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STUDYING AIR PROPERTIES IN HARDENED PORTLAND CEMENT CONCRETE WITH LINEAR TRAVERSE METHOD

By

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STUDYING AIR PROPERTIES IN HARDENED PORTLAND CEMENT CONCRETE WITH LINEAR TRAVERSE METHOD

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ABSTRACT

Air void structure in hardened concrete is critical to its durability. This project mainly focuses on investigating the air void system in hardened concrete with the microscopic analysis Linear Traverse Method specified by ASTM Specification C457-08 (Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete).

To understand the stability of the air void system in concrete, the same concrete mixes were examined with two other methods, pressure meter measurement and Air-Void Analyzer, under fresh state. The comparison of the results from the three methods for fresh and hardened concrete shows that properties of concrete vary in samples within the same batch with the same mix design, samples in different batches of the same mix design and samples with different mix designs. The measured air content from Linear Traverse Method and pressure meter are fairly close to each other, while Air-Void Analyzer measured air content is observed to be lower than that from Linear Traverse Method. The measured spacing factor from Air-Void Analyzer is observed to be higher than that from Linear Traverse Method, while the measured specific surface from Air-Void Analyzer is observed to be lower than that from Linear Traverse Method. However, no strong correlation in the measured air content and measured specific surface between Linear Traverse and Air-Void Analyzer is observed.

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NOMENCLATURE

A	-	Air Content, in %
n	-	Void Frequency (Voids per Inch)
l	-	Average Chord Length (Average Chord Intercept)
α	-	Specific Surface
p	-	Paste Content, in %
p/A	-	Paste-Air Ratio
$\bar{L}$	-	Spacing Factor

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I. INTRODUCTION

A. Background

Concrete is a composite material, which consists of cement, water, sand and coarse aggregates. Hardened concrete is always porous in some extent, due to the air voids produced during mixing and handling of the fresh concrete. The porosity of concrete varies due to the differences in the process of mixing and curing (Powers 1978). To manipulate the uniformity and quality of concrete, all the operational processes, such as mixing, transporting, conveying, placing, consolidation and curing, have to be controlled (Smith 1978). Simply maintaining the total air in concrete does not guarantee its strength and freeze-thaw durability. Research has shown that the engineering properties of concrete, including strength, durability and permeability can be highly influenced by the air void system present in hardened concrete (Verbeck 1978). Therefore, it is important to understand the structure of the air void system.

According to the ASTM Specification C457-08, air voids are defined as empty spaces enclosed by the cement paste and are either filled with air or other gases before the cement paste is set (ASTM C457 2008). The structure of the air void system in concrete can be represented by the volume of air voids, air void sizes and shapes, spacing factor and specific surface. The air void system may be altered and air content may be affected due to different factors including temperature, mixing, transportation, consolidation, and curing, the properties of voids may change, which may lead to the loss in strength and durability of concrete. Research has been devoted to the importance of air content and structure of air void system in concrete performance. With the same air content in the concrete, the larger the size of air voids, the larger the spacing factor and the smaller specific surface, and therefore the lower the freeze-thaw resistance and strength (Du and Folliard 2005).

Air voids can be divided into three categories, which are entrapped air, entrained air and capillary air, and they can be recognized by the size and shape:

1. Capillary air voids are the smallest of the three with diameter smaller than 5 micrometers. It is not easy to observe the capillary air voids visually due to their small size, and they are not considered as part of the air void system. They are irregular shaped spaces initially filled by mixing water, and they remain as air voids after the hydration of the cement paste.
2. Entrained air voids are larger than the capillary voids, with diameter less than 1 millimeter, and are spherical in shape. They are the result of the addition of air-entraining agent, which is admixture to stabilize the air bubbles.
3. Entrapped air bubbles have the largest size among the three, with 1 millimeter or larger in diameter. They are by-products of the process of mixing and placing, and can be irregular or spherical in shape. They are usually spaced farther apart and distributed unevenly throughout the concrete samples (Walker 2004).

The difference in size and shape between entrapped and entrained air can be distinguished in FIGURE 1, where the capillary air voids are too small to be captured by the camera. Both the entrapped and entrained air play very important roles in increasing the workability in fresh concrete. The air bubbles perform as some air cushions to highly decrease the friction between the aggregates and allow the fresh concrete mix to be placed more easily. With the workability increases, the water content can possibly be decreased which results in reduction of segregation and bleeding (Stiltner 2001). Segregation usually results from increase in coarse aggregates, too low or too high of the water content, and decrease in cement content. Bleeding is the migration of water to the surface due to sedimentation of solid particles. Both segregation and bleeding can be destructive and can cause the concrete not developing the required strength (Tattersall 1991).

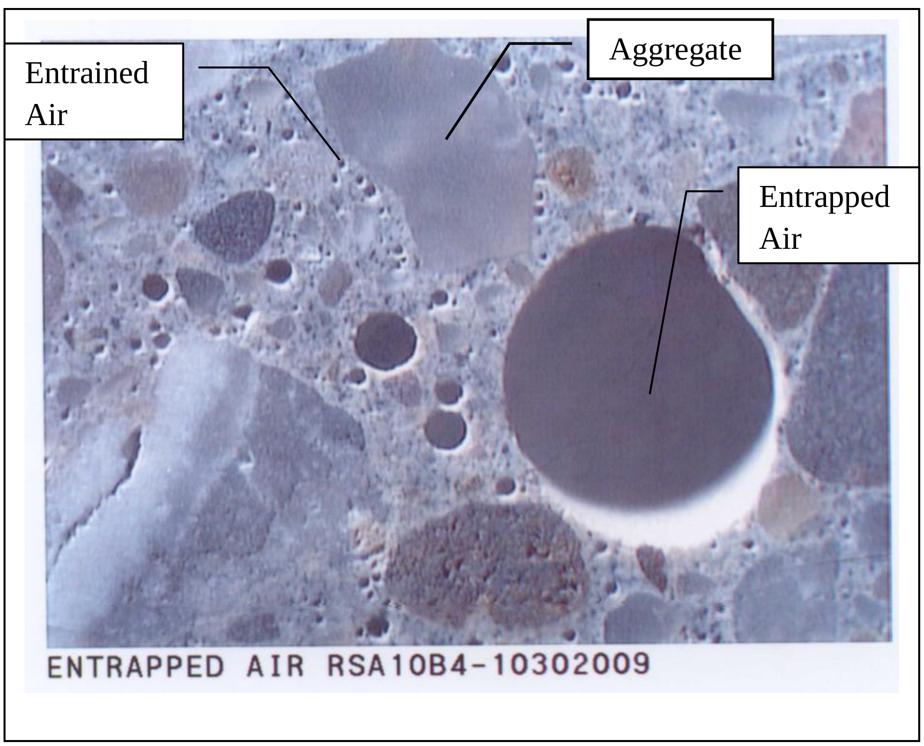


FIGURE 1 – Entrapped and Entrained Air in RSA10 B4

Besides increasing the workability of concrete mix, entrained air also plays an important role in increasing the durability and freeze-thaw resistance of concrete. As the hardened concrete is always porous in some extent, moisture from the environment can easily penetrate through it and stay in the empty spaces within the concrete structure. When water freezes and becomes ice, the volume increases. The increase in volume, in each freeze-thaw cycle, results in tensile stresses within the concrete structure that exceed the low tensile capacity of concrete. To relieve the tensile stresses, micro-cracks are created within the concrete structure. During the thawing period of the freeze-thaw cycle, more moisture penetrates through the concrete structure. The micro-cracks are cyclical damage that repeats until the concrete structure can take no more tensile stress and breaks down. To reduce this degrading phenomenon and extend the life of the concrete structure, air-entraining admixtures (AEA) are critical to stabilize the air bubbles. With the entrained air bubbles below 91.7 percent saturated with water, water can escape and have enough space to expand within the bubbles as it is freezing and becoming ice. According to previous research, with the same water-cement ratio in the concrete, non-air-entrained concrete can only survive about one-fifth of the freeze-thaw cycles of air-entrained concrete (Kosmatka et al. 2002).

To maintain the degree of workability and uniformity of concrete, it is important to control the total air content in the concrete. However, the larger-sized entrapped air bubbles produced from mechanically mixing of concrete tend to be lost during mixing. The mixing action allows the bubbles to integrate and form bubbles larger in size. The larger buoyancy forces increase the tendency of the larger bubbles to float to the surface of the concrete and vanish from the mix, while the buoyancy forces of the smaller bubbles allow the yield stress of cement paste to prevent the bubbles from escaping

(Powers 1968). Due to the disappearance of some of the air bubbles from the fresh concrete, it is understandable that the air content of the fresh concrete is always higher than that of the hardened concrete. To allow the air bubbles to function efficiently in the concrete mix, AEA are used. AEA's do not produce or generate air, instead AEA's stabilize the air bubbles present in the concrete mix (Kosmatka, Kerkhoff and Panarese 2002). Since the large entrapped air bubbles may vanish from the mix due to their buoyancy, and therefore the entrained air bubbles take the lead in controlling the performance of concrete. With the entrained air bubbles stabilized in the concrete, the desired air content can be maintained. Due to the small size of the entrained air bubbles, the desired spacing factor and specific surface can also be maintained.

As specified in ASTM Specification C457, the amount of air content required for the desired durability varies between 1.5% to 7.5%, depending on the severity of exposure and the maximum size of aggregates used. Other than the total air content in the concrete, the importance in the spacing factor and the specific surface has to be addressed. The spacing factor is considered as the most influential factor to the durability of concrete, expressing the farthest distance from any point of the paste to the edge of an air void. ASTM Specification C457 specifies the range of the spacing factor to be between 0.10mm and 0.20mm to maintain the freeze-thaw durability of the concrete. The specific surface is the total surface area of the air voids divided by their total volume. According to the ASTM Specification C457, the specific surface of air voids should be kept within the range of 23.6mm^{-1} to 43.3mm^{-1} to ensure the freeze-thaw durability of the concrete. The finer air void system has a higher value of specific surface. The specific surface can be used to compare the average size of the air voids between samples, but not the actual number of air voids with a specific size in a particular sample (Aligizaki 2006).

B. Research Objectives

The current quality control methods for concrete testing, pressure meter measurement and Air-Void Analyzer (AVA), are for fresh concrete. Due to the hydration of cement, microstructure of concrete changes a lot as the concrete sets and ages, which may lead to changes of air volume and air void sizes. Thus, to guarantee the life-time performance of concrete, it is important to make sure its air void system is stable enough to provide hardened concrete with sufficient air volume and good air void size distribution. This leads to the objective of this thesis, which is to investigate the air void system in hardened concrete with Linear Traverse Method (LTM) (ASTM C475-08). To evaluate the stability of the air void system in concrete, the obtained LTM results were then compared with the results obtained with pressure meter and AVA for the same concrete in fresh state.

By developing a correlation between the air void system in concrete under fresh state and air void system in hardened concrete, a better specification of the air void system in concrete under fresh state can be established.

II. EQUIPMENT

FIGURE 2 - Testing Room Environment with All Equipments

A. CAS-2000

The software and apparatus used for the analysis of LTM was Concrete Analysis System-2000 (CAS-2000) Version 3.3 by Princeton Economics Inc.

The software of CAS-2000 used the ASTM equations, as listed in APPENDIX 1, to determine the properties of the air void system of the concrete samples. The software CAS-2000 created standard reports listing all the parameters and void size distribution for individual LTM experiment, and all the 24 standard reports for this thesis are shown in APPENDIX 2 as the CAS-2000 Data Sheets.

The entire set up of the apparatus of CAS-2000 is shown in FIGURE 3. The apparatus includes a motorized platform with two 5.1-volt 1.6-amp Type 23T2BEHH HY Sync® AC Synchronous/DC Stepping Motors by Bodine Electric Co. The sample can be placed on the platform, and the two motors with motor number of 241OUN6140 and 241OUN6004 provide movement of the platform in the east-west and north-south direction respectively. The "START" and "STOP" buttons, speed control knob and number pad located on the apparatus can be used to control the movement of the platform and tally test data (Stiltner 2001).

B. Computer

The software of CAS-2000 is pre-installed in a Swan Technologies 486-SX computer. The software saves all the data files automatically under the subdirectory called "DATA" in the hard-disk of the computer once created. To open up files in another computer or to obtain hardcopy of the reports, the data files have to be saved in a floppy disk and transferred to another computer, since the computer is not connected to an external printer or the internet.

C. Light Source

Fiber optic light source is set up right next to the CAS-2000 platform to provide illumination at low angle of incidence. All other light source in the testing room has to be diminished to maximize the efficiency of the optic light source. With the shadows of the air voids created from the concentrated light, the air voids in the sample can be distinguished from the aggregates easily under the microscope. The distinction can be seen in FIGURE 1.

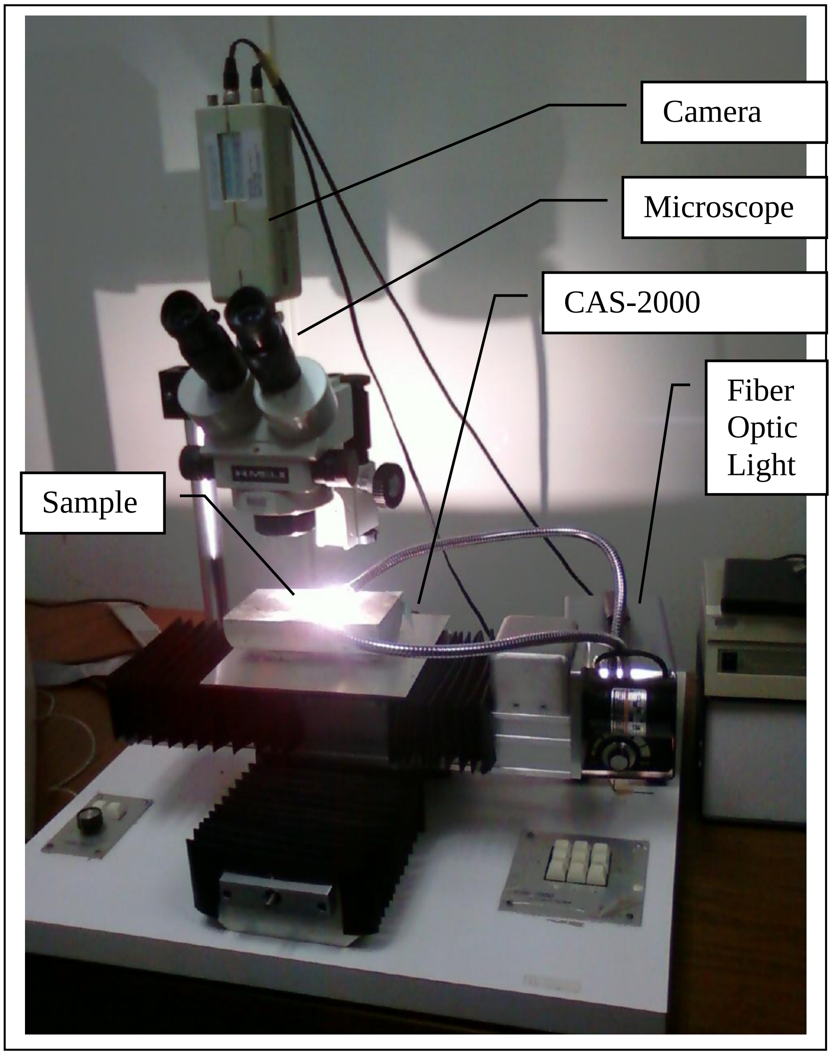


FIGURE 3 – CAS-2000, Microscope, Camera and Fiber Optic Light Source

D. Microscope and Camera

The microscope used is a Meiji EMZ-TR stereo microscope with Serial Number 41045 manufactured by the Meiji Techno Corporation, Ltd. The microscope is set up by attaching a Javeline Electronics Chromachip V CCTV camera with Model Number of JE3662HR and Serial Number of 2000597.

E. Monitor and Printer

The camera is connected to a Sony Trinitron color video monitor with Model Number PVM-1343MD and Serial Number 2021157. The image of the sample under the microscope is transferred to the monitor, with the crosshairs generated by using a Boeckeler VIA-30 video crossline generator. The image of the sample can be printed out with the Sony Mavigraph color video printer, with Model Number UP-220 and Serial Number 14610, connecting to the monitor.

FIGURE 4 – Video Monitor and Printer

III. EXPERIMENTAL PROCEDURE

A. Linear Traverse Method

According to ASTM Specification C457-08, LTM is a one-dimensional analysis to determine the volumetric composition of the concrete, including the volume of paste and the volume of air void. It sums up the distances traversed across the observation surface of a concrete sample along a series of equally spaced straight lines, as illustrated in FIGURE 5. As the line is traversed, the total length traversed (T_t), the length traversed through the air voids (T_a) and the length traversed through cement paste (T_p) is tallied. The total number of air voids intersected by the traverse line (N) is also recorded. With the series of data collected, a series of values are calculated with the list of equations provided by the ASTM Specification C457-08, shown in APPENDIX 1. The values are important in the determination of the stability of the air void system (Stiltner 2001).

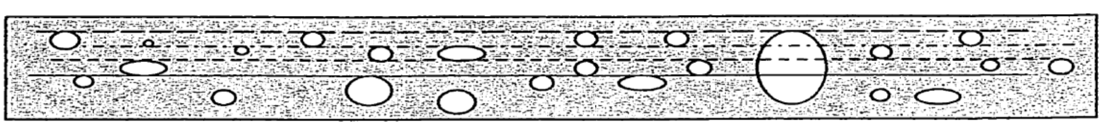


FIGURE 5 – Illustration of Different Traverses (Stiltner 2001)

Air content in % (A) and paste content (p) are calculated as the percentage of the air voids and the percentage of the hardened cement paste in the total volume of the concrete mix respectively. Average chord length or Average Chord Intercept (l) is the average length that the line of traverse intercepting the air voids. Paste-Air ratio (*p/A*) is calculated as the ratio of the volume of hardened cement paste to the volume of air voids in the concrete. Spacing factor ($\bar{L}$) is the length of the maximum distance between the peripheries of air voids in the cement paste. Void frequency (*n*) is the number of air voids intercepted by a traverse line divided by the length of that line, which can also be defined as the voids per unit length of traverse. Specific surface (α) is the surface area of the air voids divided by the volume of the air voids (ASTM C457 2008).

B. Samples Preparation

The concrete samples to be observed were obtained from concrete cylinders cast in the laboratory and job sites. The concrete cylinders were cast in size of 4”x8”. The minimum size of the observation surface is specified in ASTM C475-08, as shown in TABLE I. With the maximum size of aggregate in the concrete of this project being one inch, the total area of observation surface needed for the microscopic analysis is 12 in^2 (77 cm^2).

The observation surface was obtained in a few steps. To avoid segregation and bleeding due to the heavy and large-sizes aggregates, one inch from each end of the cylinders was cut off with a diamond blade saw. As stated in the ASTM Specification C457-08, the observation surface has to be approximately perpendicular to the layers in which the concrete was placed or perpendicular to the finished surface (ASTM C457 2008). The cylinders with about six inch in height were then sawed in half, with the observation surface perpendicular to the surface that the concrete was placed.

The dimensions of the rectangular observation surface obtained are about 4”x6”, which is about 24 in^2. During the analysis of LTM, the starting point was offsetting half inch from the two edges of the rectangular surface, and the actual area of the observation surface used were smaller than the area of the observation surface obtained. A sample of the prepared observation surface is shown in FIGURE 6, with showing the half-inch offset from the two edges and shaded area representing the actual observation surface for the analysis of LTM. The detail of the testing procedure is mentioned in Chapter III Part D (Testing Procedure) of this thesis.

During the analysis of LTM, it is important to distinguish air voids and aggregates, which can be easily confused with each other. To provide a suitable surface to recognize the two components with ease, the observation surfaces of the concrete samples have to be polished. The observation surface was polished on a vibratory table, with silicon carbide powder as abrasives and water as lubricant to obtain a smooth surface for the microscopic observation. The grinding action was started with the coarsest abrasives, and ended with the finest one. Graded abrasive with 150µm, 35µm and 17.5µm grit sizes (No. 100, 320 and 600 respectively) were used, and the sample was cleaned thoroughly after changing to a finer abrasive. The vibratory table used for the grinding processes is shown in FIGURE 7.

TABLE I
ASTM C457-08 MINIMUM AREA OF FINISHED SURFACE
FOR MICROSCOPIC MEASUREMENT

Nominal or Observed Maximum Size of Aggregate in the Concrete, mm (in.).	Total Area to be Traversed for Determination of α or $\bar{L}$, min, cm^2 ($in.^2$) Based on Direct Measurement of;	
	Total Air-Void Content	Paste-Air Ratio, *p/A*
150 (6)	1613 (250)	645 (100)
75 (3)	419 (65)	194 (30)
37.5 (1½)	155 (24)	97 (15)
25.0 (1)	77 (12)	77 (12)
19.0 (¾)	71 (11)	71 (11)
12.5 (½)	65 (10)	65 (10)
9.5(⅜)	58 (9)	58 (9)
4.75 (No. 4)	45 (7)	45 (7)

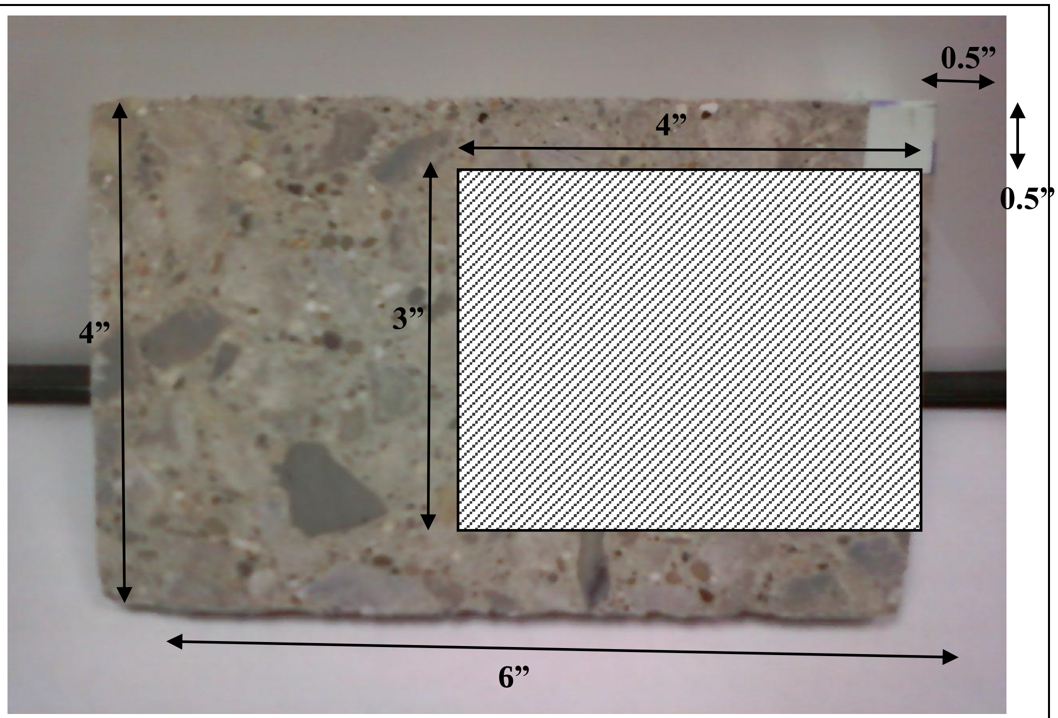


FIGURE 6 – Sample Surface and Shaded Area for the Analysis of LTM

FIGURE 7 – Vibratory Table with Abrasives and Water as Lubricant

C. Sample Placement

With the observation surface of the samples well prepared, the analysis of LTM could be started. Before each analysis started, the starting point was marked on the observation surface of the sample with a paper corner, offsetting half inch from the two edges of the rectangular surface, to ensure the same starting point for every analysis, can be seen at the upper right corner of the sample in FIGURE 6. The sample was then placed on the platform of the CAS-2000. Modeling clay was placed underneath to stabilize the sample, and the sample was leveled with placing a three-way level at two diagonals of the rectangular plane. Leveling the sample before each analysis ensures the least chance of re-focusing the microscope during analysis.

Once the sample was leveled, the fiber optic light source was adjusted to produce shadow of the air voids with a low angle incidence. All the other light sources in the testing room were diminished to ensure the concentrated light from the fiber optic light source was effective (Stiltner 2001). The LTM analysis could be started.

D. Testing Procedures

The LTM analysis was performed with the Concrete Analysis System 2000 (CAS-2000). The software of CAS-2000 was installed in the computer and could be opened up in the DOS screen. Once the CAS-2000 program was loaded, the main menu was brought up automatically as shown in FIGURE 8. In the main menu, “Linear Traverse” could be selected, and the main menu would be replaced by the “Linear Traverse” menu as shown in FIGURE 9.

On the “Linear Traverse” menu, a series of data needed to be entered. The fields for the “Originator”, “Operator”, “Date”, “Project Number”, “Sample ID” and “Notes” are all optional. The “File Name” field requires a valid MS-DOS file name to be entered, which consists of up to eight characters. Furthermore, the “x-axis length”, “y-axis length” and “Maximum Aggregate Size” were requested to be entered in inches. The “Maximum Aggregate Size” could be entered as the pre-defined letters (A through H) by ASTM

C457 listed in TABLE II, or a numeric entry could be entered for non-ASTM tests. With the “Maximum Aggregate Size” entered, the “Length of Traverse” and “Calculated Length for Y-Axis Increment” was calculated automatically as shown in TABLE II. The “Paste Volume in Percent” had to be entered, which was estimated based on the mix design in the range of 5.0% to 75.0%.

In this project, the maximum size of aggregate in the concrete was one inch, which is pre-defined as D by ASTM C457, and the total area of observation surface needed for the microscopic analysis is 12 in^2 (77 cm^2). Therefore, the “x-axis” and “y-axis” used was 4 inches and 3 inches respectively. The “Paste Volume in Percent” was entered as 27.11%, which was determined from the mix design. After all the data were entered, the “END” key was depressed to proceed.

TABLE II
ASTM C457-08 MINIMUM LENGTH OF TRAVERSE
FOR THE LINEAR TRAVERSE METHOD

Pre-defined Letter for Maximum Aggregate Size	Nominal or Observed Maximum Size of Aggregate in the Concrete, in. (mm)	Length of Traverse for Determination of α or $\bar{L}$, min, mm (in.)
A	6 (150)	4064 (160)
B	3 (75)	3048 (120)
C	1½ (37.5)	2540 (100)
D	1 (25.0)	2413 (95)
E	¾ (19.0)	2285 (90)
F	½ (12.5)	2032 (80)
G	⅜ (9.5)	1905 (75)
H	No. 4 (4.75)	1397 (55)

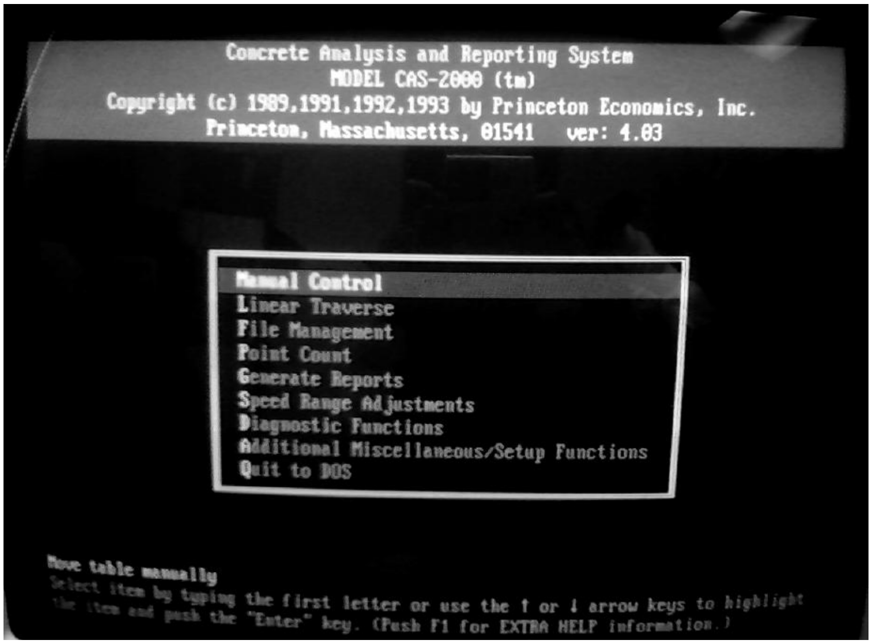


FIGURE 8 – Main Menu of CAS-2000

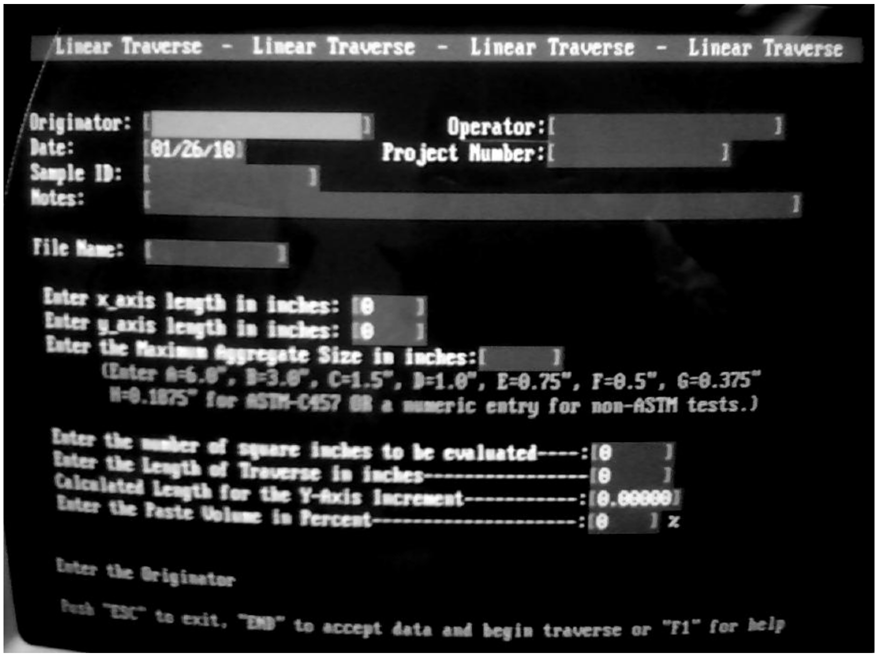


FIGURE 9 – Linear Traverse Menu of CAS-2000

Before the actual traverse started, the platform of the CAS-2000 could be adjusted using the arrow keys. The crosshairs were located at the starting point of the sample, which was marked on the observation surface with a paper corner offsetting half inch from the two edges of the rectangular surface. The focus of the microscope needed to be adjusted at this point. Throughout all the experiments, the magnification of the microscope was set to be 10X. The "ESC" key was then pressed to start the self-test of the CAS-2000 to guarantee a full range of motion throughout the experiment, and the traverse started.

The "START" button was depressed to start the motion of the platform. The speed control knob on the platform was used to adjust the speed of the platform. During the traverse, the "4" button on the numeric keypad must be held by the operator when the crosshairs moved over an air void, and released when the crosshairs passed through the air void completely. At the end of a section of the traverse line, the CAS-2000 would move the platform to the beginning of next section and the "START" button had to be depressed to start the traverse again. At the end of the line of traverse, the platform would stop automatically and the data collected could be saved.

E. Samples

The concrete samples were obtained from concrete cylinders cast in the laboratory and job sites. In the laboratory, the concrete cylinders were cast from three mix designs of concrete in the laboratory, including the Control mix with no admixture (C2), the mix with addition of AEA of Micro-air (RSA10), and the mix with addition of AEA of Vinsol

Resin (RVR15). For each mix design, there were three batches of mix (A, B and C). Concrete mixes sharing the same mix design were also from three different job sites, including from KY395 Overpass (KY395), and Jeptha Creek (J). There were a total of twelve batches of concrete mix with four different mix designs from the laboratory and job sites. All the four mix designs have the same total volume and the same volume of cement and water; thus, the same paste volume in percentage of 27.11% was used. All the mix designs of all batches are shown in TABLE III based on a volume of 3ft^3, and the concrete was mixed according to ASTM Specification C192.

There are a total of four mix designs and twelve batches. For each of the twelve batches, five cylinders were cast, three were used for the compressive strength test and two were used for LTM. For this project, the results from LTM were the main focus, and there are a total of 24 concrete cylinders used for the analysis of LTM.

F. Operating Condition

The working environment has to be comfortable for the operator during the analysis. To reduce the operator error, the analyses were performed at the same general time of day and no more than one test should be performed in a 24-hour period. With the testing room located in a building close to the railroad track, to ensure the accuracy, the analyses had to stop when a train was passing by to avoid locating the air void incorrectly due to the shake from the train.

TABLE III
MIX DESIGN OF CONCRETE SAMPLES FOR LTM

Sample ID		Cement (lb.)	Fly Ash (lb.)	Coarse Aggregates (lb.)	Fine Aggregates (lb.)	Water (lb.)	AEA (oz.)
C2	A4/ A5	34.92	0	101.89	68.21	15.04	0
	B4/ B5	34.92	0	101.89	68.21	15.04	0
	C4/ C5	34.92	0	101.89	68.21	15.04	0
RSA10	A4/ A5	31.31	0	91.35	60.64	13.99	0.35
	B4/ B5	31.31	0	91.35	60.64	13.99	0.35
	C4/ C5	31.31	0	91.35	59.64	15	0.35
RVR15	A4/ A5	31.31	0	91.35	60.64	13.99	0.35
	B4/ B5	31.31	0	91.35	60.64	13.99	0.35
	C4/ C5	31.31	0	91.35	59.64	15	0.35
RR	A4/ A5	25.65	5.66	92.2	62.87	9.75	0.53
KY395	A4/ A5	25.65	5.66	92.2	62.87	9.75	0.53
J	I4/ I5	25.65	5.66	92.2	62.87	9.75	0.53

IV. EVALUATION OF RESULTS

A. Presentation of Results

A total of 24 concrete samples were obtained from concrete cylinders cast in the laboratory and job sites. In the laboratory, three mix designs of concrete were used, including the Control mix with no air entrainment (C2), the mix with addition of AEA of Micro-air (RSA10), and the mix with addition of AEA of Vinsol Resin (RVR15). For each mix design in the laboratory, there were three batches of mix (A, B and C) and five cylinders were cast from each batch of mix. The first three cylinders cast from each batch were used for compressive strength tests, and the fourth and fifth cylinders were used for the analysis of LTM.

Samples were also obtained from three different job sites, including KY395 Overpass (KY395), R/R, and Jeptha Creek (J). In the three job sites, all the samples shared the same mix design based on Kentucky Transportation Cabinet (KYTC) with addition of synthetic air entrainment. Only one batch of mix was used in each of the job sites, and five cylinders were cast in each job site. A total of 15 cylinders were cast from the three job sites. Like the cylinders obtained from the laboratory, the first three cylinders cast from each batch were used for compressive strength tests, and the fourth and fifth cylinders were used for the analysis of LTM.

Each of the concrete samples was named beginning with the abbreviation of the mix design or the job site, followed by the batch of mix, and the last number is the number of cylinders cast from the batch. For example, in the laboratory, RSA10-A5 is the sample obtained from the fifth cylinder cast from Batch A of the mix design with addition of AEA of Micro-air (RSA10). In the job sites, KY395A4 is the sample obtained from the fourth cylinder cast from the job site of KY395 Overpass, and Batch A was the only batch.

The standard reports generated from the analysis of the LTM are shown in APPENDIX 2 (CAS-2000 Data Sheets). From the series of data collected from the LTM, a series of values were calculated, including Air Content in % (*A*), Average Chord Length or Average Chord Intercept (*l*), Void Frequency (*n*), Specific Surface (α), Paste Content in % (*p*), Paste-Air Ratio (*p/A*), and Spacing Factor ($\bar{L}$). With the LTM reports generated in English units, conversions of units were done to keep the consistency in the evaluation of results and all the results are in metric units.

The fresh concrete samples were also examined by using the test of AVA and pressure meter analysis. The air content, specific surface, spacing factor and other properties of the fresh concrete for each concrete mix were determined. The results from AVA test and pressure meter were recorded and used to compare with the results of the analysis of LTM.

1. <u>C2 (A4, A5, B4, B5, C4, and C5)</u>

Samples of Control 2 were obtained from the concrete cylinders of the mix with no air entrainment, with paste content of 27.11%. A total of three batches (A, B and C) were mixed for the same mix design. In the analysis of LTM, the total length of traverse and the area covered are 95 inches (2413 mm) and 11.5 square inches (7419.3 mm^2) respectively. All the results from the analysis of LTM for the samples of Control 2 are listed in TABLE IV and the sample of C2A5 is shown in FIGURE 10(a).

From the analysis of LTM, for Batch A, B and C of Control 2 respectively, the recorded average values of Air Content (*A*) are 0.935%, 1.505% and 1.615%, Average Chord Intercept (*l*) are 0.0167inch (0.424mm), 0.01345inch (0.342mm) and 0.011inch (0.279mm), Void Frequency (*n*) are 0.555in^{-1} (0.0219mm^{-1}), 1.12in^{-1} (0.0441mm^{-1}) and 1.47in^{-1} (0.0579mm^{-1}), Specific Surface (α) are 245.85in^{-1} (9.68mm^{-1}), 302.65in^{-1} (11.92mm^{-1}) and 364.35in^{-1} (14.34mm^{-1}), and Paste-Air Ratio (*p/A*) are 30.6, 18.385 and16.81, and Spacing Factor ($\bar{L}$) are 0.04195inch (1.066mm), 0.0276inch (0.701mm) and 0.0219inch (0.556mm).

The recorded values for Batch A, B and C were averaged to determine the overall average of Control 2, with the overall average Air Content (*A*) of 1.3517%, Average Chord Intercept (*l*) of 0.0137inch (0.348mm), Void Frequency (*n*) of 1.0483in^{-1} (0.0413mm^{-1}), Specific Surface (α) of 304.2833in^{-1} (11.98mm^{-1}), Paste-Air Ratio (*p/A*) of 21.9317, and Spacing Factor ($\bar{L}$) of 0.0305inch (0.774mm).

The results from the AVA and pressure meter for the fresh concrete of Control 2 are listed in TABLE V. The values of air content recorded from AVA for Batch A, B and C are 2.8%, 1.8% and 0.9% respectively, with an average of 1.8%. The values of the total air measured from the pressure meter were recorded as 3.0%, 2.2% and 2.4% for the three batches, with an average of 2.5%. The values of the specific surface and spacing factor of the fresh concrete were also determined in the test of AVA, with the average specific surface being 6.2mm^{-1} and average spacing factor being 1.214mm^{-1}. The results from the test of AVA and pressure meter were used to compare with the results obtained from the analysis of LTM.

TABLE IV
LINEAR TRAVERSE RESULTS FOR CONTROL 2 SAMPLES (C2)

LAB	**Control 2 (C2) No Air Entrainment**					
	Air Content (*A*)	**Average Chord Intercept (*l*)**	**Void Frequency (*n*)**	**Specific Surface (α)**	**Paste-Air Ratio (*p/A*)**	**Spacing Factor ($\bar{L}$)**
	%	**mm**	**mm^{-1}**	**mm^{-1}**	**-**	**Mm**
A4	0.73	0.3581	0.020	11.20	37.39	0.9957
A5	1.14	0.4902	0.023	8.15	23.81	1.1354
A Average	0.94	0.4242	0.022	9.68	30.60	1.0655
B4	1.71	0.3886	0.044	10.27	15.84	0.7569
B5	1.30	0.2946	0.044	13.56	20.93	0.6452
B Average	1.51	0.3416	0.044	11.92	18.39	0.7010
C4	1.64	0.2921	0.056	13.68	16.57	0.5791
C5	1.59	0.2667	0.060	15.01	17.05	0.5334
C Average	1.62	0.2794	0.058	14.34	16.81	0.5563
Overall Average	1.35	0.3484	0.041	11.98	21.93	0.7743

TABLE V
AVA AND PRESSURE METER RESULTS FOR CONTROL 2 SAMPLES (C2)

LAB		**Control 2 No Air Entrainment**			
		Control 2A	**Control 2B**	**Control 2C**	**Average**
Air Content (LTM)	%	0.935	1.505	1.615	1.3517
Air Content (AVA)	%	2.8	1.8	0.9	1.8
Air Content (Pressure Meter)	%	3.0	2.2	2.4	2.5
Slump	in.	1.00	1.25	2.00	1.42
Temperature	°F	74	75	74	74
Unit Weight	lb/ft^3	151.336	152.576	150.976	151.629
Specific Surface	mm^{-1}	4.5	6.7	6.1	6.2
Spacing Factor	mm	1.277	1.123	1.198	1.214
Durability Index		0.00	0.00	0.00	0.00
Strength	psi	6714	7138	7053	6968

2. <u>RSA10 (A4, A5, B4, B5, C4, and C5)</u>

Samples of RSA10 were obtained from the concrete cylinders of the mix with synthetic air entrainment, with paste content of 27.11%. A total of three batches (A, B and C) were mixed for the same mix design. In the analysis of LTM, the total length of traverse and the area covered are 95 inches (2413 mm) and 11.5 square inches (7419.3 mm^2) respectively. All the results from the analysis of LTM for the hardened concrete samples of RSA10 are listed in TABLE VI and the sample of RSA10-A4 is shown in FIGURE 10(b).

From the analysis of LTM for Batch A, B and C of RSA10 respectively, the recorded average values of Air Content (*A*) are 3.25%, 3.215% and 4.135%, Average

Chord Intercept (l) are 0.0052inch (0.1321mm), 0.0049inch (0.1245mm) and 0.035inch (0.0889mm), Void Frequency (n) are 6.38in^{-1} (0.251mm^{-1}), 6.51in^{-1}(0.256mm^{-1}), 11.97inch (0.471mm^{-1}), Specific Surface (α) are 774.25in^{-1} (30.48mm^{-1}), 816.05in^{-1} (32.13mm^{-1}) and 1152.45in^{-1} (45.37mm^{-1}), and Paste-Air Ratio (p/A) are 8.62, 8.635 and 6.58, and Spacing Factor ($\bar{L}$) are 0.0077inch (0.196mm), 0.00725inch (0.184mm) and 0.0046inch (0.117mm).

The recorded values for Batch A, B and C were averaged to determine the overall average of RSA10, with the overall average Air Content (A) of 3.5333%, Average Chord Intercept (l) of 0.0045inch (0.115mm), Void Frequency (n) of 8.2867in^{-1} (0.326mm^{-1}), Specific Surface (α) of 914.25in^{-1} (35.99mm^{-1}), Paste-Air Ratio (p/A) of 7.9450, and Spacing Factor ($\bar{L}$) of 0.0065inch (0.166mm).

The results from the AVA and pressure meter for the fresh concrete of RSA10 are listed in TABLE VII. The values of air content recorded from AVA for Batch A, B and C are 2.1%, 1.9% and 1.2% respectively, with an average of 1.7%. The values of the total air measured from the pressure meter were recorded as 4.9%, 4.5% and 4.6% for the three batches, with an average of 4.7%. The values of the specific surface and spacing factor of the fresh concrete were also determined in the test of AVA, with the average specific surface being 23.8mm^{-1} and average spacing factor being 0.295mm. The results from the test of AVA and pressure meter were used to compare with the results obtained from the analysis of LTM.

TABLE VI
LINEAR TRAVERSE RESULTS FOR SAMPLES
WITH SYNTHETIC MICRO-AIR (RSA10)

LAB	Synthetic Micro-Air (RSA10) Air Entrainment					
	Air Content (*A*)	**Average Chord Intercept (*l*)**	**Void Frequency (*n*)**	**Specific Surface (α)**	**Paste-Air Ratio (*p/A*)**	**Spacing Factor ($\bar{L}$)**
	%	**mm**	**mm^{-1}**	**mm^{-1}**	**-**	**mm**
A4	2.66	0.1422	0.187	28.12	10.17	0.2261
A5	3.84	0.1219	0.315	32.85	7.07	0.1651
A Average	3.25	0.1321	0.251	30.48	8.62	0.1956
B4	2.73	0.1194	0.229	33.57	9.93	0.1880
B5	3.7	0.1295	0.283	30.69	7.34	0.1803
B Average	3.22	0.1245	0.256	32.13	8.64	0.1842
C4	3.85	0.0940	0.415	43.01	7.03	0.1270
C5	4.42	0.0838	0.528	47.73	6.13	0.1067
C Average	4.14	0.0889	0.471	45.37	6.58	0.1168
Overall Average	3.53	0.1151	0.326	35.99	7.95	0.1655

TABLE VII
AVA AND PRESSURE METER RESULTS FOR SAMPLES
WITH SYNTHETIC MICRO-AIR (RSA10)

LAB		Synthetic Micro-Air (RSA10) Air Entrainment			
		RSA10-A	**RSA10-B**	**RSA10-C**	**Average**
Air Content (LTM)	%	3.255	3.215	4.135	3.5333
Air Content (AVA)	%	2.1	1.9	1.2	1.7
Air Content (Pressure Meter)	%	4.9	4.5	4.6	4.7
Slump	in.	2.50	2.25	3.00	2.58
Temperature	°F	74	74	76	75
Unit Weight	lb/ft^3	147.320	148.760	147.328	147.803
Specific Surface	mm^{-1}	22.5	20.5	28.3	23.8
Spacing Factor	mm	0.291	0.312	0.283	0.295
Durability Index		0.92	0.94	0.97	0.94
Strength	psi	6501	6592	6273	6455

3. RVR15 (A4, A5, B4, B5, C4, and C5)

Samples of RVR15 were obtained from the concrete cylinders of the mix with air entrainment of Vinsol Resin, with paste content of 27.11%. A total of three batches (A, B and C) were mixed for the same mix design. In the analysis of LTM, the total length of traverse and the area covered are 95 inches (2413 mm) and 11.5 square inches (7419.3 mm^2) respectively. All the results from the analysis of LTM for the hardened concrete samples of RVR15 are listed in TABLE VIII, and the sample of RVR15-A5 is shown in FIGURE 10(c).

From the analysis of LTM for Batch A, B and C of RVR15 respectively, the recorded average values of Air Content (*A*) are 6.22%, 5.0% and 5.8%, Average Chord Intercept (*l*) are 0.0039inch (0.0991mm), 0.003inch (0.0762mm) and 0.00315inch (0.0800mm), Void Frequency (*n*) are 16.06in^{-1} (0.632mm^{-1}), 16.75in^{-1} (0.659mm^{-1})and 18.435in^{-1} (0.726mm^{-1}), Specific Surface (α) are 1025.7in^{-1} (40.38mm^{-1}), 1339.55in^{-1} (52.74mm^{-1}) and 1264.05in^{-1} (49.77mm^{-1}), and Paste-Air Ratio (*p/A*) are 4.415, 5.42 and 4.725, and Spacing Factor ($\bar{L}$) are 0.00415inch (0.1054mm), 0.0036inch (0.0914mm) and 0.0036inch (0.0914mm).

The recorded values for Batch A, B and C were averaged to determine the overall average of RVR15, with the overall average Air Content (*A*) of 5.6733%, Average Chord Intercept (*l*) of 0.0034inch (0.0851mm), Void Frequency (*n*) of 17.0817in^{-1} (0.673mm^{-1}), Specific Surface (α) of 1209.7667in^{-1} (47.63mm^{-1}), Paste-Air Ratio (*p/A*) of 4.8533, and Spacing Factor ($\bar{L}$) of 0.0038inch (0.0961mm).

The results from the AVA and pressure meter for the fresh concrete of RVR15 are listed in TABLE IX. The values of air content recorded from AVA for Batch A, B and C are 4.6%, 3.8% and 3.3% respectively, with an average of 3.9%. The values of the total air measured from the pressure meter were recorded as 7.4%, 6.0% and 6.3% for the three batches, with an average of 6.6%. The values of the specific surface and spacing factor of the fresh concrete were also determined in the test of AVA, with the average specific surface being 27mm^{-1} and average spacing factor being 0.185mm. The results from the test of AVA and pressure meter were used to compare with the results obtained from the analysis of LTM.

TABLE VIII
LINEAR TRAVERSE RESULTS FOR SAMPLES WITH VINSOL RESIN (RVR15)

LAB	**Vinsol Resin (RVR15) Air Entrainment**					
	Air Content (*A*)	**Average Chord Intercept (*l*)**	**Void Frequency (*n*)**	**Specific Surface (α)**	**Paste-Air Ratio (*p/A*)**	**Spacing Factor ($\bar{L}$)**
	%	**mm**	**mm^{-1}**	**mm^{-1}**	**-**	**mm**
A4	5.51	0.1041	0.525	38.11	4.92	0.1194
A5	6.93	0.0940	0.739	42.66	3.91	0.0914
A Average	6.22	0.0991	0.632	40.38	4.42	0.1054
B4	5.05	0.0737	0.687	54.43	5.37	0.0889
B5	4.95	0.0787	0.632	51.04	5.47	0.0940
B Average	5.00	0.0762	0.659	52.74	5.42	0.0914
C4	6.42	0.0762	0.842	52.45	4.22	0.0813
C5	5.18	0.0838	0.609	47.08	5.23	0.1016
C Average	5.80	0.0800	0.726	49.77	4.73	0.0914
Overall Average	5.67	0.0851	0.673	47.63	4.85	0.0961

TABLE IX
AVA AND PRESSURE METER RESULTS FOR SAMPLES
WITH VINSOL RESIN (RVR15)

LAB		**Vinsol Resin (RVR15) Air Entrainment**			
		RVR15-A	**RVR15-B**	**RVR15-C**	**Average**
Air Content (LTM)	%	6.22	5.00	5.8	5.6733
Air Content (AVA)	%	4.6	3.8	3.3	3.90
Air Content (Pressure Meter)	%	7.4	6.0	6.3	6.6
Slump	in.	5.50	2.50	2.75	3.58
Temperature	°F	74	75	74	74
Unit Weight	lb/ft^3	142.128	146.456	145.904	144.829
Specific Surface	mm^{-1}	31.1	24.1	28.3	27.9
Spacing Factor	mm	0.152	0.208	0.196	0.185
Durability Index		0.99	0.92	1.00	0.97
Strength	psi	4390	5711	5615	5239

4. From Job Sites, KY395 (A4 and A5), R/R (A4 and A5) and J (I4 and I5)

Samples were obtained from the concrete cylinders cast in three job sites KY395 Overpass, R/R and Jeptha Creek. Only one batch was mixed at each job site, and synthetic air entrainment was added in the mix, with paste content of 27.11%. In the analysis of LTM, the total length of traverse and the area covered are 95 inches (2413 mm) and 11.5 square inches (7419.3 mm^2) respectively. The results from the analysis of LTM for the hardened concrete samples of KY395 Overpass, R/R and Jeptha Creek are listed in TABLE X, XI and XII respectively.

In TABLE X, from the analysis of LTM, the samples of KY395 Overpass recorded an average value of Air Content (*A*) of 4.42%, Average Chord Intercept (*l*) of 0.0039inch (0.0991mm), Void Frequency (*n*) of 11.28in^{-1} (0.444mm^{-1}), Specific Surface (α) of 1020in^{-1} (40.16mm^{-1}), Paste-Air Ratio (*p/A*) of 6.155, and Spacing Factor ($\bar{L}$) of 0.005inch (0.1270mm).

TABLE X
LINEAR TRAVERSE RESULTS FOR SAMPLES FROM JOB SITE OF KY395 OVERPASS (KY395) WITH SYNTHETIC AIR ENTRAINMENT

FIELD	**KY395 Overpass (KY395) Synthetic Air Entrainment**					
	Air Content (*A*)	**Average Chord Intercept (*l*)**	**Void Frequency (*n*)**	**Specific Surface (α)**	**Paste-Air Ratio (*p/A*)**	**Spacing Factor ($\bar{L}$)**
	%	**mm**	**mm^{-1}**	**mm^{-1}**	**-**	**mm**
A4	4.69	0.0038	12.27	1047.6	5.78	0.0047
A5	4.15	0.004	10.29	992.4	6.53	0.0053
Average	4.42	0.0039	11.28	1020	6.155	0.005

In TABLE XI, from the analysis of LTM, the samples of R/R recorded an average value of Air Content (*A*) of 6.765%, Average Chord Intercept (*l*) of 0.0048inch (0.1219mm), Void Frequency (*n*) of 13.985in^{-1} (0.551mm^{-1}), Specific Surface (α) of 826.9in^{-1} (32.56mm^{-1}), Paste-Air Ratio (*p/A*) of 4.02, and Spacing Factor ($\bar{L}$) of 0.0049inch (0.1245mm).

As shown in TABLE XII, from the analysis of LTM, the samples of Jeptha Creek recorded an average value of Air Content (*A*) of 4.925%, Average Chord Intercept (*l*) of

0.00355inch (0.0902mm), Void Frequency (*n*) of 13.915in^{-1} (0.548mm^{-1}), Specific Surface (α) of 1129.25in^{-1} (44.46mm^{-1}), Paste-Air Ratio (*p/A*) of 5.505, and Spacing Factor ($\bar{L}$) of 0.0043inch (0.1092mm).

TABLE XI
LINEAR TRAVERSE RESULTS FOR SAMPLES FROM JOB SITE OF R/R (R/R)
WITH SYNTHETIC AIR ENTRAINMENT

FIELD	**R/R (R/R) Synthetic Air Entrainment**					
	Air Content (*A*)	**Average Chord Intercept (*l*)**	**Void Frequency (*n*)**	**Specific Surface (α)**	**Paste-Air Ratio (*p/A*)**	**Spacing Factor ($\bar{L}$)**
	%	**mm**	**mm^{-1}**	**mm^{-1}**	**-**	**mm**
A4	7.2	0.0048	14.89	827.4	3.76	0.0046
A5	6.33	0.0048	13.08	826.4	4.28	0.0052
Average	6.765	0.0048	13.985	826.9	4.02	0.0049

TABLE XII
LINEAR TRAVERSE RESULTS FOR SAMPLES FROM JOB SITE OF
JEPTHA CREEK (J) WITH SYNTHETIC AIR ENTRAINMENT

FIELD	**Jeptha Creek (J) Synthetic Air Entrainment**					
	Air Content (*A*)	**Average Chord Intercept (*l*)**	**Void Frequency (*n*)**	**Specific Surface (α)**	**Paste-Air Ratio (*p/A*)**	**Spacing Factor ($\bar{L}$)**
	%	**mm**	**mm^{-1}**	**mm^{-1}**	**-**	**mm**
I4	4.93	0.0037	13.32	1079.7	5.5	0.0045
I5	4.92	0.0034	14.51	1178.8	5.51	0.0041
Average	4.925	0.00355	13.915	1129.25	5.505	0.0043

TABLE XIII
AVA AND PRESSURE METER RESULTS FOR SAMPLES FROM 3 JOB SITES WITH SYNTHETIC AIR ENTRAINMENT

FIELD		**From Job Sites Synthetic Air Entrainment**		
		KY395 Overpass (KY395)	**R/R (R/R)**	**Jeptha Creek (J)**
Air Content (LTM)	%	4.42	6.765	4.925
Air Content (AVA)	%	1.70	1.30	1.90
Air Content (Pressure Meter)	%	4.2	7.20	4.20
Slump	in.	4.50	4.75	5.50
Temperature	°F	78	77.00	77.00
Unit Weight	lb/ft^3	146.992	140.92	147.91
Specific Surface	mm^{-1}	25.3	37.67	30.2
Spacing Factor	mm	0.300	0.17	0.23
Durability Index		0.96	0.97	1.00

For the samples obtained from the three job sites, the results from the AVA and pressure meter for the fresh concrete are listed in TABLE XIII. The value of air content recorded from AVA for KY395 Overpass is 1.70%, for R/R is 1.30% and for Jeptha Creek is 1.90%. The values of the total air measured from the pressure meter for KY395 Overpass, R/R and Jeptha Creek were recorded as 7.4%, 6.0% and 6.3% respectively. The values of the specific surface and spacing factor of the fresh concrete were also determined in the test of AVA, with the average specific surface being $25.3mm^{-1}$, $37.67mm^{-1}$ and $30.2mm\text{-}^{1}$, and average spacing factor being 0.300mm, 0.17mm and 0.23mm for KY395 Overpass, R/R and Jeptha Creek respectively. The results from the test of AVA and pressure meter were used to compare with the results obtained from the analysis of LTM.

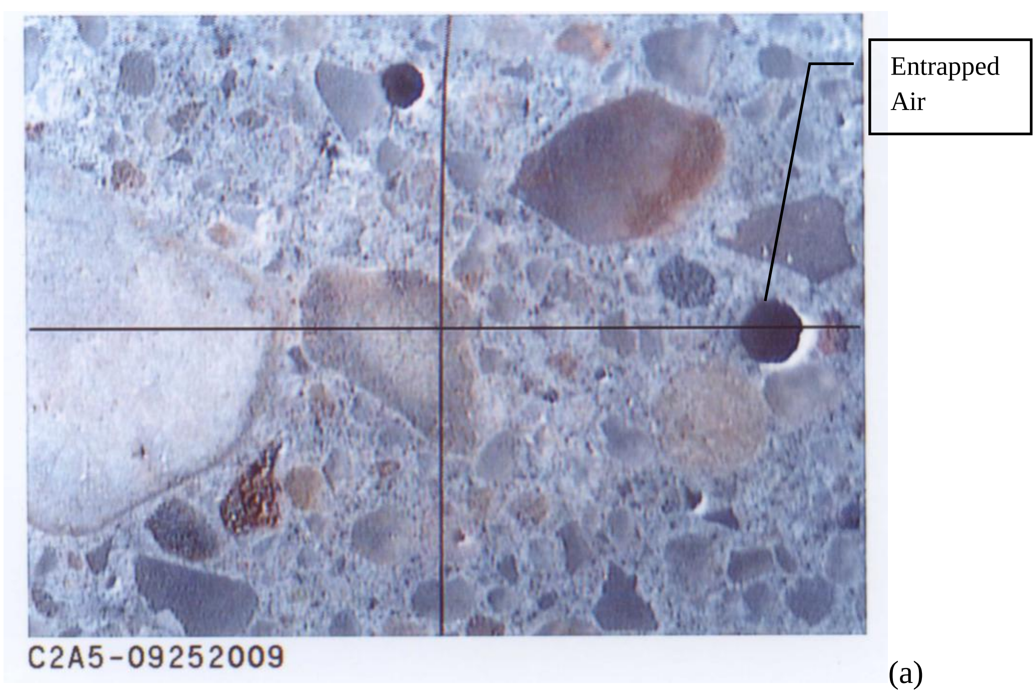
B. Evaluation of Results

The samples of the Control, RSA10 and RVR15 have different mix designs with addition of different AEA's, while the samples from three job sites, KY395 Overpass, R/R and Jeptha Creek share the same mix design. For each of the mix designs, there were three batches of mix (A, B and C). All the mix designs for different batches were listed in TABLE III in the chapter entitled "Experimental Procedure- Samples". All the samples were examined with the analysis of LTM to establish the properties of the air void system.

With the average values of the properties of the air void system, the freeze-thaw durability of the samples can be evaluated whether it is desired by comparing with the specified range of the values in the ASTM Specification C457. As specified in ASTM Specification C457, the amount of air content requires being between 1.5% to 7.5%, the spacing factor to be between 0.10mm and 0.20mm, and the specific surface of air voids should be kept within the range of $23.6mm^{-1}$ to $43.3mm^{-1}$ to maintain the desired freeze-thaw durability of the concrete.

1. LTM Results of Samples from Laboratory

In the laboratory, each of the mix designs (Control, RSA10 and RVR15) had three batches of mix (A, B and C); and two samples were obtained from each batch of mixes for LTM. There were a total of 18 samples obtained for the analysis of LTM. During the analysis of LTM, images of part of the observation surfaces under the microscope were captured with the camera and the video monitor connecting to the apparatus of CAS-2000. The images of the samples of C2-A5, RSA10-A4, and RVR15-A5 are shown in FIGURE 10. The smaller-sized entrained air voids and larger-sized entrapped air voids are labeled on the figures and can be recognized easily. The image of C2-A5 in FIGURE 10(a) has shown no existence of smaller-sized air void, which is due to the absence of AEA to stabilize the small-sized entrained air bubbles. The images of RSA10-A4 in FIGURE 10(b) and RVR15-A5 in FIGURE 10(c) show a greater amount of both smaller-sized entrained air voids and larger-sized entrapped air voids, which is due to the presence of AEA.



(a)

FIGURE 10 – Samples of (a) C2-A5, (b) RSA10-A4, and (c) RVR15-A5 for LTM

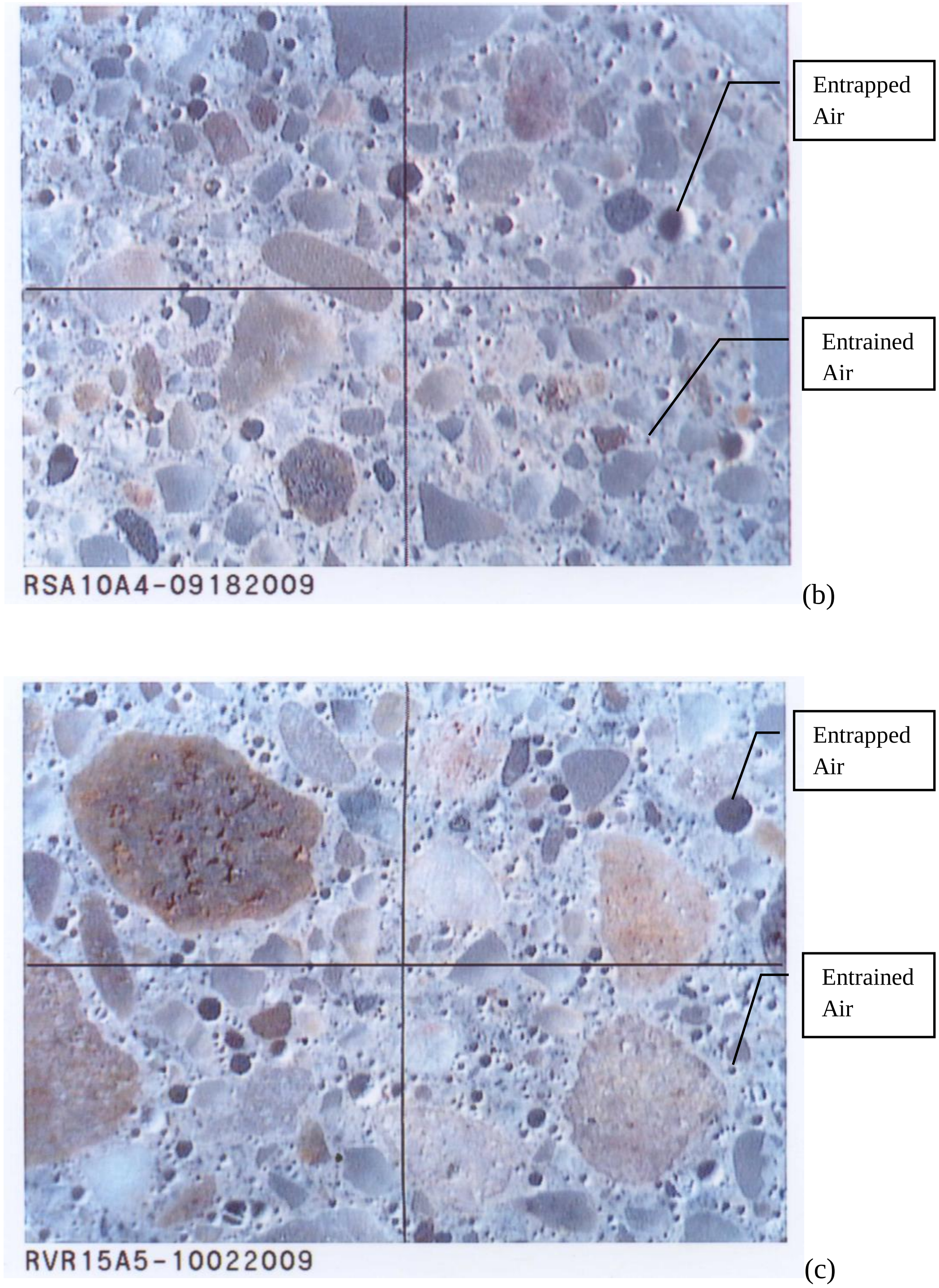


FIGURE 10 – Samples of (a) C2-A5, (b) RSA10-A4, and (c) RVR15-A5 for LTM

With the results of LTM plotted using Microsoft Excel 2007, the uniformity and the stability of the air void system can be established by comparing the properties of air void system in the samples within the same batch, from different batches of the same mix design and from different mix designs. All the LTM results of the eighteen samples from the laboratory were shown in FIGURE 11, with the differences in the results between samples within the same batch shown as the error bars in the figure.

Within the same batch of the mix, it is understandable that there are some moderate variations in the LTM results due to the unevenly distribution of air voids. However, the variations can be large sometimes. The analysis of LTM was performed twice on the same sample of C2-A4 and RSA10-A4. The variations between LTM results of the same sample were shown to be little, which indicated the operator error was relatively small to influence the results and did not cause the large variations. The large variations in the values can be observed from the air content of RVR15 mix in FIGURE 11(a), average chord intercept of Control mix in FIGURE 11(b), the void frequency of RVR15 mix in FIGURE 11(c), and paste-air ratio of Control mix in FIGURE 11(e).

The average chord intercept roughly indicates the size of the air voids present in the samples, while the paste-air ratio compares the volume of air voids with the volume of hardened cement paste. In the Control mix, there was no addition of AEA to stabilize the air bubbles and it results in the absence of small-sized entrained air voids in the Control samples. With no AEA stabilizing the air bubbles, the size of the air voids can vary a lot. With the large variation in size of the air voids, the volume of voids varies. This explains the large variations present in the average chord intercept and the paste-air ratio of Control mix.

The void frequency is always related to both the air content and the size of air voids. For samples with the same air content with air voids smaller in size, the void frequency is higher. For the RVR15 samples, with the high air content, the large variations in the air content and the void frequency indicate that the air void system may not be uniformly distributed in the air entrained concrete with Vinsol Resin (RVR15). The air void system in the RVR15 samples has low stability. During analysis of LTM, the randomly picked location sometimes may cause some variations in the air content. Other than the variations in the LTM results within the same batch of the mix, it is understood that the variations in the LTM results of the different batches of the mix and the variations can sometimes be huge. For example, there is large variation in the paste-air ratio of Control mix in FIGURE 11(e). One of the reasons as stated was the absence of AEA to stabilize the air voids. The variations can also be related to the differences in the operational processes, such as mixing, placing and curing. Additionally, the same mix design was mixed in different time periods to obtain different batches. The differences in environmental parameters, like the change in temperature and humidity, can also result in the variation of the air void properties and the LTM results.

There are also variations in the LTM results among the three mix designs. All the six parameters shown in the FIGURE 11 were taken into account for the comparison among the three mix designs. In FIGURE 11(a), the air contents of samples from LTM, defining as the percentages of the air voids in the concrete mixes, are shown; and the air content of Control is the least among the three with an average of 1.3517%. The air content of RSA10 has an average of 3.5333%, while RVR15 has the highest air content among the three with an average of 5.6733%. The least air contents in the Control mix is due to the absence of AEA in the Control mix to stabilize the air bubbles and some of the air bubbles vanished from the mix before the concrete hardened. The loss in air bubbles lowered the air content in the Control mix. With the same amount of AEA (0.35 oz.) added in the mix of RSA10 and RVR15, it is shown that the mix of RVR15 has the highest air content. Thus, it can be concluded that Vinsol Resin (RVR15) did a better job in stabilizing the air bubbles in the concrete mix, assuming insignificant effect from the differences in the operational processes and environmental parameters.

The average chord intercept, the void frequency, the specific surface and the spacing factor are highly related to each other. The presence of more smaller-sized air voids allows the air voids to spread out more evenly with the presence of more air voids for the same air content, and thus, the sample results in a lower average chord intercept, higher void frequency, larger specific surface and smaller spacing factor.

From FIGURE 11(b), the average chord intercept of Control is the highest among the three with an average of 0.348mm. The one of RSA10 has an average of 0.115mm, while RVR15 has the lowest average chord intercept with an average of 0.0851mm. Without any AEA in the Control mix to stabilize the air bubbles, the air bubbles merged to form larger bubbles and there was absence of small-sized entrained air. This highly increased the size of the air voids and the average chord intercept, which roughly indicates the average size of the air voids. From the results of LTM, the air voids in the mix of RVR15 are smaller in size than the voids in the mix of RSA10. This shows that

RVR15 did a better job in stabilizing the air bubbles, while RSA10 still allows part of the air bubbles to merge and form bigger bubbles.

With the same air content, the void frequency in a sample increases with the decrease in the air void size. This is due to the presence of a higher number of air voids. From FIGURE 11(c), the void frequency of Control is the lowest among the three with an average of $0.0413mm^{-1}$. The one of RSA10 has an average of $0.326mm^{-1}$, while RVR15 has the highest void frequency with an average of $0.673mm^{-1}$. Without adding any AEA to stabilize the air bubbles in the Control mix, some of the smaller-sized bubbles merged to form larger bubbles. With least air content in the Control mix and no small-sized entrained air, the void frequency in the Control mix is the least. The higher void frequency in the mix of RVR15, again, showed the better work done by the Vinsol Resin to stabilize the small-sized air bubbles with least bubbles merged and more small-sized bubbles were still present after the concrete hardened.

In FIGURE 11(d), the specific surface of the Control mix is the lowest among the three with an average of $11.98mm^{-1}$. The one of RSA10 has an average of $35.99mm^{-1}$, while RVR15 has the highest specific surface with an average of $47.63mm^{-1}$. The specific surface is the surface area of the air voids divided by the volume of the air voids. The Sample with more smaller-sized air voids has the higher specific surface, which is the sample of the RVR15 mix. Without the presence of any AEA, the Control mix has the lowest air content and the least small-sized air voids.

Paste-Air ratio is the ratio of the volume of hardened cement paste to the volume of air voids. From FIGURE 11(e), the paste-air ratio of Control is the highest among the three with an average of 21.93. The one of RSA10 has an average of 7.95, while RVR15 has the lowest paste-air ratio with an average of 4.85. With the higher air content and void frequency, the sample of the RVR15 mix has the largest volume of air voids compared to the other two mixes, and therefore, has the lowest paste-ratio.

The spacing factor is highly related to the void frequency. With higher void frequency and lower average chord intercept on the same observation surface area, there are more smaller-sized air voids spreading out more evenly, and thus, the air voids are closer to each other with a lower spacing factor. FIGURE 11(f), the one of Control is the highest among the three with an average of 0.7743mm. The one of RSA10 has an average of 0.1655mm, while RVR15 has the lowest spacing factor with an average of 0.0961. The sample of Control mix represents the observation surface area with lower void frequency and larger average chord intercept, and therefore, has a higher spacing factor.

The values of the LTM results can be used to compare with the specified range of the values in the ASTM Specification C457 to determine whether the samples meet the requirement for the desired freeze-thaw durability. As specified in ASTM Specification C457, the amount of air content requires being between 1.5% to 7.5%, the spacing factor to be between 0.10mm and 0.20mm, and the specific surface of air voids should be kept within the range of 23.6mm^{-1} to 43.3mm^{-1} to maintain the desired freeze-thaw durability of the concrete.

For the Control mix with 1.35% in air content, 11.98mm^{-1} in specific surface and 0.7743mm in spacing factor, none of the properties has fulfilled the requirement, and the samples of Control do not provide enough resistance to the freeze-thaw cycles. To fulfill the requirement, AEA should be used. Using AEA to stabilize the air bubbles, with presence of more smaller-sized air bubbles, the air content and specific surface can be increased, and the spacing factor can be decreased. The results from the analyses for RSA10 and RVR15 show the effect of AEA's.

From LTM, the RSA10 mix has air content of 3.53%, specific surface of 35.99mm^{-1} and spacing factor of 0.1655mm. These values were used to compare with the required values in the ASTM Specification C457. All the properties meet the requirement to maintain the desired freeze-thaw durability of the concrete; therefore, the samples of RSA10 provide enough resistance to freeze-thaw cycles.

The results from LTM of RVR15 mix show that the samples have air content of 5.67% and spacing factor of 0.0961mm, which are close enough to meet the requirement. However, the specific surface of 47.63mm^{-1} do not fulfill the requirement. Therefore, the samples of RVR15 may not provide sufficient resistance to the freeze-thaw cycles. The higher specific surface shows that the average air void size may be too small and may not be able to perform their duties to provide space for the expansion of moisture during freeze-thaw cycles.

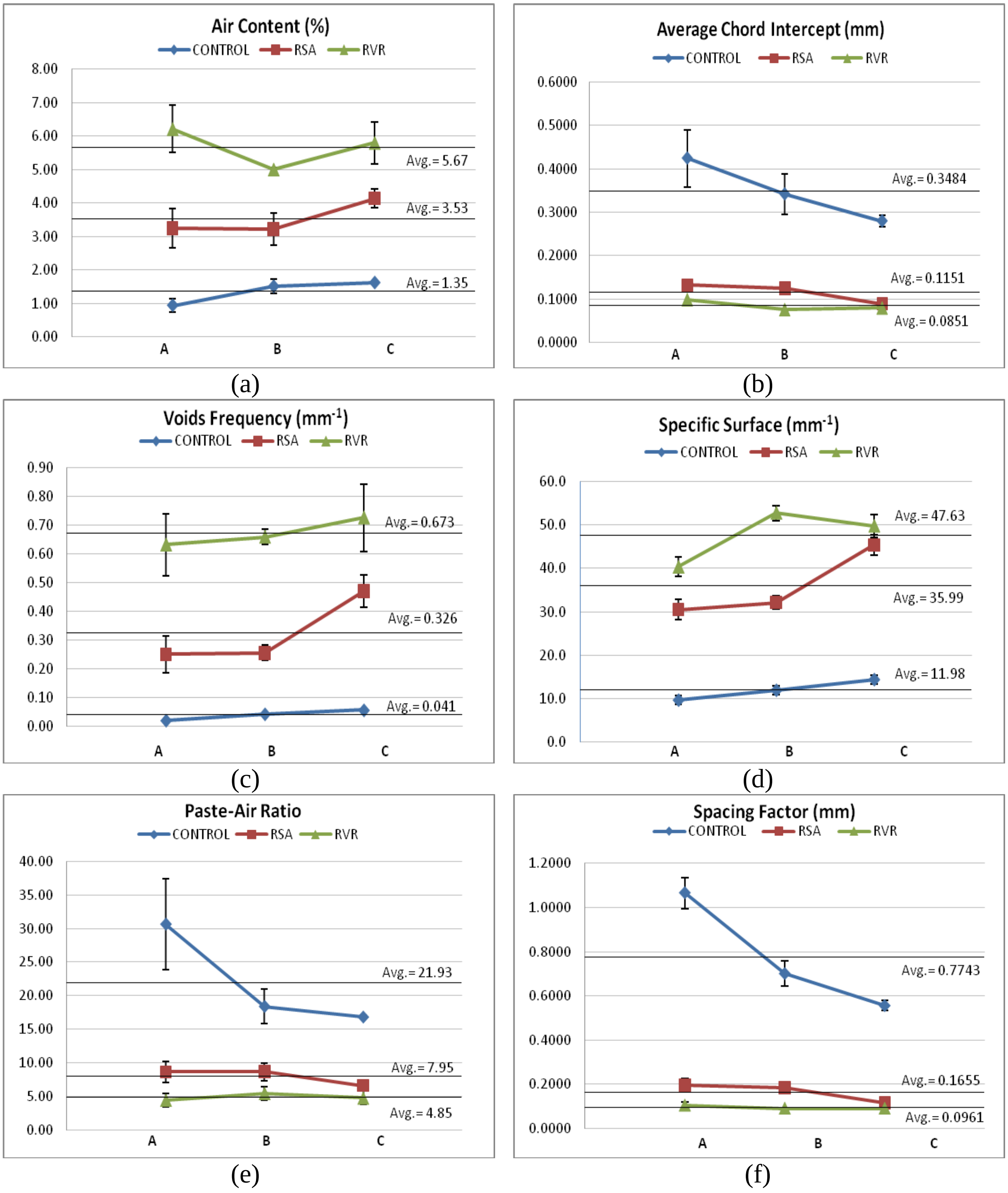


FIGURE 11 – LTM Results of Samples from Laboratory:
(a) Air Content in %, (b) Average Chord Intercept in mm, (c) Void Frequency in mm^{-1}, (d) Specific Surface in mm^{-1}, (e) Paste-Air Ratio, and (f) Spacing Factor (mm)

2. <u>LTM Results of Samples from Job Sites</u>

The samples for the three job sites (KY395 Overpass, R/R and Jeptha Creek) share the same mix design and two samples were obtained from each job site. There were a total of six samples obtained for the analysis of LTM. During the analysis of LTM, image of the observation surface of RR-A5 under the microscope was captured with the camera and the video monitor connecting to the apparatus of CAS-2000, shown in FIGURE 12. A greater amount of both smaller-sized entrained air voids and larger-sized entrapped air voids can be seen and are labeled on the figure. The results of LTM were plotted using Microsoft Excel 2007 in FIGURE 13. Since the samples from the three job sites share the same mix design, the stability of the air void system can be established by comparing the properties of air void system of samples from different job sites.

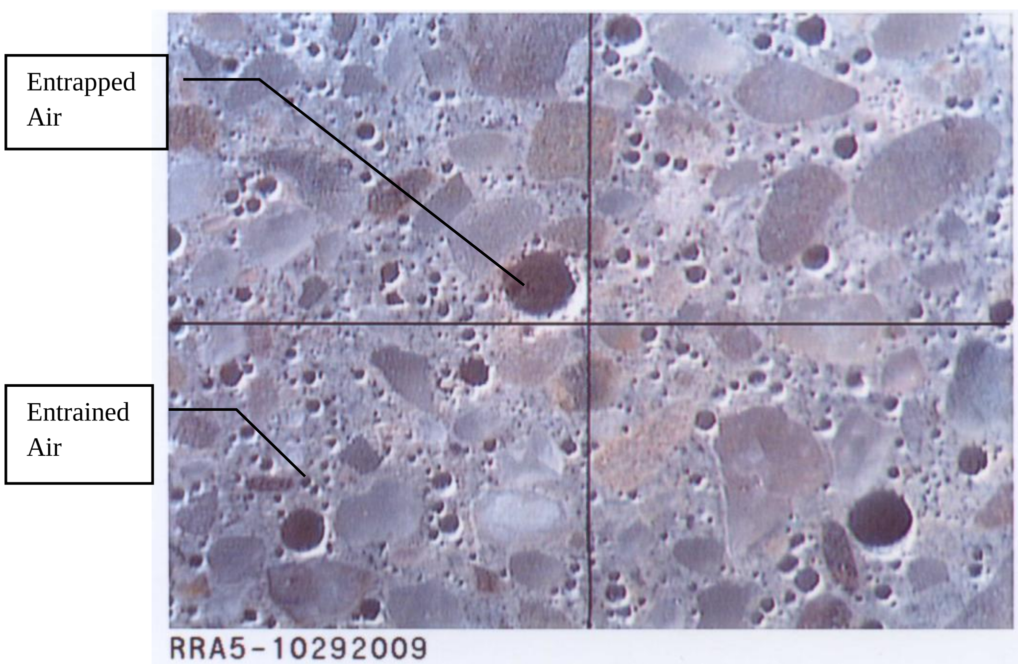


FIGURE 12 – Samples from Job Site of R/R

Even though all the samples shared the same mix design, it is understandable that there are some variations in the LTM results. The variation can be observed to be reasonable from the first five parameters shown in FIGURE 13(a)-(e). However, the variations can be large sometimes, which can be observed from the spacing factor in FIGURE 13(f). The variations can be the result from the differences in environmental parameters, like the change in temperature and humidity. Another important reason causing the variation is observed to be the differences in the construction procedures, including casting, vibration, transporting, consolidating and curing. However, the environmental changes can hardly be overcome, while the influence due to the changes in construction procedures can be easily minimized. One should pay close attention to avoid any defect in the concrete due to the construction procedures that may influence the spacing factor, which is a dominant parameter to durability and freeze-thaw resistance.

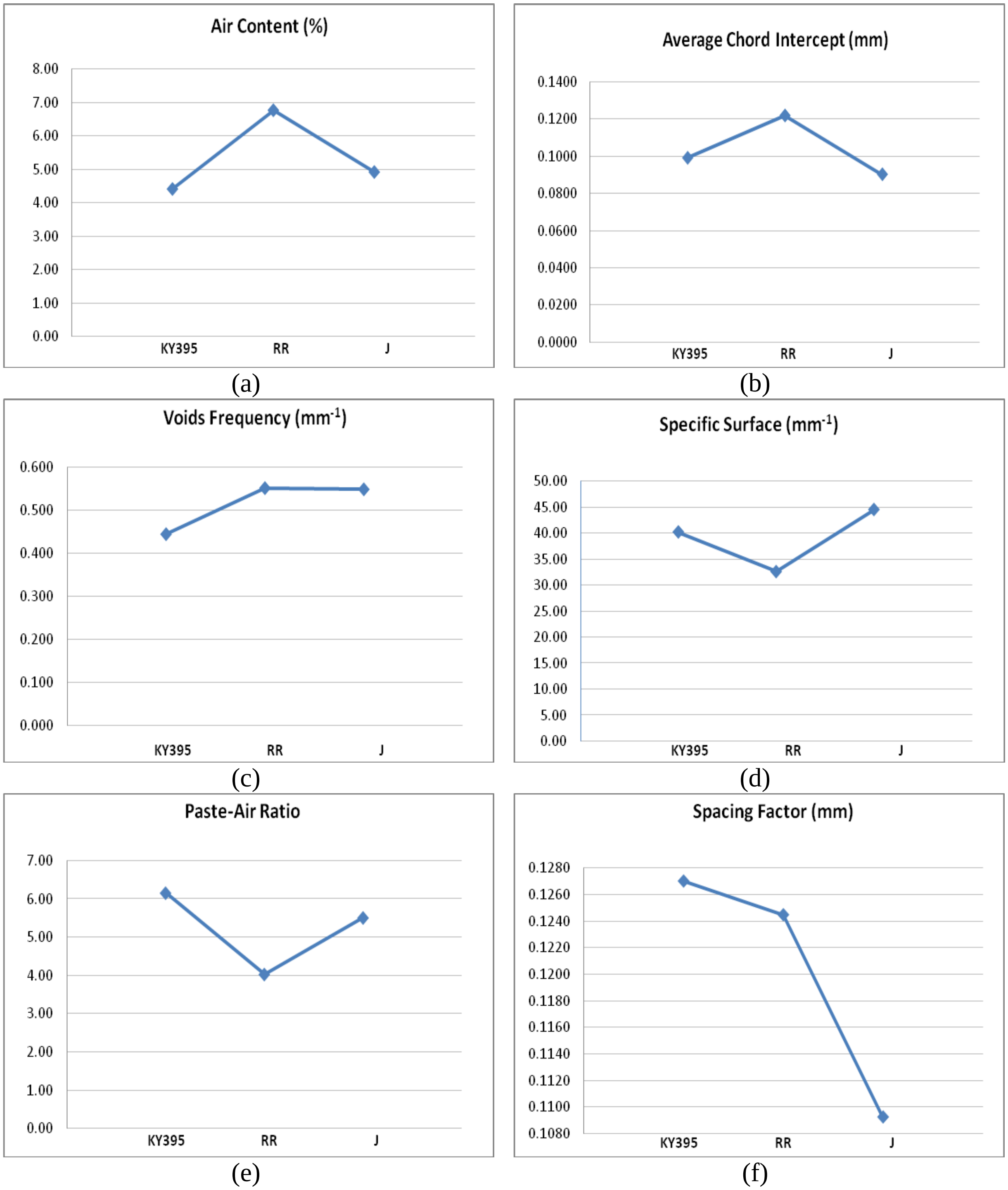


FIGURE 13 – LTM Results of Samplesfrom Job Sites:
(a) Air Content in %, (b) Average Chord Intercept in mm, (c) Void Frequency in mm^{-1}
(d) Specific Surface in mm^{-1}, (e) Paste-Air Ratio, and (f) Spacing Factor (mm)

3. Comparison of Different Analysis Methods (LTM, AVA and Pressure Meter)

The analysis of LTM was used to determine the properties of hardened concrete, while the pressure meter and AVA were used to determine the properties of fresh concrete. The concrete samples used for the pressure meter and AVA are the same as those used for LTM in the laboratory. The results from the pressure meter and AVA were plotted versus the results from LTM using Microsoft Excel 2007 to establish the relationship of different analysis methods.

In FIGURE 14, the average air contents for the six different mix designs from the pressure meter versus LTM were plotted. A trendline passing through the origin and a 45-degree dotted line were added in the figure. It is used to compare with the 45-degree dotted line plotted manually on the same figure, and the slope of the trendline is relatively close to 45 degree. This represents that the results of the pressure meter are correlated with those of LTM, which change in the air content from pressure meter corresponds to similar change in that from LTM.

With all the data points laying along the trendline in FIGURE 14, the values of air content from the pressure meter are relatively correlated to those from LTM. Both the pressure meter and the analysis of LTM took entrained air and entrapped air bubbles into account, and this explains the correlation between results from the pressure meter and LTM. With most of the data points being above the 45-degree line, the air content measured from the pressure meter is shown to be higher than that from LTM for the same sample. This can be explained by the loss of large-sized air bubbles due to buoyancy in the fresh concrete.

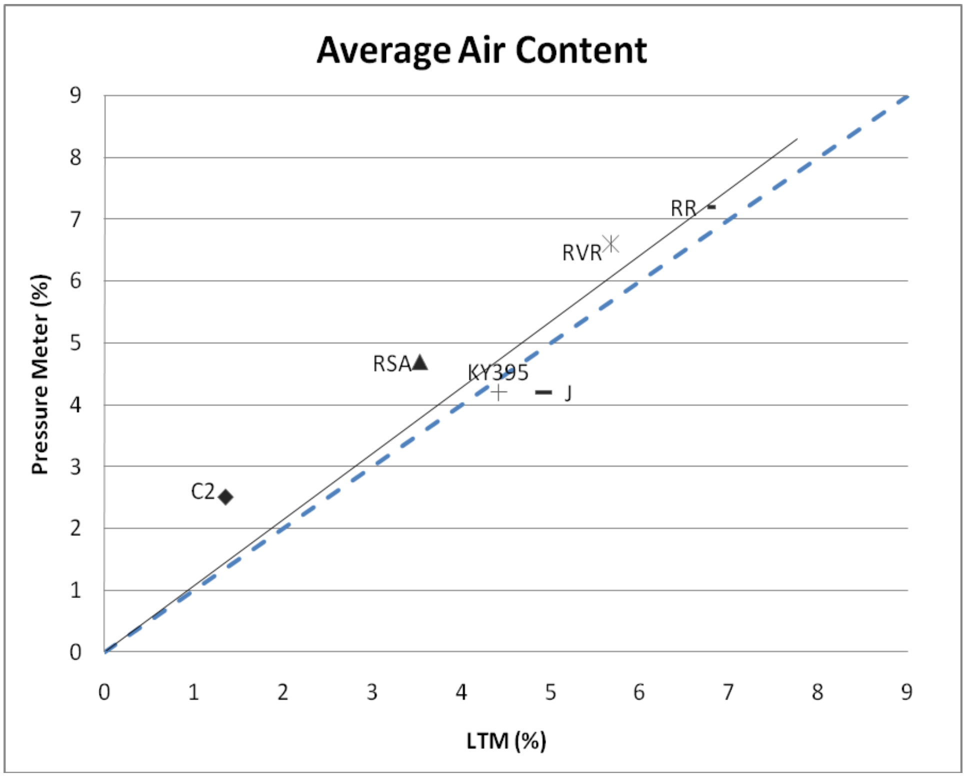


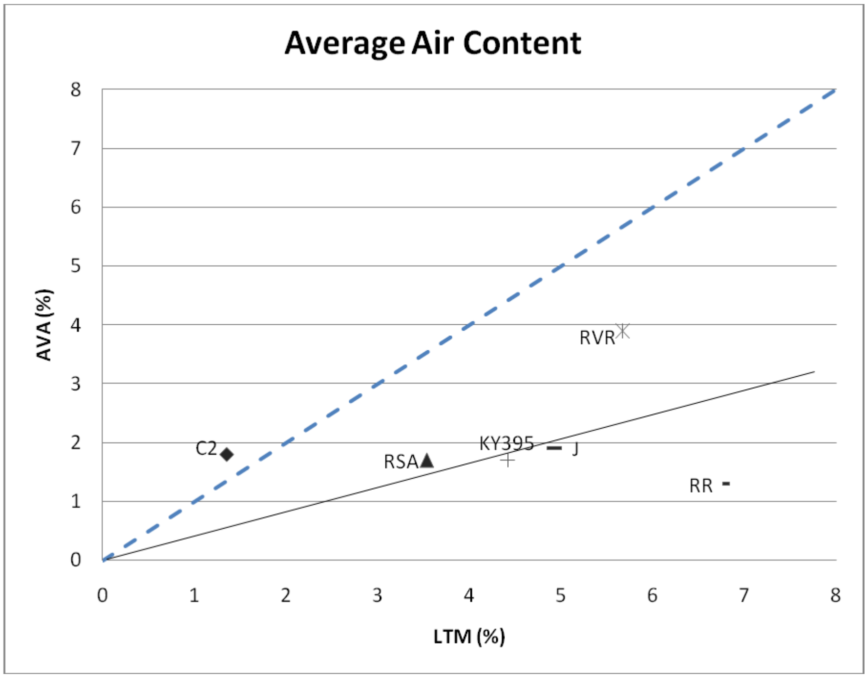
FIGURE 14 – Pressure Meter versus LTM: Average Air Content in %

The results from AVA and LTM were used to determine the relationship between two analysis methods. Three parameters were measured from AVA, and they were plotted versus LTM using Microsoft Excel 2007, shown in FIGURE 15, with solid trendlines and 45-degree dotted lines added.

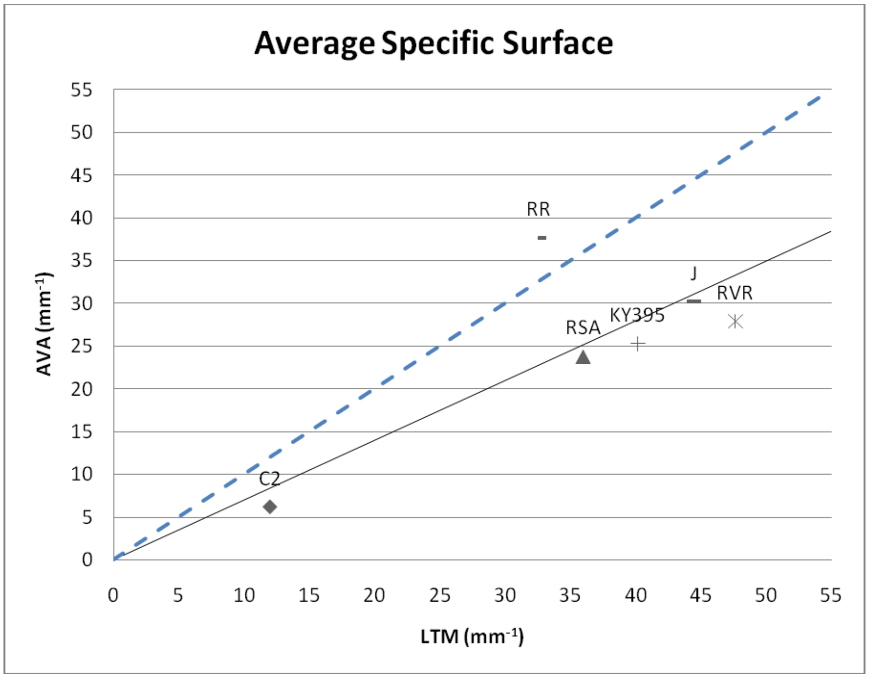
The average air contents measured from AVA versus those from LTM were plotted in FIGURE 15(a). The trendline passing through the origin in the figure has a slope much smaller than 45 degrees, representing that the analysis of LTM is more sensitive than AVA, and change in the air content from AVA corresponds to greater change in that from LTM. With the data points not scattering along the trendline in the figure, the air contents from AVA are not strongly correlated with those from LTM. Since the test of AVA measured the properties of entrained air voids and LTM measured both entrapped and entrained air voids, it is understandable to have a lower air content measured from AVA than the one measured from LTM for the same sample. The relationship can be seen in FIGURE 15(a), with most of the data points scattered below the 45-degree dotted line, except for the Control mix. The difference in the Control mix from other mixes can be explained by the absence of entrained air in the Control mix without addition of AEA. Since AVA focuses on the smaller-sized entrained air bubbles and LTM focuses on both entrained and entrapped air voids, without the presence of entrained air in the Control mix, the differences between the results of the two methods become smaller.

In FIGURE 15(b), the data points of average specific surface from AVA were plotted versus the ones from LTM. The trendline of the plot has a slope of slightly smaller than 45 degrees. This represents that the analysis of LTM is slightly more sensitive than AVA, and change in the specific surface from AVA corresponds to greater change in that from LTM. With most of the data points scattered below the 45-degree dotted line in the figure, except that for R/R, the values of specific surface from AVA are relatively lower than those from LTM for the same sample. The specific surface is the surface area of the air voids divided by the volume of the air voids. Since the type of air bubbles measured by LTM is different from AVA and the data points not scattering along the trendline in the figure, there is no strong correlation shown between the specific surface of the air voids measured from LTM and the one measured from AVA. In the case of R/R in FIGURE 15(b), the average specific surface seems not correlating with that of the same mix design and the other mix designs. The variation in the average specific surface can be explained by the differences in the construction procedures, like mixing, transporting and curing.

The data points of average spacing factor measured from AVA were plotted versus those from LTM in FIGURE 15(c). All of the values resulted from AVA are relatively higher than those from LTM with the trendline having a slope larger than 45 degrees. This represents that the analysis of AVA is more sensitive than LTM, and change in the spacing factor from AVA corresponds to smaller change in that from LTM. With all the data points scattered above the 45-degree dotted line in the figure, the values of spacing factor from AVA are relatively higher than those from LTM. This can be explained by the type of air voids being taken into account in the two methods. Since more air bubbles were taken into account in the analysis of LTM, both entrained and entrapped air, the spacing between air bubbles would be measured to be smaller than from AVA, which only measured the entrained air bubbles. Therefore, the spacing factor from AVA is understandable to be higher than that from LTM. Since all the data points scatter along the trendline, the relationship in spacing factor between AVA and LTM is shown to be constant.

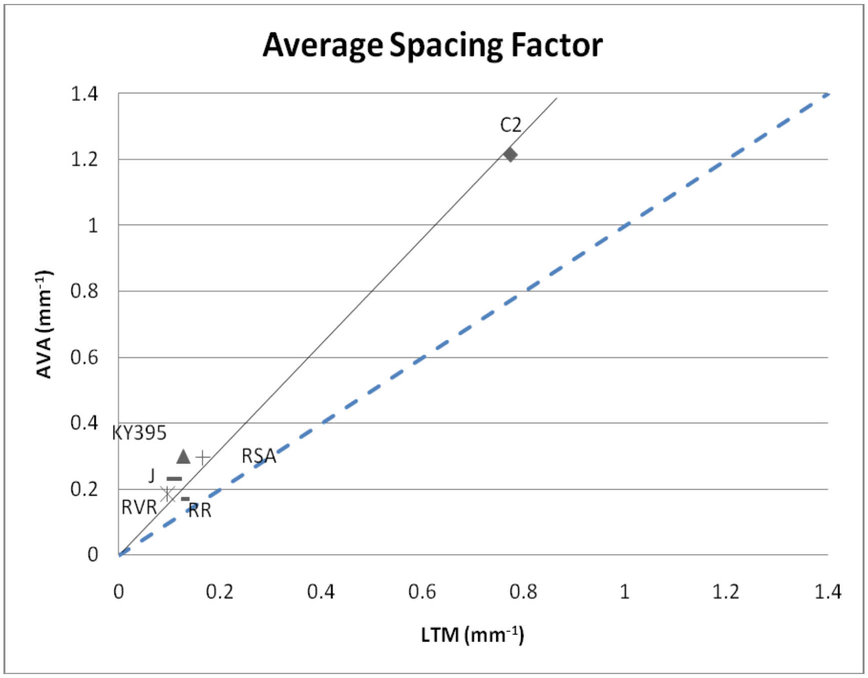


(a)



(b)

FIGURE 15 – AVA versus LTM: Properties of Different Mix Designs (a) Average Air Content in %, (b) Average Specific Surface in mm^{-1}, and (c) Average Spacing Factor in mm.



(c)

FIGURE 15 – AVA versus LTM: Properties of Different Mix Designs (a) Average Air Content in %, (b) Average Specific Surface in mm^{-1}, and (c) Average Spacing Factor in mm.

V. CONCLUSIONS

Concrete samples were obtained from concrete cylinders cast in the laboratory and job sites, and different mix designs were used with addition of different AEA's. The analysis of LTM was performed and a series of data related to the properties of concrete were obtained. The values of the series of data from LTM were discussed in detail in the chapters "Evaluation of Results". The following is a summary of the conclusions of the research performed:

1. Properties measured from LTM are fairly steady in most of the cases within the same batch with the same mix design, but variations are sometimes present, not only in samples with different mix designs.

2. Mix design with no air entrainment (Control) does not fulfill the requirements specified in ASTM Specification C457 to provide enough resistance to freeze-thaw cycles.

3. Mix design with addition of AEA of Vinsol Resin (RVR15) at the level tested fulfills most of the requirements specified in ASTM Specification C457 to provide enough resistance to freeze-thaw cycles, except the specific surface.

4. The mix with addition of AEA of Micro-air (RSA10) at the level tested fulfills the requirements to provide enough resistance to freeze-thaw cycles.

5. The same mix design may have different properties depending on the variations in the operational processes, including mixing, transporting, consolidating and curing, and, possibly, in the changes in environmental parameters, like the

temperature and humidity.

6. The air content measured from pressure meter is similar to that from LTM, with both methods measuring both entrained and entrapped air voids.

7. Lower air content and higher spacing factor were measured from AVA, comparing to that from LTM, since AVA measures entrained air voids only and LTM measures both entrained and entrapped air voids.

8. Most of the samples have lower specific surface measured from AVA than that from LTM, except the sample from job site of RR, but the correlation of specific surface measured from the two methods is not obvious.

VI. RECOMMENDATIONS

The analysis of Linear Traverse Method can be observed to be extremely time-consuming, with each analysis taking approximately three to four hours and has to be done manually. It is also believed that the results can be highly influenced by operator subjectivity. Automating the analysis of the Linear Traverse Method system by replacing the human operator with a computer can save time and allows the same job to be done more accurately.

The analysis of the Linear Traverse Method has to be done on hardened concrete. It is not recommended to use for quality control, since the quality check on a concrete structure should be done before the concrete hardened. However, the analysis of Linear Traverse Method is recommended to be used for studying the stability of air void system or comparison of air void systems in different mix designs.

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APPENDIX 1 - EQUATIONS USED

CAS-2000 EQUATIONS

GENERAL TERMS:

AVI:	Air void intercepts.
Paste:	Refers to total paste points counted
Entrapped_Air:	Refers to entrapped air points counted.
Entrained_Air:	Refers to entrained air points counted.
Coarse_Agg:	Refers to coarse aggregate points counted.
Fine_Agg:	Refers to fine aggregate points counted.
Other-1, Other-2:	Refers to "Other-1" and "Other-2" tally points.
Skip:	Refers to "Skip" button.
Actual_Traverse_Length:	Refers to the actual length of traverse as opposed to the programmed length of traverse
Avg_Air_Per_Inch:	Refers to the average number of air voids per inch of travel

Total_Points = Entrapped_Air + Entrained_Air + Coarse_Agg + Fine_Agg+ Other-1
+ Other-2 + Skip
(Note: Last three, only if enabled by operator in "Additional Functions Screen" from the Main Menu.)

FOR CALCULATIONS OF LINEAR TRAVERSE DATA:

Total_Air_Voids = AVI + Entrapped_Air + Entrained_Air.

Paste_Volume = (Paste_Content / Total_Points) * 100.0.

Avg_Air_Per_Inch = (Total_Air_Voids / Actual_Traverse_Length).

Fine_Agg_Volume = (Fine_Agg / Total_Points) * 100.0.

Coarse_Agg_Volume = (Coarse_Agg / Total_Points) * 100.0.

Average_Chord_Intercept =

Total_Sum_Length_Of_All_Voids/Total_Number_Of_Voids.

Voids_Per_Inch = Total_Number_Of_Voids / Total_X_Axis_Travel_Executed.

Specific_Surface = 4.0 / Average_Chord_Intercept.

Air_Void_Content = 100 * Average_Chord_Intercept * Voids_Per_Inch.

Paste_To_Air_Ratio = Paste_Volume / Air_Void_Content.

Spacing_Factor:

If Paste_Volume / Air_Void_Content <= 4.342, then
Spacing_Factor = Paste_Volume / (400*Avg_Air_Per_Inch).

If Paste_Volume / Air_Void_Content > 4.342, then
Spacing_Factor =
(3/Specific_Surface)*(1.4*CubeRoot((Paste_Volume/Air_Void_Content
)+1)-1.

ASTM SPECIFICATION C457-08

LINEAR TRAVERSE METHOD

N = total number of air voids intersected,
R_i = number of rotations of the respective lead screws
P_i = pitch of the corresponding lead screws,

Calculate:
T_t = Total Length of Traverse = sum of $P_i * R_i$
T_a =Traverse Length Through Air = $P_a * R_a$
T_p = Traverse Length Through Paste = $P_p * R_p$

Air Content (A), in %:

$$A = \frac{T_a * 100}{T_t}$$

Void Frequency (n):

$$n = \frac{N}{T_t}$$

Average Chord Length (l):

$$l = \frac{T_a}{N} \quad \text{or} \quad l = \frac{A}{100n}$$

Specific Surface (α):

$$\alpha = \frac{4}{l} \quad \text{or} \quad \alpha = \frac{4N}{T_a}$$

Paste Content (p), in %:

$$p = \frac{T_p * 100}{T_t}$$

Paste-Air Ratio (p/A):

$$\frac{p}{A} = \frac{T_p}{T_a}$$

Spacing Factor ($\bar{L}$):

When p/A is less than or equal to 4.342

$$\bar{L} = \frac{T_p}{4N}$$

When p/A is greater than 4.342

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(1 + \frac{p}{A}\right)^{1/3} - 1\right]$$

APPENDIX 2 - CAS-2000 DATA SHEETS

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- C2A4
Date------- 09/25/09   Project #- LN
File------- LN_C2A4
Assumed Paste Content = 27.1%
TESTING, COMPARE W/ RSA10A4

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 0.7 in
Total Number of Voids----------------- 49

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------ 2	(4.08%)	[0.00%]
Voids 10.0 to 20.0-------------- 0	(0.00%)	[0.00%]
Voids 20.0 to 30.0-------------- 0	(0.00%)	[0.00%]
Voids 30.0 to 40.0-------------- 4	(8.16%)	[0.01%]
Voids 40.0 to 50.0-------------- 10	(20.41%)	[0.05%]
Voids 50.0 to 60.0-------------- 2	(4.08%)	[0.01%]
Voids 60.0 to 70.0-------------- 4	(8.16%)	[0.03%]
Voids 70.0 to 80.0-------------- 2	(4.08%)	[0.02%]
Voids 80.0 to 90.0-------------- 2	(4.08%)	[0.02%]
Voids 90.0 to 100.0------------- 3	(6.12%)	[0.03%]
Voids 100.0 to 200.0------------ 11	(22.45%)	[0.16%]
Voids 200.0 to 393.7------------ 8	(16.33%)	[0.23%]
Voids 393.7 and greater -------- 1	(2.04%)	[0.18%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0141 in
Voids per Inch------------------------ 0.52
Specific Surface (1/in)--------------- 284.6
Paste to Air Ratio-------------------- 37.39
Air Content--------------------------- 0.73 %
Spacing Factor------------------------ 0.0392 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- C2A5
Date------- 09/25/09   Project #- LN
File------- LN_C2A5
Assumed Paste Content = 27.1%
CONTROL

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 1.1 in
Total Number of Voids----------------- 56

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	1	(1.79%)	[0.00%]
Voids 10.0 to 20.0--------------	0	(0.00%)	[0.00%]
Voids 20.0 to 30.0--------------	0	(0.00%)	[0.00%]
Voids 30.0 to 40.0--------------	1	(1.79%)	[0.00%]
Voids 40.0 to 50.0--------------	5	(8.93%)	[0.02%]
Voids 50.0 to 60.0--------------	4	(7.14%)	[0.02%]
Voids 60.0 to 70.0--------------	6	(10.71%)	[0.04%]
Voids 70.0 to 80.0--------------	5	(8.93%)	[0.04%]
Voids 80.0 to 90.0--------------	2	(3.57%)	[0.02%]
Voids 90.0 to 100.0-------------	2	(3.57%)	[0.02%]
Voids 100.0 to 200.0------------	16	(28.57%)	[0.24%]
Voids 200.0 to 393.7------------	8	(14.29%)	[0.22%]
Voids 393.7 and greater --------	6	(10.71%)	[0.51%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0193 in
Voids per Inch------------------------ 0.59
Specific Surface (1/in)--------------- 207.1
Paste to Air Ratio-------------------- 23.81
Air Content--------------------------- 1.14 %
Spacing Factor------------------------ 0.0447 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- C2B4
Date------- 10/02/09   Project #- LN
File------- LN_C2B4
Assumed Paste Content = 27.1%
CONTROL

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 1.6 in
Total Number of Voids----------------- 106

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	4	(3.77%)	[0.00%]
Voids 10.0 to 20.0--------------	7	(6.60%)	[0.01%]
Voids 20.0 to 30.0--------------	8	(7.55%)	[0.02%]
Voids 30.0 to 40.0--------------	10	(9.43%)	[0.04%]
Voids 40.0 to 50.0--------------	9	(8.49%)	[0.04%]
Voids 50.0 to 60.0--------------	7	(6.60%)	[0.04%]
Voids 60.0 to 70.0--------------	6	(5.66%)	[0.04%]
Voids 70.0 to 80.0--------------	5	(4.72%)	[0.04%]
Voids 80.0 to 90.0--------------	5	(4.72%)	[0.04%]
Voids 90.0 to 100.0-------------	4	(3.77%)	[0.04%]
Voids 100.0 to 200.0------------	23	(21.70%)	[0.34%]
Voids 200.0 to 393.7------------	11	(10.38%)	[0.29%]
Voids 393.7 and greater --------	7	(6.60%)	[0.76%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0153 in
Voids per Inch------------------------ 1.12
Specific Surface (1/in)--------------- 260.8
Paste to Air Ratio-------------------- 15.84
Air Content--------------------------- 1.71 %
Spacing Factor------------------------ 0.0298 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- C2B5
Date------- 11/05/09   Project #- LN
File------- LN_C2B5.
Assumed Paste Content =   27.1%
CONTROL

Total Travel Executed----------------- 95.0   in
Total Area Covered-------------------- 11.5   Sq. in
Total Void Length--------------------- 1.2   in
Total Number of Voids----------------- 106

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	5	(4.72%)	[0.00%]
Voids 10.0 to 20.0--------------	8	(7.55%)	[0.01%]
Voids 20.0 to 30.0--------------	11	(10.38%)	[0.03%]
Voids 30.0 to 40.0--------------	13	(12.26%)	[0.05%]
Voids 40.0 to 50.0--------------	10	(9.43%)	[0.05%]
Voids 50.0 to 60.0--------------	11	(10.38%)	[0.06%]
Voids 60.0 to 70.0--------------	11	(10.38%)	[0.08%]
Voids 70.0 to 80.0--------------	4	(3.77%)	[0.03%]
Voids 80.0 to 90.0--------------	2	(1.89%)	[0.02%]
Voids 90.0 to 100.0-------------	4	(3.77%)	[0.04%]
Voids 100.0 to 200.0------------	13	(12.26%)	[0.20%]
Voids 200.0 to 393.7------------	9	(8.49%)	[0.28%]
Voids 393.7 and greater --------	5	(4.72%)	[0.45%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0116 in
Voids per Inch------------------------ 1.12
Specific Surface (1/in)--------------- 344.5
Paste to Air Ratio-------------------- 20.93
Air Content--------------------------- 1.30   %
Spacing Factor------------------------ 0.0254 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN Sample ID- C2C4
Date------- 11/06/09 Project #- LN
File------- LN_C2C4
Assumed Paste Content = 27.1%
CONTROL

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 1.6 in
Total Number of Voids----------------- 135

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	16	(11.85%)	[0.00%]
Voids 10.0 to 20.0--------------	7	(5.19%)	[0.01%]
Voids 20.0 to 30.0--------------	15	(11.11%)	[0.04%]
Voids 30.0 to 40.0--------------	14	(10.37%)	[0.05%]
Voids 40.0 to 50.0--------------	14	(10.37%)	[0.06%]
Voids 50.0 to 60.0--------------	15	(11.11%)	[0.09%]
Voids 60.0 to 70.0--------------	5	(3.70%)	[0.03%]
Voids 70.0 to 80.0--------------	8	(5.93%)	[0.06%]
Voids 80.0 to 90.0--------------	3	(2.22%)	[0.03%]
Voids 90.0 to 100.0-------------	3	(2.22%)	[0.03%]
Voids 100.0 to 200.0------------	20	(14.81%)	[0.29%]
Voids 200.0 to 393.7------------	10	(7.41%)	[0.29%]
Voids 393.7 and greater --------	5	(3.70%)	[0.64%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0115 in
Voids per Inch------------------------ 1.42
Specific Surface (1/in)--------------- 347.4
Paste to Air Ratio-------------------- 16.57
Air Content--------------------------- 1.64 %
Spacing Factor------------------------ 0.0228 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- C2C5
Date------- 11/24/09   Project #- LN
File------- LN_C2C5.
Assumed Paste Content =   27.1%
W/ CONTROL

Total Travel Executed----------------- 95.0   in
Total Area Covered-------------------- 11.5   Sq. in
Total Void Length--------------------- 1.5   in
Total Number of Voids----------------- 144

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	18	(12.50%)	[0.01%]
Voids 10.0 to 20.0--------------	14	(9.72%)	[0.02%]
Voids 20.0 to 30.0--------------	25	(17.36%)	[0.07%]
Voids 30.0 to 40.0--------------	13	(9.03%)	[0.05%]
Voids 40.0 to 50.0--------------	9	(6.25%)	[0.04%]
Voids 50.0 to 60.0--------------	6	(4.17%)	[0.03%]
Voids 60.0 to 70.0--------------	10	(6.94%)	[0.07%]
Voids 70.0 to 80.0--------------	4	(2.78%)	[0.03%]
Voids 80.0 to 90.0--------------	2	(1.39%)	[0.02%]
Voids 90.0 to 100.0-------------	4	(2.78%)	[0.04%]
Voids 100.0 to 200.0------------	12	(8.33%)	[0.17%]
Voids 200.0 to 393.7------------	20	(13.89%)	[0.56%]
Voids 393.7 and greater --------	7	(4.86%)	[0.48%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0105 in
Voids per Inch------------------------ 1.52
Specific Surface (1/in)--------------- 381.3
Paste to Air Ratio-------------------- 17.05
Air Content--------------------------- 1.59   %
Spacing Factor------------------------ 0.0210 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN
Sample ID- RSA10A4
Date------- 09/25/09
Project #- LN
File------- LN_RSAA4
Assumed Paste Content = 27.1%
TESTING, COMPARE W/ C2A4

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 2.5 in
Total Number of Voids----------------- 452

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	27	(5.97%)	[0.01%]
Voids 10.0 to 20.0--------------	109	(24.12%)	[0.17%]
Voids 20.0 to 30.0--------------	80	(17.70%)	[0.21%]
Voids 30.0 to 40.0--------------	60	(13.27%)	[0.22%]
Voids 40.0 to 50.0--------------	60	(13.27%)	[0.28%]
Voids 50.0 to 60.0--------------	26	(5.75%)	[0.15%]
Voids 60.0 to 70.0--------------	16	(3.54%)	[0.11%]
Voids 70.0 to 80.0--------------	16	(3.54%)	[0.12%]
Voids 80.0 to 90.0--------------	9	(1.99%)	[0.08%]
Voids 90.0 to 100.0-------------	8	(1.77%)	[0.08%]
Voids 100.0 to 200.0------------	23	(5.09%)	[0.32%]
Voids 200.0 to 393.7------------	8	(1.77%)	[0.23%]
Voids 393.7 and greater --------	10	(2.21%)	[0.68%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0056 in
Voids per Inch------------------------ 4.76
Specific Surface (1/in)--------------- 714.2
Paste to Air Ratio-------------------- 10.17
Air Content--------------------------- 2.66 %
Spacing Factor------------------------ 0.0089 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN Sample ID- RSA10A5
Date------- 09/25/09 Project #- LN
File------- LN_RSAA5
Assumed Paste Content = 27.1%
W/ RSA10

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 3.6 in
Total Number of Voids----------------- 760

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	61	(8.03%)	[0.02%]
Voids 10.0 to 20.0--------------	240	(31.58%)	[0.38%]
Voids 20.0 to 30.0--------------	165	(21.71%)	[0.44%]
Voids 30.0 to 40.0--------------	89	(11.71%)	[0.32%]
Voids 40.0 to 50.0--------------	61	(8.03%)	[0.29%]
Voids 50.0 to 60.0--------------	37	(4.87%)	[0.21%]
Voids 60.0 to 70.0--------------	20	(2.63%)	[0.14%]
Voids 70.0 to 80.0--------------	7	(0.92%)	[0.05%]
Voids 80.0 to 90.0--------------	6	(0.79%)	[0.05%]
Voids 90.0 to 100.0-------------	7	(0.92%)	[0.07%]
Voids 100.0 to 200.0------------	41	(5.39%)	[0.60%]
Voids 200.0 to 393.7------------	13	(1.71%)	[0.35%]
Voids 393.7 and greater --------	13	(1.71%)	[0.90%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0048 in
Voids per Inch------------------------ 8.00
Specific Surface (1/in)--------------- 834.3
Paste to Air Ratio-------------------- 7.07
Air Content--------------------------- 3.84 %
Spacing Factor------------------------ 0.0065 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- RSA10B4
Date------- 10/30/09   Project #- LN
File------- LN_RSAB4.
Assumed Paste Content = 27.1%
W/ RSA10

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 2.6 in
Total Number of Voids----------------- 553

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	31	(5.61%)	[0.01%]
Voids 10.0 to 20.0--------------	131	(23.69%)	[0.22%]
Voids 20.0 to 30.0--------------	140	(25.32%)	[0.36%]
Voids 30.0 to 40.0--------------	94	(17.00%)	[0.34%]
Voids 40.0 to 50.0--------------	45	(8.14%)	[0.21%]
Voids 50.0 to 60.0--------------	25	(4.52%)	[0.15%]
Voids 60.0 to 70.0--------------	8	(1.45%)	[0.05%]
Voids 70.0 to 80.0--------------	8	(1.45%)	[0.06%]
Voids 80.0 to 90.0--------------	13	(2.35%)	[0.12%]
Voids 90.0 to 100.0-------------	8	(1.45%)	[0.08%]
Voids 100.0 to 200.0------------	34	(6.15%)	[0.44%]
Voids 200.0 to 393.7------------	10	(1.81%)	[0.28%]
Voids 393.7 and greater --------	6	(1.08%)	[0.41%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0047 in
Voids per Inch------------------------ 5.82
Specific Surface (1/in)--------------- 852.7
Paste to Air Ratio-------------------- 9.93
Air Content--------------------------- 2.73 %
Spacing Factor------------------------ 0.0074 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- RSA10B5
Date------- 10/30/09   Project #- LN
File------- LN_RSAB5.
Assumed Paste Content =   27.1%
W/ RSA10B5

Total Travel Executed----------------- 95.0   in
Total Area Covered-------------------- 11.5   Sq. in
Total Void Length--------------------- 3.5   in
Total Number of Voids----------------- 684

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	28	(4.09%)	[0.01%]
Voids 10.0 to 20.0--------------	103	(15.06%)	[0.17%]
Voids 20.0 to 30.0--------------	176	(25.73%)	[0.46%]
Voids 30.0 to 40.0--------------	115	(16.81%)	[0.41%]
Voids 40.0 to 50.0--------------	84	(12.28%)	[0.39%]
Voids 50.0 to 60.0--------------	48	(7.02%)	[0.28%]
Voids 60.0 to 70.0--------------	29	(4.24%)	[0.20%]
Voids 70.0 to 80.0--------------	12	(1.75%)	[0.09%]
Voids 80.0 to 90.0--------------	10	(1.46%)	[0.09%]
Voids 90.0 to 100.0-------------	8	(1.17%)	[0.08%]
Voids 100.0 to 200.0------------	52	(7.60%)	[0.73%]
Voids 200.0 to 393.7------------	15	(2.19%)	[0.45%]
Voids 393.7 and greater --------	4	(0.58%)	[0.32%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0051 in
Voids per Inch------------------------ 7.20
Specific Surface (1/in)--------------- 779.4
Paste to Air Ratio-------------------- 7.34
Air Content--------------------------- 3.70   %
Spacing Factor------------------------ 0.0071 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN
Sample ID- RSA10C4
Date------- 10/31/09
Project #- LN
File------- LN_RSAC4.
Assumed Paste Content = 27.1%
W/ RSA10

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 3.7 in
Total Number of Voids----------------- 1000

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	144	(14.40%)	[0.06%]
Voids 10.0 to 20.0--------------	298	(29.80%)	[0.48%]
Voids 20.0 to 30.0--------------	181	(18.10%)	[0.47%]
Voids 30.0 to 40.0--------------	120	(12.00%)	[0.44%]
Voids 40.0 to 50.0--------------	80	(8.00%)	[0.38%]
Voids 50.0 to 60.0--------------	51	(5.10%)	[0.29%]
Voids 60.0 to 70.0--------------	28	(2.80%)	[0.19%]
Voids 70.0 to 80.0--------------	18	(1.80%)	[0.14%]
Voids 80.0 to 90.0--------------	14	(1.40%)	[0.12%]
Voids 90.0 to 100.0-------------	9	(0.90%)	[0.09%]
Voids 100.0 to 200.0------------	39	(3.90%)	[0.56%]
Voids 200.0 to 393.7------------	13	(1.30%)	[0.36%]
Voids 393.7 and greater --------	5	(0.50%)	[0.27%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0037 in
Voids per Inch------------------------ 10.53
Specific Surface (1/in)--------------- 1092.5
Paste to Air Ratio-------------------- 7.03
Air Content--------------------------- 3.85 %
Spacing Factor------------------------ 0.0050 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- RSA10C5
Date------- 11/03/09   Project #- LN
File------- LN_RSAC5.
Assumed Paste Content =   27.1%
W/ RSA10

Total Travel Executed----------------- 95.0   in
Total Area Covered-------------------- 11.5   Sq. in
Total Void Length--------------------- 4.2   in
Total Number of Voids----------------- 1274

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	207	(16.25%)	[0.09%]
Voids 10.0 to 20.0--------------	328	(25.75%)	[0.51%]
Voids 20.0 to 30.0--------------	285	(22.37%)	[0.74%]
Voids 30.0 to 40.0--------------	167	(13.11%)	[0.60%]
Voids 40.0 to 50.0--------------	81	(6.36%)	[0.38%]
Voids 50.0 to 60.0--------------	63	(4.95%)	[0.36%]
Voids 60.0 to 70.0--------------	37	(2.90%)	[0.26%]
Voids 70.0 to 80.0--------------	21	(1.65%)	[0.17%]
Voids 80.0 to 90.0--------------	17	(1.33%)	[0.15%]
Voids 90.0 to 100.0-------------	18	(1.41%)	[0.18%]
Voids 100.0 to 200.0------------	34	(2.67%)	[0.49%]
Voids 200.0 to 393.7------------	14	(1.10%)	[0.38%]
Voids 393.7 and greater --------	2	(0.16%)	[0.12%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0033 in
Voids per Inch------------------------ 13.41
Specific Surface (1/in)--------------- 1212.4
Paste to Air Ratio-------------------- 6.13
Air Content--------------------------- 4.42   %
Spacing Factor------------------------ 0.0042 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- RVR15A4
Date------- 10/02/09   Project #- LN
File------- LN_RVRA4
Assumed Paste Content = 27.1%
W/ RVR15

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 5.2 in
Total Number of Voids----------------- 1267

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	153	(12.08%)	[0.07%]
Voids 10.0 to 20.0--------------	237	(18.71%)	[0.38%]
Voids 20.0 to 30.0--------------	283	(22.34%)	[0.73%]
Voids 30.0 to 40.0--------------	193	(15.23%)	[0.71%]
Voids 40.0 to 50.0--------------	135	(10.66%)	[0.64%]
Voids 50.0 to 60.0--------------	96	(7.58%)	[0.55%]
Voids 60.0 to 70.0--------------	49	(3.87%)	[0.34%]
Voids 70.0 to 80.0--------------	26	(2.05%)	[0.20%]
Voids 80.0 to 90.0--------------	22	(1.74%)	[0.20%]
Voids 90.0 to 100.0-------------	4	(0.32%)	[0.04%]
Voids 100.0 to 200.0------------	50	(3.95%)	[0.68%]
Voids 200.0 to 393.7------------	9	(0.71%)	[0.28%]
Voids 393.7 and greater --------	10	(0.79%)	[0.69%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0041 in
Voids per Inch------------------------ 13.34
Specific Surface (1/in)--------------- 967.9
Paste to Air Ratio-------------------- 4.92
Air Content--------------------------- 5.51 %
Spacing Factor------------------------ 0.0047 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- RVR15A5
Date------- 10/09/09   Project #- LN
File------- RVRA5
Assumed Paste Content = 27.1%
W/ RVR15

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 6.6 in
Total Number of Voids----------------- 1784

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	295	(16.54%)	[0.15%]
Voids 10.0 to 20.0--------------	469	(26.29%)	[0.74%]
Voids 20.0 to 30.0--------------	341	(19.11%)	[0.88%]
Voids 30.0 to 40.0--------------	233	(13.06%)	[0.86%]
Voids 40.0 to 50.0--------------	139	(7.79%)	[0.66%]
Voids 50.0 to 60.0--------------	84	(4.71%)	[0.48%]
Voids 60.0 to 70.0--------------	54	(3.03%)	[0.37%]
Voids 70.0 to 80.0--------------	40	(2.24%)	[0.32%]
Voids 80.0 to 90.0--------------	33	(1.85%)	[0.30%]
Voids 90.0 to 100.0-------------	15	(0.84%)	[0.15%]
Voids 100.0 to 200.0------------	55	(3.08%)	[0.77%]
Voids 200.0 to 393.7------------	18	(1.01%)	[0.53%]
Voids 393.7 and greater --------	8	(0.45%)	[0.74%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0037 in
Voids per Inch------------------------ 18.78
Specific Surface (1/in)--------------- 1083.5
Paste to Air Ratio-------------------- 3.91
Air Content--------------------------- 6.93 %
Spacing Factor------------------------ 0.0036 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN
Sample ID- RVR15B4
Date------- 11/06/09
Project #- LN
File------- LN_RVRB4.
Assumed Paste Content = 27.1%
W/ RVR15

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 4.8 in
Total Number of Voids----------------- 1658

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	499	(30.10%)	[0.27%]
Voids 10.0 to 20.0--------------	512	(30.88%)	[0.78%]
Voids 20.0 to 30.0--------------	284	(17.13%)	[0.73%]
Voids 30.0 to 40.0--------------	125	(7.54%)	[0.45%]
Voids 40.0 to 50.0--------------	81	(4.89%)	[0.38%]
Voids 50.0 to 60.0--------------	43	(2.59%)	[0.25%]
Voids 60.0 to 70.0--------------	26	(1.57%)	[0.18%]
Voids 70.0 to 80.0--------------	19	(1.15%)	[0.15%]
Voids 80.0 to 90.0--------------	13	(0.78%)	[0.11%]
Voids 90.0 to 100.0-------------	9	(0.54%)	[0.09%]
Voids 100.0 to 200.0------------	24	(1.45%)	[0.34%]
Voids 200.0 to 393.7------------	12	(0.72%)	[0.36%]
Voids 393.7 and greater --------	11	(0.66%)	[0.97%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0029 in
Voids per Inch------------------------ 17.45
Specific Surface (1/in)--------------- 1382.6
Paste to Air Ratio-------------------- 5.37
Air Content--------------------------- 5.05 %
Spacing Factor------------------------ 0.0035 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN Sample ID- RVR15B5
Date------- 11/13/09 Project #- LN
File------- LN_RVRB5
Assumed Paste Content = 27.1%
W/ RVR15

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 4.7 in
Total Number of Voids----------------- 1525

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	438	(28.72%)	[0.29%]
Voids 10.0 to 20.0--------------	497	(32.59%)	[0.75%]
Voids 20.0 to 30.0--------------	242	(15.87%)	[0.63%]
Voids 30.0 to 40.0--------------	117	(7.67%)	[0.42%]
Voids 40.0 to 50.0--------------	60	(3.93%)	[0.28%]
Voids 50.0 to 60.0--------------	39	(2.56%)	[0.22%]
Voids 60.0 to 70.0--------------	32	(2.10%)	[0.22%]
Voids 70.0 to 80.0--------------	20	(1.31%)	[0.16%]
Voids 80.0 to 90.0--------------	12	(0.79%)	[0.11%]
Voids 90.0 to 100.0-------------	12	(0.79%)	[0.12%]
Voids 100.0 to 200.0------------	28	(1.84%)	[0.41%]
Voids 200.0 to 393.7------------	16	(1.05%)	[0.47%]
Voids 393.7 and greater --------	12	(0.79%)	[0.88%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0031 in
Voids per Inch------------------------ 16.05
Specific Surface (1/in)--------------- 1296.5
Paste to Air Ratio-------------------- 5.47
Air Content--------------------------- 4.95 %
Spacing Factor------------------------ 0.0037 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN Sample ID- RVR15C4
Date------- 11/19/09 Project #- LN
File------- LN_RVRC4
Assumed Paste Content = 27.1%
W/ RVR15

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 6.1 in
Total Number of Voids----------------- 2032

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	608	(29.92%)	[0.30%]
Voids 10.0 to 20.0--------------	512	(25.20%)	[0.80%]
Voids 20.0 to 30.0--------------	311	(15.31%)	[0.82%]
Voids 30.0 to 40.0--------------	197	(9.69%)	[0.71%]
Voids 40.0 to 50.0--------------	140	(6.89%)	[0.66%]
Voids 50.0 to 60.0--------------	81	(3.99%)	[0.47%]
Voids 60.0 to 70.0--------------	46	(2.26%)	[0.31%]
Voids 70.0 to 80.0--------------	32	(1.57%)	[0.25%]
Voids 80.0 to 90.0--------------	19	(0.94%)	[0.17%]
Voids 90.0 to 100.0-------------	11	(0.54%)	[0.11%]
Voids 100.0 to 200.0------------	48	(2.36%)	[0.67%]
Voids 200.0 to 393.7------------	18	(0.89%)	[0.53%]
Voids 393.7 and greater --------	9	(0.44%)	[0.62%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0030 in
Voids per Inch------------------------ 21.39
Specific Surface (1/in)--------------- 1332.3
Paste to Air Ratio-------------------- 4.22
Air Content--------------------------- 6.42 %
Spacing Factor------------------------ 0.0032 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN Sample ID- RVR15C5
Date------- 11/20/09 Project #- LN
File------- LN_RVRC5.
Assumed Paste Content = 27.1%
W/ RVR15

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 4.9 in
Total Number of Voids----------------- 1471

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	372	(25.29%)	[0.19%]
Voids 10.0 to 20.0--------------	399	(27.12%)	[0.63%]
Voids 20.0 to 30.0--------------	224	(15.23%)	[0.59%]
Voids 30.0 to 40.0--------------	157	(10.67%)	[0.58%]
Voids 40.0 to 50.0--------------	89	(6.05%)	[0.42%]
Voids 50.0 to 60.0--------------	61	(4.15%)	[0.35%]
Voids 60.0 to 70.0--------------	40	(2.72%)	[0.27%]
Voids 70.0 to 80.0--------------	23	(1.56%)	[0.18%]
Voids 80.0 to 90.0--------------	9	(0.61%)	[0.08%]
Voids 90.0 to 100.0-------------	17	(1.16%)	[0.17%]
Voids 100.0 to 200.0------------	56	(3.81%)	[0.83%]
Voids 200.0 to 393.7------------	18	(1.22%)	[0.54%]
Voids 393.7 and greater --------	6	(0.41%)	[0.35%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0033 in
Voids per Inch------------------------ 15.48
Specific Surface (1/in)--------------- 1195.8
Paste to Air Ratio-------------------- 5.23
Air Content--------------------------- 5.18 %
Spacing Factor------------------------ 0.0040 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- KY395A4
Date------- 12/01/09   Project #- LN
File------- LN_KYA4
Assumed Paste Content = 27.1%
AT JOB SITE KY 395

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 4.5 in
Total Number of Voids----------------- 1166

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	247	(21.18%)	[0.16%]
Voids 10.0 to 20.0--------------	297	(25.47%)	[0.45%]
Voids 20.0 to 30.0--------------	185	(15.87%)	[0.48%]
Voids 30.0 to 40.0--------------	128	(10.98%)	[0.46%]
Voids 40.0 to 50.0--------------	78	(6.69%)	[0.37%]
Voids 50.0 to 60.0--------------	62	(5.32%)	[0.36%]
Voids 60.0 to 70.0--------------	39	(3.34%)	[0.26%]
Voids 70.0 to 80.0--------------	23	(1.97%)	[0.18%]
Voids 80.0 to 90.0--------------	19	(1.63%)	[0.17%]
Voids 90.0 to 100.0-------------	14	(1.20%)	[0.14%]
Voids 100.0 to 200.0------------	48	(4.12%)	[0.72%]
Voids 200.0 to 393.7------------	18	(1.54%)	[0.51%]
Voids 393.7 and greater --------	8	(0.69%)	[0.42%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0038 in
Voids per Inch------------------------ 12.27
Specific Surface (1/in)--------------- 1047.6
Paste to Air Ratio-------------------- 5.78
Air Content--------------------------- 4.69 %
Spacing Factor------------------------ 0.0047 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- KY395A5
Date------- 12/04/09   Project #- LN
File------- LN_KYA5
Assumed Paste Content = 27.1%
AT JOB SITE KY395

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 3.9 in
Total Number of Voids----------------- 978

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	177	(18.10%)	[0.09%]
Voids 10.0 to 20.0--------------	254	(25.97%)	[0.39%]
Voids 20.0 to 30.0--------------	168	(17.18%)	[0.43%]
Voids 30.0 to 40.0--------------	115	(11.76%)	[0.42%]
Voids 40.0 to 50.0--------------	57	(5.83%)	[0.27%]
Voids 50.0 to 60.0--------------	45	(4.60%)	[0.26%]
Voids 60.0 to 70.0--------------	26	(2.66%)	[0.17%]
Voids 70.0 to 80.0--------------	27	(2.76%)	[0.21%]
Voids 80.0 to 90.0--------------	19	(1.94%)	[0.17%]
Voids 90.0 to 100.0-------------	12	(1.23%)	[0.12%]
Voids 100.0 to 200.0------------	61	(6.24%)	[0.86%]
Voids 200.0 to 393.7------------	11	(1.12%)	[0.29%]
Voids 393.7 and greater --------	6	(0.61%)	[0.47%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0040 in
Voids per Inch------------------------ 10.29
Specific Surface (1/in)--------------- 992.4
Paste to Air Ratio-------------------- 6.53
Air Content--------------------------- 4.15 %
Spacing Factor------------------------ 0.0053 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- RRA4
Date------- 11/12/09   Project #- LN
File------- LN_RRA4
Assumed Paste Content = 27.1%
RRA4 JOB SITE

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 6.8 in
Total Number of Voids----------------- 1415

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	146	(10.32%)	[0.09%]
Voids 10.0 to 20.0--------------	311	(21.98%)	[0.48%]
Voids 20.0 to 30.0--------------	290	(20.49%)	[0.76%]
Voids 30.0 to 40.0--------------	168	(11.87%)	[0.61%]
Voids 40.0 to 50.0--------------	134	(9.47%)	[0.63%]
Voids 50.0 to 60.0--------------	111	(7.84%)	[0.64%]
Voids 60.0 to 70.0--------------	63	(4.45%)	[0.43%]
Voids 70.0 to 80.0--------------	33	(2.33%)	[0.26%]
Voids 80.0 to 90.0--------------	27	(1.91%)	[0.24%]
Voids 90.0 to 100.0-------------	20	(1.41%)	[0.20%]
Voids 100.0 to 200.0------------	72	(5.09%)	[1.02%]
Voids 200.0 to 393.7------------	25	(1.77%)	[0.74%]
Voids 393.7 and greater --------	15	(1.06%)	[1.09%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0048 in
Voids per Inch------------------------ 14.89
Specific Surface (1/in)--------------- 827.4
Paste to Air Ratio-------------------- 3.76
Air Content--------------------------- 7.20 %
Spacing Factor------------------------ 0.0046 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- RRA5
Date------- 10/29/09   Project #- LN
File------- LN_RRA5
Assumed Paste Content = 27.1%
RRA5, FROM SITE

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 6.0 in
Total Number of Voids----------------- 1243

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	79	(6.36%)	[0.02%]
Voids 10.0 to 20.0--------------	187	(15.04%)	[0.31%]
Voids 20.0 to 30.0--------------	242	(19.47%)	[0.65%]
Voids 30.0 to 40.0--------------	245	(19.71%)	[0.89%]
Voids 40.0 to 50.0--------------	143	(11.50%)	[0.67%]
Voids 50.0 to 60.0--------------	91	(7.32%)	[0.52%]
Voids 60.0 to 70.0--------------	76	(6.11%)	[0.52%]
Voids 70.0 to 80.0--------------	42	(3.38%)	[0.33%]
Voids 80.0 to 90.0--------------	24	(1.93%)	[0.21%]
Voids 90.0 to 100.0-------------	23	(1.85%)	[0.23%]
Voids 100.0 to 200.0------------	66	(5.31%)	[0.95%]
Voids 200.0 to 393.7------------	18	(1.45%)	[0.54%]
Voids 393.7 and greater --------	7	(0.56%)	[0.48%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0048 in
Voids per Inch------------------------ 13.08
Specific Surface (1/in)--------------- 826.4
Paste to Air Ratio-------------------- 4.28
Air Content--------------------------- 6.33 %
Spacing Factor------------------------ 0.0052 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN   Sample ID- JI4
Date------- 11/13/09   Project #- LN
File------- LN_JI4
Assumed Paste Content = 27.1%
AT JOB SITE

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 4.7 in
Total Number of Voids----------------- 1265

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	253	(20.00%)	[0.17%]
Voids 10.0 to 20.0--------------	327	(25.85%)	[0.50%]
Voids 20.0 to 30.0--------------	238	(18.81%)	[0.62%]
Voids 30.0 to 40.0--------------	154	(12.17%)	[0.56%]
Voids 40.0 to 50.0--------------	97	(7.67%)	[0.45%]
Voids 50.0 to 60.0--------------	54	(4.27%)	[0.31%]
Voids 60.0 to 70.0--------------	33	(2.61%)	[0.23%]
Voids 70.0 to 80.0--------------	28	(2.21%)	[0.22%]
Voids 80.0 to 90.0--------------	17	(1.34%)	[0.15%]
Voids 90.0 to 100.0-------------	14	(1.11%)	[0.14%]
Voids 100.0 to 200.0------------	27	(2.13%)	[0.38%]
Voids 200.0 to 393.7------------	13	(1.03%)	[0.36%]
Voids 393.7 and greater --------	10	(0.79%)	[0.84%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0037 in
Voids per Inch------------------------ 13.32
Specific Surface (1/in)--------------- 1079.7
Paste to Air Ratio-------------------- 5.50
Air Content--------------------------- 4.93 %
Spacing Factor------------------------ 0.0045 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

ACCUMULATED LINEAR TRAVERSE DATA

Originator- LN
Operator--- LN
Sample ID- JI5
Date------- 12/03/09
Project #- LN
File------- LN_JI5
Assumed Paste Content = 27.1%
AT JOB SITE

Total Travel Executed----------------- 95.0 in
Total Area Covered-------------------- 11.5 Sq. in
Total Void Length--------------------- 4.7 in
Total Number of Voids----------------- 1378

Void Size Breakdown (increments of 0.0001 inches)

Voids less than 10.0------------	227	(16.47%)	[0.13%]
Voids 10.0 to 20.0--------------	358	(25.98%)	[0.55%]
Voids 20.0 to 30.0--------------	262	(19.01%)	[0.68%]
Voids 30.0 to 40.0--------------	182	(13.21%)	[0.66%]
Voids 40.0 to 50.0--------------	113	(8.20%)	[0.53%]
Voids 50.0 to 60.0--------------	77	(5.59%)	[0.44%]
Voids 60.0 to 70.0--------------	52	(3.77%)	[0.35%]
Voids 70.0 to 80.0--------------	23	(1.67%)	[0.18%]
Voids 80.0 to 90.0--------------	30	(2.18%)	[0.27%]
Voids 90.0 to 100.0-------------	9	(0.65%)	[0.09%]
Voids 100.0 to 200.0------------	31	(2.25%)	[0.46%]
Voids 200.0 to 393.7------------	11	(0.80%)	[0.31%]
Voids 393.7 and greater --------	3	(0.22%)	[0.27%]

LINEAR TRAVERSE CALCULATIONS

Average Chord Intercept--------------- 0.0034 in
Voids per Inch------------------------ 14.51
Specific Surface (1/in)--------------- 1178.8
Paste to Air Ratio-------------------- 5.51
Air Content--------------------------- 4.92 %
Spacing Factor------------------------ 0.0041 in

Values in "( )" next to "Void Size" columns show void "Count" distribution relative to "Total Number of Voids".
Values in "[ ]" next to "Void Size" columns show void "Length" distribution relative to total "Air Content".

VITA

Lokman Ng was born on June 3, 1984 in Hong Kong, the daughter of Christine Wong and Dickhong Ng. She attended kindergarten, primary school, secondary school and post-secondary school at Munsang College in Hong Kong.

In 2003, Lokman moved from her hometown, Hong Kong, to the United States of America. She entered the J. B. Speed School of Engineering in the University of Louisville, Kentucky, in August 2004. She was inducted into the National Civil Engineering Honor Society, Chi Epsilon, in May 2006. In May 2009, she received her bachelor degree, with Highest Honor, in Civil Engineering.

On a personal note, Lokman loves her parents, her sister and their family’s dog, Yoshi, very much. Without them, she would have never succeeded.