality of the air void distribution. For the data collected this limit is met when the SAM number is less than 0.50 psi except for the 0.41 w/cm WROS mixture. A SAM number of 0.30 psi is required to satisfy Freeman's limit for a 0.41 w/cm WROS mixture. For each mixture type, except the 0.45 WROS + PC mixture, data points were well distributed over a typical range of frequency of -200 μm chords. If Freeman's limit of 6.0 and the corresponding SAM number of 0.50 psi is used then only 8.5% of the data points fall in a region in which they either pass the SAM test but fail Freeman's limit or fail the SAM test but pass Freeman's limit. Comparing the SAM number to the frequency of -200 μm chords is another indication that the SAM number is an accurate measure of the quality of the air void distribution.

Test Method Repeatability

Table 15 showed very little difference in the SAM air content and SAM number between both meters even though both meters had different operators. There was at most a 10% difference in SAM air contents and a standard deviation of no more than 0.14 psi in the SAM numbers. This suggests that the results are repeatable and not operator dependent. The results from Figures 12, 14, and 17 also have high r^2 values despite the variability that already exists in the data from hardened air void analysis. For mixtures with low SAM numbers there exists a large variability in the SAM number. This is because of the accuracy of the digital pressure gage used to measure the equilibrium pressures during the test. The mixtures with low SAM number tend to have a larger volume of air, which results in a larger drop in pressure from the initial pressures to the equilibrium pressures. The mixtures with high SAM numbers tend to have lower volumes of air in the concrete samples, which result in a smaller drop in pressure to reach equilibrium. The percent difference is larger because the values measured are also larger. The absolute difference between the two SAMs was on average 0.15 psi for both large and small SAM number and the 0.1 psi accuracy is cause for the larger percent differences at the lower pressures.

Practical Implications

The SAM has been shown to be able to accurately predict the quality of an air void system in fresh concrete. The SAM is a simple and inexpensive device that can be used in the field to predict the quality of an air void system within minutes on concrete mixtures. This device could be used to measure critical changes in the field such as before and after a paver or pumping. This data will provide critical information not previously possible. The SAM can also be utilized in a laboratory to evaluate any number of mixtures with varying mixture materials and proportions, water to cement ratios, and admixture combinations and dosages. Care should be taken when applying the SAM test method and data to mixtures that differ from those investigated in this paper. While over 50 concrete mixtures were investigated for this work more is needed to validate the performance. For all the mixtures investigated a SAM number of 0.50 psi seems to correlate with a spacing factor of 0.008". However, if meters with chambers of different proportions or if a different series of pressures are used then this may change the results. Furthermore, concrete mixtures with a high yield stress and high viscosity were shown to impact the readings made with the device. This needs to be further investigated.

CHAPTER 6 – CONCLUSION

This work has outlined an innovative test method for measuring the quality of the air void system in fresh concrete called the SAM. The meter was shown to be able to measure total air content as outlined by ASTM C 231. The average percent difference between these measurements is 5.5% for over 100 samples. This is an outstanding correlation. Also, the meter uses a set of higher pressure steps to measure the air void quality of the concrete. The output of the meter or SAM number has shown to correlate well with the spacing factor, specific surface, and void frequency as measured by ASTM C 457. A quadratic curve fit has shown to be the best for all of the parameters investigated. For the data collected a SAM number of 0.50 psi or less was shown to be a good recommendation to produce concrete with a spacing factor of 0.008". This is suggested to provide freeze thaw resistant concrete by ACI 201.
It was observed that the mixtures with a very low slump (0.25" to 1") showed an offset in the performance to the other mixtures of slumps greater than 2". This needs to be further investigated.

Further laboratory testing should be done with the SAM should be further tested in the laboratory to better understand the mechanisms behind the results. Field tests should be performed using the SAM so that higher quality concrete can be ensured for concretes in a freeze thaw harsh environment. In addition SAMs should be used by a number of labs to find the inter laboratory precision. Furthermore, the SAM should be pursued as a standard test method that can be used for quality control in field applications. The test provides a relatively inexpensive manner to immediately determine the quality of the air void system in fresh concrete. This is a great benefit to the construction industry.

CHAPTER 7 – FUTURE WORK

While a useful test has been produced by this work there are several improvements that can still be made. These include reducing the time and steps required in the test. Furthermore more work is needed for this test to be evaluated by different laboratories, and by concrete mixtures in the field. Some of this work is ongoing and will be reported in future publications.

REFERENCES

1. Powers, T.C., “Void Spacing as a Basis for Producing Air-Entrained Concrete”, ACI Journal, Proc. V. 50, (1954) 741-760.
2. Powers, T.C., “Void Spacing as a Basis for Producing Air-Entrained Concrete”, ACI Journal, Part 2 Proc. V. 50, (1954) 760-6-760-15.
3. Backstrom, J.E., “The Air-void Systems of Highway Research Board Cooperative Concretes”, U.S. Department of the Interior Bureau of Reclamation, Concrete Laboratory Report No. C-824, April 6, 1956.
4. American Concrete Institute Committee 201, 2008, “Guide to Durable Concrete,” American Concrete Institute, Farmington Hills, MI, 49 pp.
5. Klieger, P., “Further Studies on the Effect of Entrained Air on Strength and Durability of Concrete with Carious Sizes of Aggregate”, Proceedings, Highway Research Board, 1956, PP. 16-17: Bulletin No. 77, Research and Development Laboratory, Portland Cement Association, Skokie, IL.
6. American Concrete Institute Committee 318, 2011, “Building Code Requirements for Structural Concrete and Commentary,” American Concrete Institute, Farmington Hills, MI, 503 pp.
7. Freeman, J.M., “Stability and Quality of Air Void Systems in Concretes with Superplasticizers”, Thesis, Oklahoma State University, Stillwater, OK, 2012.
8. Felice, R., “Frost Resistance of Modern Air Entrained Concrete Mixtures”, Thesis, Oklahoma State University, Stillwater, OK, July 2012.
9. Pigeon, M., and Pleau, R., “Durability of Concrete in Cold Climates”, E&FN Spon, London, 1995.
10. Ley, M. T., “Effects of Fly Ash on the Ability to Entrain and Stabilize Air in Concrete”, Dissertation, University of Texas at Austin, August 2007a.
11. ASTM C231, 2004, “Standard Test Method for Air Content for Freshly Mixed Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

12. ASTM C457, 2012, “Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.
13. Hover, K., “Analytical Investigation of the Influence of Air Bubble Size on the Determination of the Air Content of Freshly Mixed Concrete,” Cement, Concrete, and Aggregates, CCAGDP, Vol. 10, No. 1, Summer 1988, pp. 29-34.
14. ASTM C150, 2011, “Standard Specification for Portland Cement,” American Society for Testing and Materials, West Conshohocken, Pennsylvania.
15. ASTM C33, 2013, “Standard Specification for Concrete Aggregates,” American Society for Testing and Materials, West Conshohocken, Pennsylvania.
16. ASTM C260, 2010, “Standard Specification for Air-Entraining Admixtures for Concrete,” American Society for Testing and Materials, West Conshohocken, Pennsylvania.
17. ASTM C494, 2005, “Standard Test Method for Chemical Admixtures for Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.
18. ASTM C143, 2003, “Standard Test Method for Slump of Hydraulic Cement Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.
19. Jakobsen, U.H., Pade, C., Thaulow, N., Brown, D., Sahu, S., Magnusson, O., De Buck, S., and De Schutter, G., “Automated air void analysis of hardened concrete – a around robin study”, Cement and Concrete Research, Vol. 36, pp. 1444-1452, 2006.
20. Peterson, K., Sutter, L. and Radlinski, M., “Practical Application of a Flatbed Scanner for Air-Void Characterization of Hardened Concrete,” J. ASTM Intl., Vol. 6, No. 9.
21. Ramezanianpour, A. M., & Hooton, R. D. (2010). “Evaluation of Two Automated Methods for Air-Void Analysis of Hardened Concrete. Journal of ASTM International, 7(2), Retrieved from http://www.astm.org/DIGITAL_LIBRARY/JOURNALS/JAI/PAGES/JAI102476.htm

22. ASTM C138, 2013, “Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete”, American Society for Testing and Materials, West Conshohocken, Pennsylvania.
23. CSA A23.2-09 “Test Methods and Standard Practices for Concrete”, Canadian Standards Association, Toronto, Canada. 2009.

APPENDIX

Tables 16, 17, and 18 summarize the statistical information determined by the software used for the “All Mixtures” data set comparing the three hardened parameter to the SAM number. The same model that was chosen to represent the “All Mixtures” data sets for each of the three hardened parameters was also used to represent the individual mixtures.

Table 16: Statistical output of different models and parameters when comparing all of the mixtures spacing factor and SAM results.

Model	Statistical Parameter			
	r^2	Adjusted r^2	Akaike information criterion	σ
Linear	0.56	0.55	28.2	0.30
Quadratic	0.61	0.60	23.6	0.29
Cubic	0.62	0.60	24.7	0.29
4th Order Polynomial	0.64	0.60	24.4	0.29
Weighted Linear	0.65	0.65	25.4	100.62
Weighted Quadratic	0.65	0.64	27.1	101.35
Weighted Cubic	0.69	0.68	22.5	96.20
Weighted 4th Order Poly.	0.71	0.68	22.6	95.46
Log-Log Linear	0.33	0.32	61.3	0.42
Log-Log Quadratic	0.33	0.31	63.3	0.42
Box-Cox (x)	0.59	0.58	25.1	0.30
Box-Cox (y)	0.57	0.56	39.3	0.34
Robust Linear	NA	NA	28.2	0.31
Robust Quadratic	NA	NA	23.6	0.28
Robust Cubic	NA	NA	24.8	0.29
Robust 4th Order Polynomial	NA	NA	24.4	0.26
Robust Weighted Linear	NA	NA	25.5	103.95
Robust Weighted Quadratic	NA	NA	27.3	101.52
Robust Weighted Cubic	NA	NA	22.6	102.30
Robust Weighted 4th Order Poly.	NA	NA	22.7	95.81

Table 17: Statistical output of different models and parameters when comparing all of the mixtures specific surface and SAM results.

Model	Statistical Parameter			
	r^2	Adjusted r^2	Akaike information criterion	σ
Linear	0.47	0.46	37.9	0.33
Quadratic	0.48	0.46	38.8	0.33
Cubic	0.50	0.47	38.9	0.33
4th Order Polynomial	0.51	0.46	40.5	0.33
Weighted Linear	0.40	0.39	41.9	0.00
Weighted Quadratic	0.40	0.37	43.9	0.00
Weighted Cubic	0.41	0.38	44.5	0.00
Weighted 4th Order Poly.	0.41	0.36	46.5	0.00
Log-Log Linear	0.36	0.35	36.2	0.33
Log-Log Quadratic	0.36	0.34	38.1	0.33
Box-Cox (x)	0.47	0.46	37.7	0.33
Box-Cox (y)	0.48	0.47	47.8	0.37
Robust Linear	NA	NA	37.9	0.35
Robust Quadratic	NA	NA	38.9	0.35
Robust Cubic	NA	NA	39.0	0.32
Robust 4th Order Polynomial	NA	NA	40.6	0.31
Robust Weighted Linear	NA	NA	41.9	0.00
Robust Weighted Quadratic	NA	NA	43.9	0.00
Robust Weighted Cubic	NA	NA	44.6	0.00
Robust Weighted 4th Order Poly.	NA	NA	46.7	0.00

Table 18: Statistical output of different models and parameters when comparing all of the mixtures chords -200µm and SAM results.

Model	Statistical Parameter			
	r^2	Adjusted r^2	Akaike information criterion	σ
Linear	0.54	0.53	30.2	0.31
Quadratic	0.60	0.58	25.8	0.29
Cubic	0.62	0.60	24.2	0.29
4th Order Polynomial	0.64	0.61	23.3	0.28
Weighted Linear	0.34	0.33	42.9	0.11
Weighted Quadratic	0.35	0.32	44.8	0.11
Weighted Cubic	0.38	0.34	44.1	0.11
Weighted 4th Order Poly.	0.38	0.33	46.0	0.11
Log-Log Linear	0.33	0.32	61.5	0.42
Log-Log Quadratic	0.33	0.31	63.1	0.42
Box-Cox (x)	0.56	0.55	28.7	0.31
Box-Cox (y)	0.56	0.55	41.7	0.35
Robust Linear	NA	NA	30.3	0.31
Robust Quadratic	NA	NA	25.9	0.29
Robust Cubic	NA	NA	24.3	0.28
Robust 4th Order Polynomial	NA	NA	23.3	0.26
Robust Weighted Linear	NA	NA	42.9	0.09
Robust Weighted Quadratic	NA	NA	44.9	0.09
Robust Weighted Cubic	NA	NA	44.1	0.08
Robust Weighted 4th Order Poly.	NA	NA	46.0	0.08