Field Study of Air Content Stability in the Slipform Paving Process

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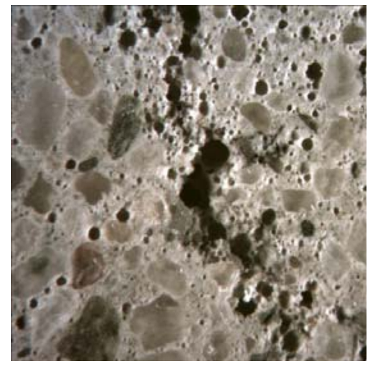

Field Study of Air Content Stability in the Slipform Paving Process Final Report

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December 2012

providing engineering solutions to improve pavement performance

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16. Abstract

This study evaluated the impacts of construction on the air content and air-void systemstructure of portland cement concrete pavements. The primary intent was to quantify the air content of freshconcrete before and after it has gone through the slipform paver. The air-void system parameters of hardenedconcrete were then assessed using cast and extracted core specimens. The results of the air content testing on fresh concrete and the concrete cylinder specimens cast in the field suggested that there is some loss of air as the concrete passes through the paver. Laboratory testing performed on cores extracted from the pavement did not provide any conclusive evidence that entrained air is lost during the slipform paving process. In fact, many of the extracted cores had measured air content valuesthat were much higher than the specification requirement. If excessive, this could result in increased permeability and low-strength related issues. Although a rigorous statistical analysis was not performed, the results suggest that the air content testing on fresh concrete is not capturing the "true" air content of the concrete placed with a slipform paver. The fresh concrete air content is generally lower than the air content measured in the cores.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

EXECUTIVE SUMMARY

Background

A number of factors are known to affect the air content of paving concrete, including portland cement type and content, supplementary cementitious materials type and content, admixtures, mixer type and mixing duration, placement methods, ambient temperatures, and so on. In addition, some of the air that is present when the concrete is placed on-grade in front of the paver is lost as it is vibrated and consolidated during the slipform paving process (Whiting and Nagi 1998; Taylor et al. 2007). Recognizing this, a number of state highway agencies (SHAs) specify that concrete either be sampled after the paver (e.g., Kansas, Indiana) or that the air content of concrete placed on grade in front of the paver be higher than that normally required with the assumption that some air will be lost as the concrete passes through the paver (e.g., Wisconsin, Iowa). In the case of the Wisconsin Department of Transportation (WisDOT), the target air content for concrete on grade in front of the paver is 5.5 to 8.5 percent, with the assumption that approximately 1 percent of the air will be lost as it is vibrated and consolidated by the paver. This issue is of increasing importance as WisDOT moves to adopt performance-related specifications as there is a need to select the "correct" amount of air necessary to ensure resistance to freeze-thaw damage while also not compromising the strength and permeability of the hardened concrete.

In order for the air in concrete to be effective at preventing or minimizing free-thaw damage, it must be entrained (versus entrapped) as a dense network of closely spaced microscopic spherical bubbles. Pioneering research by T. C. Powers led to the development of an expression called the spacing factor that describes, for the majority of the paste, the distance to the nearest air void (Snyder, Natesaiyer, and Hover 2001). Typically, the entrained spherical air bubbles should range in size from 50 to 200 µm (Mehta and Montiero 2005) and the spacing factor, measured in accordance with ASTM C457 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*, should be less than 0.008 in (0.200 mm) to be effective in protecting the hydrated cement paste from freeze-thaw damage (ACI 2008). Debate exists over whether those requirements are too strict for modern paving concrete, which typically has a lower water-to-cementitious ratio (*w/cm*) then that used to develop the criteria in the 1950s and 1960s; in fact, the Canadian Standards Association (CSA) A23.1 Clause 4.3.3.3 on air-void parameters specifies a maximum spacing factor of 0.009 in (0.230 mm) for most concrete, but increases this limit to 0.010 in (0.250 mm) if the *w/cm* is 0.36 or less as is common in high-performance concrete and silica fume overlays (CSA 2011).

Alternatively, as air is entrained in concrete there is a commensurate loss of strength. If the upper limit of the air content specification is broached, the loss of strength can be significant and accompanied by an increase in permeability, both of which can negatively affect the durability of the concrete. In some cases, the coalescence of air voids at the interfaces of aggregates has been noted as a result of too much entrained air being present (Taylor et al. 2007). Furthermore, air loss and the potential disruption of the air-void system by internal vibration and manipulation of the surface as the concrete is paved are also possible. Often, problems associated with this are attributed to the concrete itself and not specifically to the paver used, although the frequency of internal vibration is of concern (Stutzman 1999; Taylor et al. 2007). The creation of "vibrator trails" in slipform concrete is one artifact of air loss (as well as mix segregation) caused by internal vibration. Another is the loss of air near the surface, although this is rare in slipform paving unless additional finishing is applied. Nevertheless, the impact of specific concrete plants or pavers on the in-place concrete air-void system is rarely studied unless something has gone wrong.

Study Objectives

The objective of this study is to evaluate the impacts of vibration and consolidation of modern slipform pavers used in Wisconsin on the air-void structure and air content of portland cement concrete pavements. The primary intent is to quantify the air content of fresh concrete before and after it has gone through the slipform paver. The air-void system parameters of hardened concrete are then assessed using cast and extracted core specimens. Determining the changes that occur to the air content and air-void system parameters will assist in identifying appropriate air content target values, thereby allowing WisDOT and the Wisconsin paving industry to optimize the properties of the mix to ensure the in-place concrete meets or exceeds desired properties.

Summary

Under this project, the impacts of the slipform paving on the air content and on the air-void system parameters of portland cement concrete pavements in Wisconsin were studied through limited laboratory and field testing. Twelve field projects were selected for this study which included a broad range of variables including aggregate type, batch plant type, paver type, and geographical locations.

The total air content testing performed on fresh concrete and the microscopical evaluation of field-cast cylinder specimens indicated that there could potentially be a loss of total air, on the order of 1 percent, resulting from the concrete passing through the slipform paver. However, microscopical evaluation performed on cores extracted from the pavement did not provide conclusive evidence that entrained air is lost during the slipform paving process. These conflicting results could potentially be attributed to the field preparation method, in which an inserted vibrator was used to consolidate the concrete. The specimens prepared using the concrete obtained after the paver were thus consolidated twice (first by the paver and then by the internal vibration when during the cylinder preparation). Hence, it is not possible to determine the air loss due to the consolidation efforts of the paver alone.

Figures ES-1 and ES-2 summarize the air content measured in the fresh concrete, field-cast cylinders, and the core samples extracted from the pavement. Figure ES-1 reports the laboratory results of the hardened air content using automated analysis methods [not an ASTM standard test method; described by Sutter, Van Dam and Thomas (2007)], whereas figure ES-2 reports the laboratory results based on ASTM C457 manual analysis methods.

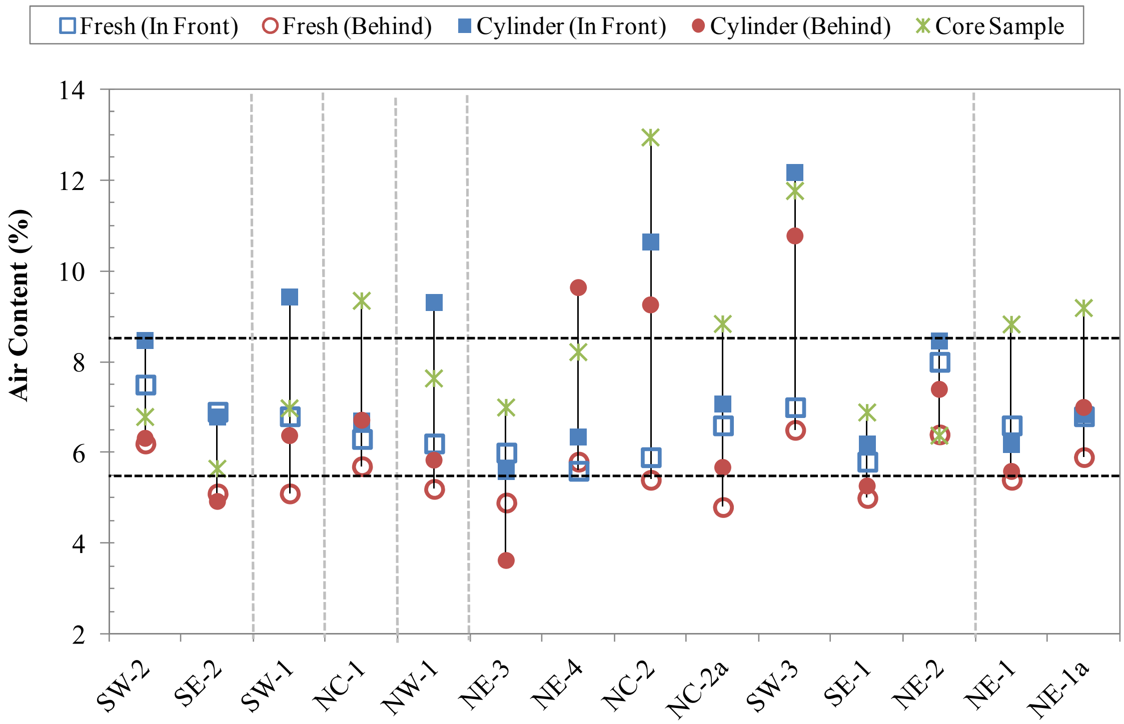

Figure ES-1. Summary of air contents measured in the field and laboratory (Automated Method).

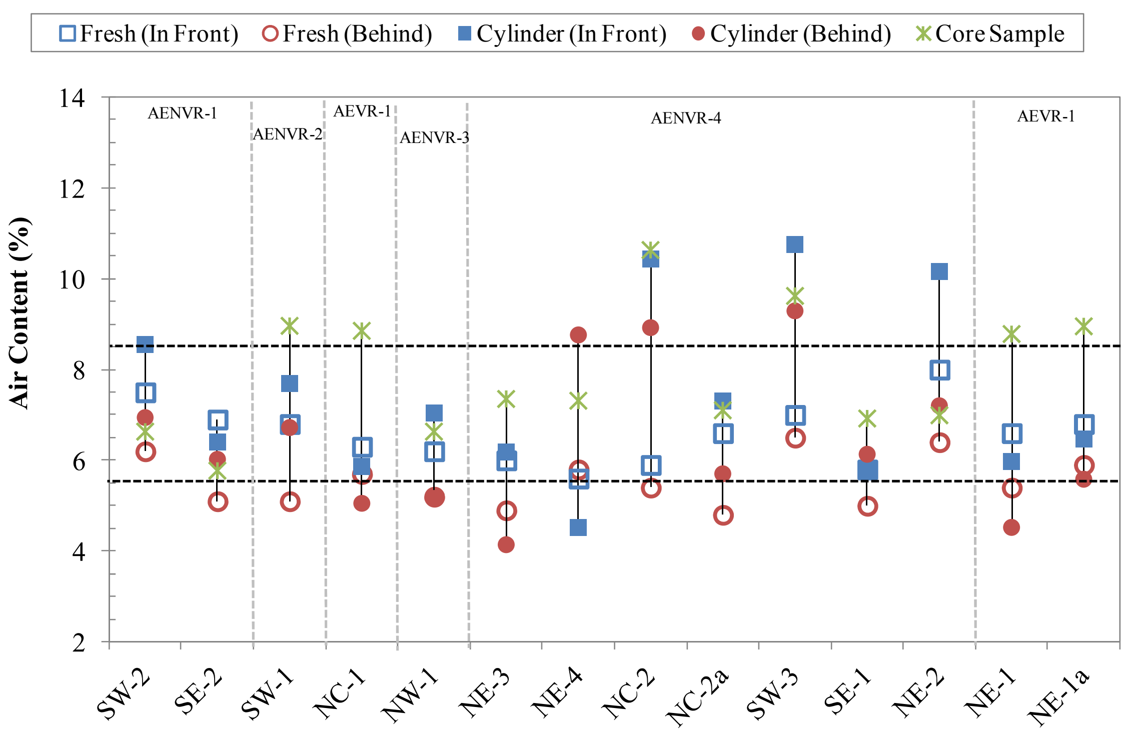

Figure ES-2. Summary of air contents measured in the field and laboratory (ASTM C457 Manual Method).

Overall Summary of Findings

This research study involved the evaluation of the impact of the construction process on the air content and the air-void system parameters of portland cement concrete pavements through limited laboratory and field investigations. An overall summary of the conclusions from the study is presented below:

- The results of the air content testing on fresh concrete and microscopic evaluation of concrete cylinder specimens cast in the field suggested that there may be loss of total air (approximately 1 percent) as the concrete passes through the paver. However, microscopic evaluation performed on cores extracted from the pavement did not provide conclusive evidence that entrained air is lost due to the slipform paving process.
- Consistent with the specified test methods and standards of practice, the fresh concrete placed in the air meter and in the cylinder molds was consolidated using an internal vibrator. Thus, concrete sampled and tested after passing through the slipform paver was consolidated twice, first by the paver and then again by the internal vibration used on the specimens during preparation. It is reasonable to expect that the additional consolidation effort would result in a decrease in the measured air contents. However, this occurrence makes it impossible to determine the amount of air loss due to the slipform paver and that which was lost due to the internal vibration during consolidation.
- In some cases, it appears that the internal vibration used in the preparation of field-cast cylinders may have led to the accumulation of air voids around the aggregates. Alternative methods of consolidation, such as rodding or the use of a vibration table, may be the preferred compaction method.
- Many of the extracted cores had measured air content values that were higher than the specified air content. High air contents can result in issues with increased permeability and low strength. Some extracted cores also exhibited segregation issues, accumulation of air voids around the aggregates, and coalescence of air voids in the paste. The majority of the extracted cores also showed significant variation in the air content through the depth of the specimen.
- The results of this study suggest that the air content testing on fresh concrete is not capturing the "true" air content of the concrete placed with a slipform paver. The fresh concrete air content is generally lower than the air content measured in the core samples.

Future Research

Based on the results of this work, recommendations for future work activities are summarized below:

- The field and laboratory investigations performed in this study suggest that the use of internal vibration to create specimens is problematic, as is evident from the vibrator insertion marks seen in many of the field-cast specimens, indicating segregation issues. Due to these observations, a study to investigate the influence of internal vibration on strength development, air content, air-void system parameters, permeability, and freeze-thaw durability is suggested. These can be compared to specimens consolidated using hand rodding (this, however, may not be practical for some stiff paving mixtures that have slumps of less than 1 inch) and a vibrator table.

- Since internal vibration is the most popular consolidation method used in the industry, a study to evaluate the impact of the vibrator diameter and the vibration frequency on hardened concrete properties is suggested.
- In order to get a better understanding on the impact of the paving process and other concrete mix design parameters on the air content and the air-void system parameters of concrete pavements, a rigorous experiment should be designed where multiple locations within a single project site are tested. Laboratory investigations should be followed by periodic field investigations to monitor and understand the long-term impacts.
- The air content test method based on the pressure meter was developed when Vinsol resin-based air entraining admixtures were in widespread use. In general, the air bubbles entrained by non-Vinsol resin-based air entraining admixtures are finer and there is concern that the pressure meter may not be as sensitive to the presence of these finer air bubbles. A study should be considered to determine the sensitivity of commonly used quality control tools for the determination of air content in fresh concrete to assess their effectiveness in accurately measuring the total air in modern concrete paving mixtures.

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CHAPTER 1. INTRODUCTION

Background

A number of factors are known to affect the air content of paving concrete, including such items as portland cement type and content, supplementary cementitious materials type and content, admixtures, batch plant type and mixing duration, placement methods, ambient temperatures, and so on. In addition, some of the air that is present when the concrete is placed in front of the paver is lost as it is vibrated and consolidated through the slipform paver (Whiting and Nagi 1998; Taylor et al. 2007). Recognizing this, a number of state highway agencies (SHAs) now specify that concrete either be sampled after the paver (e.g., Kansas, Indiana) or that the air content of concrete placed on grade in front of the paver be higher than that normally required with the assumption that some air will be lost as the concrete passes through the paver (e.g., Wisconsin, Iowa). In the case of the Wisconsin Department of Transportation (WisDOT), the target air content for concrete on grade in front of the paver is 5.5 to 8.5 percent, with the assumption that approximately 1 percent of the air will be lost as it is vibrated and consolidated by the paver. This issue is of increasing importance as WisDOT moves to adopt performance-related specifications as there is a need to select the "correct" amount of air necessary to ensure resistance to freeze-thaw damage while also not compromising the strength and permeability of the hardened concrete.

The need for entrained air in concrete is based on decades of research that began in the 1930s, with work conducted in Kansas in 1933 and in New York State in 1938. The microscopic air bubbles that are purposefully entrained in concrete are essential to protect it against freeze-thaw damage, essentially acting as tiny pressure relief valves that dissipate stress as saturated concrete freezes. As a result, air entrained concrete is universally specified for road construction throughout most of the U.S., including the upper Midwest (e.g. Wisconsin, Michigan, Minnesota, Iowa, and so on). Even in areas not exposed to freeze-thaw conditions, air is commonly entrained in concrete for workability.

Conceptually, the mechanism leading to freeze-thaw damage in concrete is quite simple, resulting from the 9 percent volume expansion that occurs as water in small capillary pores (which are dispersed throughout the hydrated paste) transitions from liquid to solid as it freezes. In this theory, the hydraulic pressure generated in the remaining liquid water can fracture the surrounding concrete unless it is relieved. However, research has shown that the actual mechanism is much more complex, as it also involves the generation of osmotic pressures that develop as the ionic concentration of the pore solution changes during the formation of ice. Many chemical deicers tend to amplify that mechanism by altering the pore solution chemistry, producing thermal shock, and increasing the level of saturation due to their hydrophilic nature. Other theories on why damage occurs abound but regardless of the exact mechanism, it is clear that a minimum volumetric content of air must be entrained in the concrete and that this air must be distributed as microscopic bubbles spaced closely enough to protect the paste from damage during freezing.

Based on this knowledge, modern concrete practices dictate that under severe freezing and thawing conditions where the concrete will be subjected to chemical deicers, the target amount of total air should be between 5.5 and 7.5 percent, depending on the size of the coarse aggregate (ACI 2008). Section 501.3.2.4.2 of the 2011 WisDOT Standard Specifications requires that slipformed concrete contain 5.5 to 8.5 percent air, measured at the point of discharge in accordance with AASHTO T 152 (ASTM C231), *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method* (AASHTO 2011b).

In order for the air in concrete to be effective at preventing or minimizing free-thaw damage, it must be entrained (versus entrapped) as a network of closely spaced, microscopic spherical bubbles. Pioneering research by T. C. Powers led to the development of an expression called the spacing factor that describes, for the majority of the paste, the required minimum distance in the paste to the nearest air void (Snyder, Natesaiyer, and Hover 2001). Typically, the entrained spherical air bubbles should range in size from 50 to 200 μm (Mehta and Montiero 2005) and the spacing factor, measured in accordance with ASTM C457 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete* (ASTM 2011), should be less than 0.008 in (0.200 mm) to be effective in protecting the hydrated cement paste from freeze-thaw damage (ACI 2008). Debate exists over whether those requirements are too strict for modern paving concrete, which typically has a lower water-to-cementitious ratio (*w/cm*) then that which was used to develop the criterion in the 1950s and 1960s; in fact, the Canadian Standards Association (CSA) A23.1 Clause 4.3.3.3 on air-void parameters specifies a maximum spacing factor of 0.009 in (0.230 mm) for most concrete, but increases this limit to 0.010 in (0.250 mm) if the w/cm is 0.36 or less as is common in high-performance concrete and silica fume overlays (CSA 2011).

At the same time, as air is entrained in concrete there is a commensurate loss of strength. If the upper limit of the air content specification is broached, the loss of strength can be significant and accompanied by an increase in permeability, both of which can negatively affect the durability of the concrete. In some cases, the coalescence of air voids at the interfaces of aggregates has been noted as a result of too much entrained air being present (Taylor et al. 2007). Furthermore, air loss and the potential disruption of the air-void system by internal vibration and manipulation of the finished surface as the concrete is paved are also possible. Often, problems associated with this are attributed to the concrete itself and not specifically to the paver used, although the operating frequency of the internal vibrators is of concern (Stutzman 1999; Taylor et al. 2007). The creation of "vibrator trails" in slipform concrete is one artifact of air loss (as well as mix segregation) caused by internal vibration. Another is the loss of air at the surface, although this is rare in slipform paving unless additional finishing is applied. Nevertheless, the impact of specific concrete plants or pavers on the in-place concrete air-void system is rarely studied unless something has gone wrong.

As WisDOT moves towards the adoption of performance-related specifications, the influence of these variables need to be quantified, and if necessary, recommendations for changes to current values for concrete field properties need to be made.

Project Objectives

The objective of this study is to evaluate the impacts of vibration and consolidation of modern slipform pavers used in Wisconsin on the air-void structure and air content of portland cement concrete pavements. The primary intent is to quantify the air content of fresh concrete before and after it has passed through the slipform paver. The air-void system parameters of hardened concrete was assessed using cast and extracted specimens. Knowing what changes occur to the air content and air-void system parameters assists in identifying appropriate air content target values, thereby allowing WisDOT and the Wisconsin paving industry to optimize the properties of the mix to ensure the in-place concrete meets or exceeds desired properties.

Research Approach

The project objectives were accomplished by completion of the following four work tasks:

1. Conduct a review of available literature, focusing on air content, air entrainment, and loss of air and changes in the entrained air-void system parameters as a result of the slipform paving process. The literature review focused on research performed in the last 10 years.

2. Develop a detailed testing matrix used for testing air contents on paving projects as well as guiding the subsequent testing of hardened concrete in the laboratory.

3. (a) Conduct field testing to measure fresh concrete properties that include air content measurement in accordance with AASHTO T 152, *Air Content of Freshly Mixed Concrete by the Pressure Method* (AASHTO 2011b) and unit weight measurement in accordance with AASHTO T 1212, *Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete* (AASHTO 2011a).

   (b) Extract cores from the same paving projects for laboratory evaluation of hardened air contents.

   (c) Analyze air-void system parameters of field specimens in accordance with ASTM C457, *Standard Test Method for Microscopical Determination of the Parameters of the Air-Void System in Hardened Concrete: Procedure B, the Modified Point-Count Method*.

4. Conduct data analysis to determine the degree of air loss due to the slipform paving process and determine factors affecting changes in air content and air-void system parameters and document results of the study in this final report for use by WisDOT to assist in improving policy and specification decisions.

Report Organization

This report consists of five chapters (including this one) and four appendices, as summarized below:

- Chapter 2. Background and Problem Statement.
- Chapter 3. Field Projects and Data Collection Program.
- Chapter 4. Laboratory and Data Analysis.
- Chapter 5. Findings and Recommendations.
- Appendix A. Annotated Bibliography.
- Appendix B. Field Data.
- Appendix C. Project Portfolios.
- Appendix D. Laboratory Testing Report.

Chapter 1 summarized the general background information on air-void system parameters and how they relate to freeze-thaw durability of portland cement concrete, and also described the objectives and scope of the project. The following chapter includes a literature review focusing on air entrainment admixtures, air content testing, and loss of air during the slipform paving process.

CHAPTER 2. LITERATURE REVIEW

Introduction

A literature review was performed covering the topics pertinent to this study. The literature review focuses on air-entraining admixtures, air content testing, factors affecting air content, and the impact of the paving process on the air content and air-void system parameters. An annotated bibliography of the references reviewed is provided in Appendix A.

Literature Review

This section presents the literature review conducted as a part of Task 1. The search focused on work performed in the past 10 years, and included a review of the Transportation Research Information Service (TRIS) database, the Transportation Research Board's (TRB's) Research in Progress database, selected state DOT specifications, and several other sources. The search results have been categorized into several distinct areas: air entraining admixtures, assessment of air content and entrained air-void system, factors affecting air content in field concrete, and air content and air-void system parameters before and after the paver.

Air-Entraining Admixtures

Air is entrained in concrete through the use of air-entraining admixtures (AEAs), which are described under AASHTO M 154 (ASTM C260), and specified in the 2011 WisDOT specifications under Section 501.2.2. AEAs work at the air-water interface, stabilizing the air that is incorporated into the concrete during mixing. The AEA molecules are known as surfactants, having one end that is hydrophilic, meaning it is attracted to water, and the other end being hydrophobic, which is repelled by water. This reduces surface tension at the air-water interface and allows the bubbles to remain stable, small, and well-distributed within the concrete (Taylor et al. 2007). In addition, the hydrophilic end of most AEA molecules are attracted to cement grains, which results in a coating of calcium salts (sometimes referred to as a hydration shell) that stabilizes the bubbles (Nagi et al. 2007).

One major gap that exists in the current understanding of the effectiveness of AEAs is that most information regarding the influence of the entrained air-void system on freeze-thaw damage is based solely on the use of Vinsol resin-based AEAs, as these were commonly used in the past. Today, the use of non-Vinsol resin-based AEAs, many of which are synthetic detergents, has increased (Kosmatka, Kerkhoff, and Panarese 2002) to the point where Vinsol resin-based AEAs are becoming difficult to obtain in some markets. Laboratory studies have found that, in general, synthetic detergent-based AEAs produce a finer air-void system that is less likely to be affected by vibration, fueling speculation that it might be possible to maintain freeze-thaw durability at a lower overall air content (Sutter, Van Dam, and Thomas 2007; Tanesi and Meininger 2006).

Nevertheless, conclusive evidence demonstrating either positive or negative performance of synthetic AEAs is elusive. There have been reported cases of synthetic detergent-based AEAs resulting in high amounts of entrained air that clustered or coalesced along aggregate interfaces, resulting in poor strength (Cross et al. 2000; Ghafoori and Barfield 2009). However, similar clustering was also observed when some non-detergent-based AEAs were used, although not with Vinsol resin-based AEA (Kozikowski et al. 2005). The tendency for air bubbles generated using synthetic detergents to have a greater propensity to coalesce relates to their greater mobility in the cement paste as they do not adhere or bridge to cement grains to the same degree as those generated from salt-type AEAs (Ghafoori and Barfield 2009). This would also lessen the stability of air bubbles created using synthetic detergents as they will not form the calcium salt hydration shell.

A study conducted by the Portland Cement Association (PCA) tested the ability for various AEAs to maintain an air-void system during mixing up to 90 minutes at various equivalent cement alkali levels (0.21, 0.60, and 1.20 percent Na_2O_{eq}) (Dubovoy, Gebler, and Klieger 2002). It was found that, regardless of the alkali level, AEAs made from salts of fatty acids created the most stable air-void systems, losing little air over a 90-minute agitation period and almost always having spacing factors below the recommended 0.008 in (0.200 mm) limit. Neutralized Vinsol resin AEAs were slightly affected by alkali-level, but with less air loss as alkali level increased. Although air was lost over the 90-minute agitation period, it was less than the air lost when synthetic detergent-based AEAs were used. Also, although the spacing factor was negatively impacted at the lowest cement alkalinity level, it was relatively stable at the middle and highest alkali levels. The synthetic detergent-based AEAs, which included a sulfonated hydrocarbon-based and alkyl-benzyl sulfonate-based AEAs, created unstable air-void systems especially as alkali level increased, which was reflected in a loss in air and significant increases in spacing factor over the 90-minute agitation period.

Some states have recognized the possible problems from admixture interaction and non-Vinsol resin-based AEAs. Kansas, for example, allows only AEAs based on Vinsol resins or tall oil to be used if the mixture also contains a plasticizer or high-range water-reducer (KDOT specifications, 401.3h), whereas South Dakota allows Vinsol resin-based AEA or products that have been approved by the DOT (SD Standard Specification Item 751, which is similar to Section 501.2.2 in WisDOT's 2011 Standard Specifications).

Assessment of Air Content and Entrained Air-Void System

The air content of fresh concrete is most often assessed through the use of the pressure meter as described in AASHTO T 152 (ASTM C231), *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method*, or modified versions thereof. Some states also allow the use of the volumetric method, AASHTO T 196 (ASTM C173), *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method*, especially if highly porous or lightweight aggregates are being used. WisDOT's 2011 Standard Specifications Section 501.3.2.4.2 requires the use of the pressure meter with testing conducted "at the contract-required frequency and as the engineer directs." Illinois, Michigan, Minnesota, and South Dakota require air content tests on the plastic concrete before placement (IDOT Standard Specifications, Section 1020.08; MDOT Standard Specifications, Section 601.03; MnDOT Concrete Manual, Section 5-694.532; SDDOT Concrete Paving Manual, Section 4-81). Iowa and Missouri specify a post-paver, as-constructed air content, but routinely measure the air content before placement. In both cases, air content after the paver is checked periodically on site and correlated to that in front of the paver. Further details are discussed later in this document.

A number of highway agencies are supplementing conventional testing of air content in fresh concrete with additional testing. The Indiana DOT, for example, specifies a hardened, as-constructed air content of 6.5 to 7.5 percent, as determined from cores taken after construction (INDOT Standard Specifications, Section 509.05). The Kansas DOT specifies both an in-place air content of at least 4.0 percent as measured by the pressure method and a maximum air-void spacing factor of 0.01 in (0.25 mm) measured using the Air-Void Analyzer (AVA) (see Taylor et al. [2007] for a description of the theory behind the AVA). If the spacing factor is not met in initial testing, the Kansas DOT provides guidance to establish a new target air content using the measured air content and the measured spacing factor (KDOT Standard Specifications, Section 401.3h).

For hardened concrete, the only accepted standardized method for estimating the air-void system parameters of concrete is through microscopic methods conducted in accordance with ASTM C457 (referred to as "manual methods" in this document), although automated methods have been developed that have reasonable predictive ability (Sutter, Van Dam, and Thomas 2007).

In the 1990s, the Ontario Ministry of Transportation (MTO) changed their engineering and construction practices such that responsibility for the quality of the end product was shifted to the contractor (Schell and Konecny 2003). An end-result specification for the as-constructed air-void system parameters was implemented requiring sampling from the finished pavement and testing in accordance with ASTM C457. Instead of specifying the air content at the time of construction, the air content and maximum air-void spacing factor in the as-constructed concrete were specified. Furthermore, there is no upper limit to the allowable air content in the hardened concrete as compressive strength for acceptance is obtained from cores. Initial contractor resistance was allayed by requiring contractors to perform tests on hardened concrete samples prior to placement, and monetary penalties for failing the air-void system parameters were introduced gradually. Additionally, contractors were required to determine the plastic air content that led to an acceptable air-void system during mixture design, and then had to meet that plastic air content in the field. During the first 5 years of the end-result specification's use, 95 percent of concrete test lots were in compliance with the new specification. Slipformed concrete accounted for 19 percent of that data, and only one failing test was recorded in the slipformed concrete.

Considerable investigative work is being done to develop methods for quantifying air-void system parameters. For example, researchers at the Oklahoma Transportation Center are currently working on the development of a robust field technique based on the pressure meter to quantify the air-void distribution in fresh concrete. This would be an important construction tool, since currently only total air content of fresh concrete can be measured using conventional pressure meters, and the resulting value reflects both entrained and entrapped air. Although the AVA can be used to estimate air-void system parameters, there are some concerns about its accuracy, particularly when used with stiff slipform paving concrete. A similar study is being conducted at Penn State University, which had a secondary goal of resolving the Pennsylvania DOT's hardened air specification with their plastic air specification. Finally, a study is also on-going at the University of Kentucky to evaluate available technologies for measuring the air content of plastic and hardened concrete, evaluating air content, bubble size, and spacing, developing guidelines for utilizing new techniques for air content determination of plastic concrete, and establishing trial projects to evaluate new technologies and procedures (information retrieved from the TRB Research in Progress database).

Factors Affecting Air Content in Field Concrete

As described previously, the type of portland cement and content, the type and amount of supplementary cementitious materials (SCMs), admixtures, placement methods, ambient temperatures, among other items, are all known to affect the air content of concrete. It is also well known that the air-void system is created through the action of the concrete mixer, which "traps" the air in the mix through the stabilizing influence of the AEA. Although mixing time is a recognized factor, little is published on the impact of different types of concrete plants. Also, there is some air lost during construction as the concrete is placed by the slipform paver. Nevertheless, the impact of specific concrete plants or slipform pavers on the in-place concrete air content and air-void system is rarely studied unless something has gone wrong.

A study by the Portland Cement Association (PCA) researched the phenomenon of air void clustering. Air void clustering is the coalescence of air voids, particularly along aggregate particles, which leads to decreased strength (Kozikowski et al. 2005). Laboratory testing was conducted in two phases, one to consistently recreate air void clustering and the other to vary concrete mix properties and techniques to determine which had the greatest impact. Four AEAs were tested (neutralized Vinsol resin, tall oil, fatty acid, and resin/rosin) and the targeted air content was 5.5 percent ± 1 percent. In the first round of testing, however, it was discovered that air void clustering could be produced whenever a non-Vinsol admixture was used, and the concrete was retempered, meaning the concrete was remixed with water. It was also noted that air void clustering was not observed when neutralized Vinsol resin was used, and that both timing of the admixture addition and moisture condition of the aggregate had no effect. Clustering seemed to increase with finer air-void systems, though this was not conclusively shown. Based on this study, when non-Vinsol AEAs are used, care should be taken not to retemper the concrete, which could otherwise lead to air void clustering and reductions in concrete strength.

A German study also shows that re-tempering adversely affects the concrete's air-void system, and indicated that it can lead to excessively high air contents (Eickschen 2004). In the case of shorter mixing times, the AEA is not broken down sufficiently during initial mixing, and if the concrete is mixed later during re-tempering, excessive air contents will result. It is worth noting that according to the applicable German standard, concrete for roads must contain at least 1.8 percent by volume of air voids having diameters up to 0.012 in (0.3 mm), and the spacing factor must not exceed 0.008 in (0.20 mm). For general use, it is assumed that a 4.5 percent total air content (5.5 percent for concrete containing plasticizers or superplasticizers) will produce acceptable air-void system characteristics. When used in moderate quantities, the AEAs tested in this study did not cause problems with the air-void system. But it was stated that caution should be taken to avoid overdosing of AEAs to compensate for short mixing times or ineffective mixing, as problems will result later in construction. Temperature should also be a consideration as a higher AEA dosage was required at higher temperatures.

Air Content and Air-Void System Parameters Before and After the Paver

Air loss and the potential disruption of the air-void system by internal vibration and/or manipulation of the finished surface as the concrete is paved are also considerations. Often, problems associated with this are attributed to the concrete itself and not specifically to the paver used, although the operating frequency of internal vibration is of concern (Stutzman 1999; Taylor et al 2007). The creation of "vibrator trails" in slipform concrete is one artifact of air loss (as well as mix segregation) caused by internal vibration. A 1999 study by the Iowa DOT determined that, in general, if the specified vibrator speed was maintained between 5000 and 8000 vibrations per minute (vpm), problems did not occur. However, the study acknowledged that significant variables and interactions existed at each project, including concrete mixture parameters, and that the process is too complex to be solved by simply limiting the vibration speed (Tymkowicz and Steffes 1999). The Iowa DOT now requires the air loss to be determined on large projects (Iowa DOT Standard Specifications, Section 2301.04C), as will be discussed later.

The following sections summarize some of the current practices of a few midwestern states in specifying air content of concrete paving mixtures.

Iowa DOT

The Iowa DOT requires an air content of 6 percent in the finished concrete, but measures the air content before the paver. For large projects (over 7500 yd^2), the air content before and after the paver is measured and a percent loss is determined for the first eleven loads of concrete. This is used to determine a target air content to be measured before the paver. Thereafter, the percent loss is measured for every half day of paving, and the pre-paver target air content is adjusted as necessary to ensure that 6 percent air is achieved in the finished concrete. For smaller projects (less than 7500 yd^2), 1.5 percent air loss is assumed, making the target air content before the paver 7.5 percent plus 1.5 percent or minus 1 percent (Iowa DOT Standard Specifications, Section 2301.04C).

Missouri DOT

The Missouri DOT (MoDOT) specifies a minimum air content of 5 percent in front of the paver in addition to the air loss through the paver. Air loss is determined at a minimum once per half day of paving. Based on the DOT's experience, the air loss is between 1.5 and 2.5 percent. The air content is measured in accordance with the AASHTO T 152 procedure and MoDOT does not specifically prescribe whether vibration or rodding should be used to determine the air contents when measuring air loss through the paver (MoDOT Standard Specifications, Section 502.11.2.3).

Kansas DOT

The Kansas DOT specifies a minimum air content of 4 percent behind the paver. The maximum air content allowed in front of the paver is 10 percent and immediate steps are required to be taken to reduce the air content when it exceeds 8 percent. For a typical portland cement concrete pavement, the concrete mix is designed to attain the target air content plus 0.5 percent to account for loss through the paver. Air loss is determined once per half day of paving. If the air content behind the paver falls below 5 percent, steps are taken to increase the air content appropriately. When two consecutive air content measurements behind the paver fall below 4 percent, the paving operation is suspended and the concrete is removed and replaced. The Kansas DOT allows both AASHTO T 196 (i.e. Roll-A-Meter) and AASHTO T 152 (pressure meter) test methods to measure air contents of fresh concrete, and does not explicitly state whether vibration or rodding must be used to consolidate the specimens for the AASHTO T 152 test (Kansas DOT Standard Specifications, Section 401.3 h).

Relationship between Air Content and Strength

As air is entrained in concrete, the strength generally decreases. The strength loss per unit increase in air content is greater at lower *w/cm* ratios (i.e., higher strengths). In general, a 5 percent strength loss can be expected for each percentage of air added to the concrete (Bloem 1950). However, this can vary between 2 and 6 percent depending on the actual mix design. It should be noted that these strength loss correlations are determined based on properly consolidated concrete mixtures. For concrete that is not consolidated properly, higher strength losses may be expected.

Typical relationships between compressive strength and *w/cm* for various air contents is shown in figure 1(a). Figure 1(b) shows the typical relationships between compressive strength and air content for concretes with different cement contents.

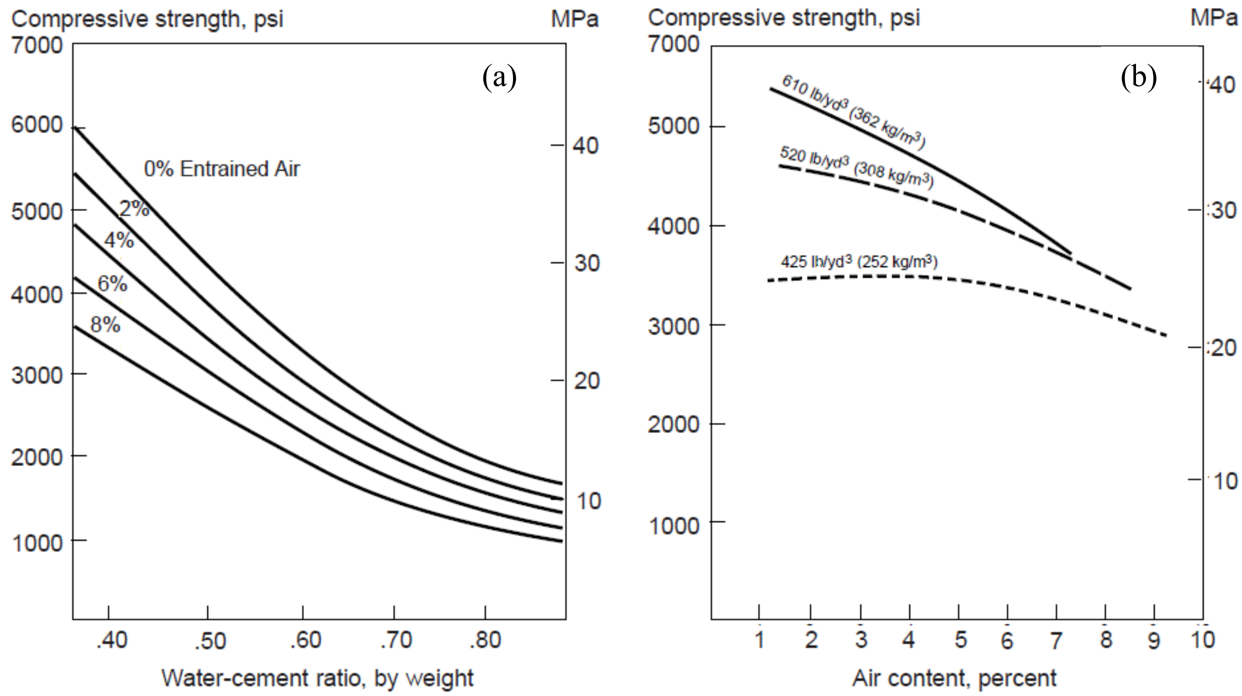

Figure 1. Relationships between compressive strength. *w/cm*, and air content (Walker and Bloem 1955, Bloem 1950).

Ozyildirim (1990) conducted a laboratory study to evaluate the impact of air content on the compressive strength of concretes with cementitious materials content of over 600 lbs/yd^3 and a maximum *w/cm* of 0.45. Ten batches were tested for fresh properties (air content, slump, and unit weight). Six batches used Vinsol resin-based AEAs and the remaining four batches used synthetic AEAs. The relationship between the air content measured by a Type A pressure meter (according to ASTM C231) and the 28-day compressive strength measured using 4x8 inch cylinders is shown in figure 2.

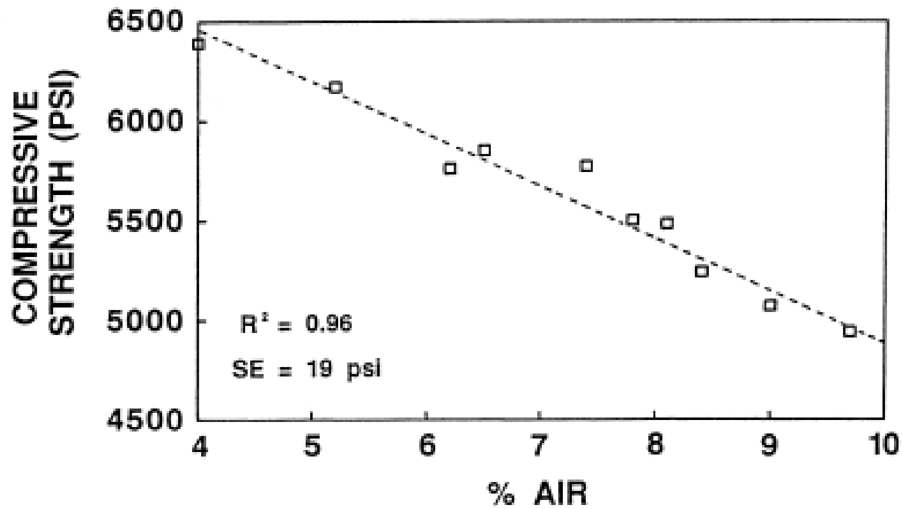

Figure 2. Relationship between compressive strength. and air content (Ozyildirim 1990).

Most agencies set their maximum air content values in the range of 8 to 10 percent, with WisDOT's upper value set at 8.5 percent. Using the relationship from the chart above, it is observed that a nearly 25 percent loss of strength is associated with an increase in air content from 4 to 10 percent.

Comparison of Air Contents in Fresh and Hardened Concrete

When air content measurements are conducted in accordance with properly calibrated testing equipment according to ASTM C231 (or AASHTO T 152), differences between the Type A and Type B meters (both employing the principle of Boyle's law) are generally within the reproducibility of the test protocols. However, larger differences may be observed when comparing air contents in fresh and hardened concretes. In general, the differences between fresh and hardened air contents measured from the same batch of concrete is within ±1 to 2 percent of each other (Whiting and Nagi 1998). These differences may be attributed to the following:

- Air loss due to vibration, pumping, extended mixing and transportation.
- Air transfer from smaller to larger bubbles at lower pressures that may increase the final air contents.
- Systematic errors and precision of the test method.

A scatter plot showing the relationship between fresh and hardened air contents is shown in figure 3 (Nagi and Whiting 1994).

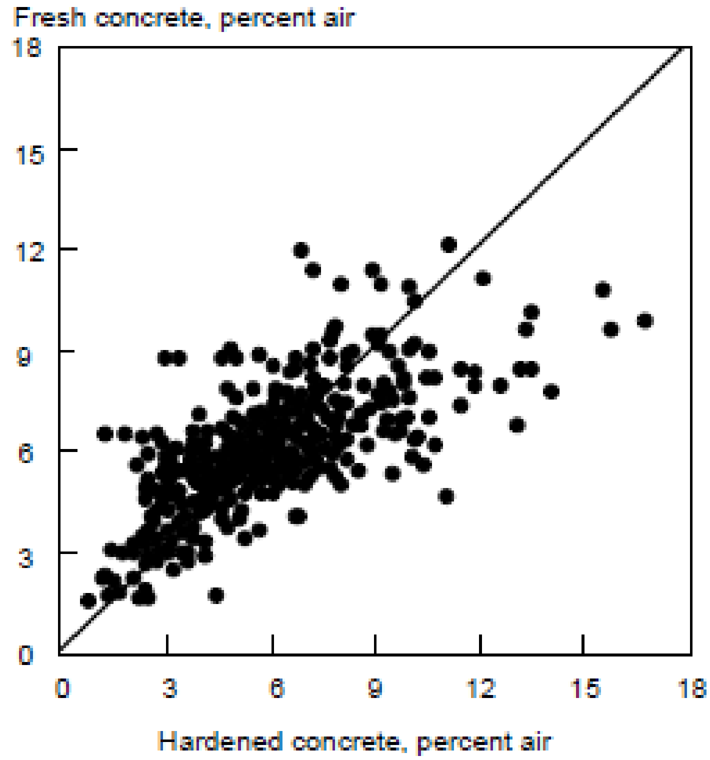

Figure 3. Relationship between fresh and hardened air contents (Nagi and Whiting 1994).

The study conducted by Nagi and Whiting (1994) used 400 separate comparisons from various laboratory and field studies. The mean air content for both fresh and hardened concrete was about 6 percent. The mean absolute difference was found to be around 1.3 percent. Overall, the typical absolute difference between the fresh and hardened air contents is within 2 percent, not taking into consideration the unusual observations where the fresh and hardened concrete air contents are considerably different.

Ozyildirim (1990) conducted laboratory and field studies to evaluate the differences in the air contents measured in fresh and hardened concretes. The study concluded that in the range of 4 to 10 percent, there is practically no difference between the air content of fresh concrete as measured by pressure meters and the air content of hardened concrete as determined using the ASTM C457, Procedure A, Linear Traverse Method. The study concluded that in many cases, the differences were not statistically significant at the 5 percent level.

In Note 1 of ASTM C457-12, it is stated that the air content determined in hardened concrete is usually consistent with the air contents measured on fresh concrete (using the test methods ASTM C138/138M, C173/173M, and C231). However, it also notes that significant differences may be observed if the sample of fresh concrete is consolidated to a different degree than the sample later examined microscopically. For concretes with relatively high air contents (over 7.5 percent), the air contents measured in hardened concrete may be one or more percent higher than that determined by the ASTM C231 test method. The last point is ambiguous as it does not stipulate whether “high air contents” means that the fresh concrete air content is over 7.5 percent or whether it is the hardened concrete air content is over 7.5 percent.

Impact of Vibration on Air-Void System Parameters

Stark (1986) conducted a study to examine the effect of vibration on the air-void system parameters and freeze-thaw durability of concrete. Laboratory specimens were made using water-cement ratios of 0.40, 0.50, 0.60, and 0.70. These specimens were then subjected to internal vibration at frequencies of 8000, 11,000, and 14,000 vpm prior to freeze-thaw testing in a 4 percent sodium chloride solution. ASTM C457, Procedure A, Linear Traverse Method was used to study the air-void system characteristics. The test results indicated that internal vibration adversely affected the quality of the entrained air-void systems compared to those that were not vibrated, particularly in concretes with the higher *w/cm* subjected to vibration frequency of 14,000 vpm. This trend was also observed in the measured freeze-thaw durability of the hardened concrete.

Summary

The following general conclusions can be drawn from the review of the available literature:

- It is well established that an entrained air-void system having numerous, well-distributed and closely spaced spherical air bubbles is essential to protect the hydrated cement paste from freeze-thaw damage. The amount of total air required varies with the coarse aggregate size and exposure, but typically falls in the range of 5 to 7 percent. More importantly is the average spacing from a point in the paste to the nearest air void, quantified by the spacing factor measured in according to ASTM C457. According to ASTM C457, the spacing factor should be no greater than 0.008 in (0.200 mm), although some standards allow greater spacing factors for higher quality, lower *w/cm* concrete.
- Air is entrained in concrete through the use of AEAs, which are surfactant materials that work at the interface between air and water. The AEAs stabilize air bubbles created through the agitation of the mixer. Traditionally, AEAs based on Vinsol resin or other naturally-derived substances have been used quite effectively, but more recently synthetic detergent-based AEAs are becoming more common. Issues regarded air-void stability, and clustering have become more acute recently, with the synthetic detergent-based AEAs being implicated in some of these cases.
- The most frequently used test to assess the air content of fresh concrete is the pressure meter (ASTM C231), but it can only be used to estimate total air content (i.e., it cannot differentiate entrapped air from entrained air) and it cannot make a determination of the specific size or spacing of the air bubbles. The AVA is used by some agencies, but overall it is a sensitive device with questionable reliability, particularly for stiff, slipform paving concrete. The only standardized and accepted method to determine the air-void system parameters is on hardened concrete in accordance with ASTM C457. Most agencies still rely exclusively on measurements of total air made using the pressure meter, although a few are requiring that actual air-void system parameters be verified as well, whether obtained from the fresh concrete using the AVA or hardened concrete using ASTM C457.
- It is well understood that multiple factors affect the amount of air entrained in the concrete and the stability of that air over time. These factors include, but are not limited to, cement type and content, SCM type and content, aggregate type, admixture interactions, mixing type and duration, temperature, and time from mixing to placement. No literature was uncovered that specifically examined the influence that different concrete mixing plants have on the air-void system. Although the influence of some of

these factors is well understood, the number of factors and the complexity of the interactions have made broadly applicable guidance elusive.

- Although it is known that air will be lost through the slipform paver, most agencies test the air content of the concrete before the paver. Some have required testing after paving for approval, but it is more common to establish—on a job-by-job basis—a correlation between the air before and after the paver, and then routinely test before the paver for quality control. No literature was uncovered that specifically examined the influence of different paver types on the as-constructed air-void system parameters.
- Multiple studies have found that the correlation between the total air content measured on fresh concrete in the field and that measured microscopically on hardened concrete in the lab (ASTM C457) is quite good over the normal working range of air contents. ASTM C457 states that the measurement of hardened air may be higher by 1 percentage point or more in concrete with relatively high air contents (usually over 7.5 percent).

The following chapter describes details of the testing matrix, field projects, and the data collection program.

CHAPTER 3. FIELD PROJECTS AND DATA COLLECTION PROGRAM

Introduction

This chapter presents the details on the field projects and the data collection program undertaken in this study. The final testing matrix used for evaluating air contents on paving projects as well as the subsequent testing of hardened concrete in the laboratory is also discussed in this chapter. Concrete mix design details on each paving job included in this study are also presented.

Final Testing Matrix

As discussed in Chapter 2, many factors influence the final air content and air-void system parameters of concrete placed with a slipform paver. The air content and the stability of the air-void system is influenced by the materials used (cement, SCMs, chemical admixtures, aggregate grading and texture, and water), mixture properties (*w/cm* and slump), batching (sequencing, mixer type and size, mixing speed and duration), transport (type of truck, time of delivery, agitation, retempering), placement (type of placement), consolidation (type of paver, vibration frequency and duration), finishing (type, timing), and temperature. With this vast number of variables, no single study can be designed to provide statistically valid results that will be universally applicable to all conditions. Instead, the experimental plan used in this project was designed to make use of the significant amount of information that already exists regarding most of these factors, and then test a representative number of projects to validate WisDOT's current approach to providing sufficient air content for freeze-thaw durability.

The following major variables were considered in the study:

- Coarse aggregate type (two levels): northern glacial gravel and southern crushed limestone.
- Air entraining admixture (two levels): Vinsol resin-based AEA and non-Vinsol resin-based AEA.
- Concrete plant (two levels): Designated as BP-1 and BP-2 .
- Paving machines (four levels): Designated as P-1, P-2, P-3, and P-4.

Conducting a full-factorial experiment would result in a *2x2x2x4* experimental matrix, requiring 32 projects be evaluated. Testing this many projects was infeasible. A partial factorial experimental design could have been employed to reduce the number of required projects to eight or so, but this would be of limited use because the independent variables are known not to be random and there are multiple known and unknown interactions between the variables that will result in confounding of the experimental results. For example, based on the information provided by WisDOT, only one contractor (designated as C-6) is using the BP-2 designated concrete plant, whereas most others are using a BP-1 designated concrete plant. Moreover, since C-6 is primarily located in the southeastern part of the state, it was difficult to find a project in which C-6 was operating in the northern part of the state working with northern glacial gravel. Assuming that a difference is observed on a project constructed by C-6, it would be impossible to tell whether that difference was from the use of the BP-2 concrete plant, the coarse aggregate source, or any number of other variables that are not included in the study. Furthermore, C-6 does not operate a P-1 paver, but instead only a P-3 paver, again resulting in confounding.

There are many other similar known and unknown limitations and interrelationships among the independent variables (coarse aggregate type, AEA, concrete plant, and paving machine) that prevent the effective application of a statistically derived experimental plan for this project. And this discussion does not consider the fact that it will be impossible to control other variables that are known to have a large impact on air content and the characteristics of the air-void system, such as cement type and content, fly ash source and content, other chemical admixtures, mixing speed and times, and temperature. Thus, conducting a statistically valid experiment to address these factors is beyond the scope of this project.

In order to conduct a meaningful study considering the limitations discussed above, the construction projects selected for evaluation represent "typical" conditions that are likely to occur throughout Wisconsin. Field testing (measurement of air content and unit weight behind and in front of the paver) was used to assess whether the major variables under consideration (coarse aggregate type, AEA type, concrete plant type, paver type) have an important influence on the loss of air or changes in the air-void system as the concrete passes through the paver. Using this approach, 12 projects (designated by region and sequential number) were selected for this study, as shown in table 1. Figure 4 indicates the general location of the projects on a map.

Table 1. Projects selected for study.

Region*	County	Project ID	Contractor	Paving Start Date	Field Testing Date	PCC Thickness (in.)
NW	Polk	NW-1	C-1	23-Jun-2011	24-Jun-2011	9.50
NE	Fond du Lac	NE-1	C-2	23-May-2011	26-May-2011	9.00
	Outagamie	NE-2		24-May-2011	24-May-2011	8.50
	Winnebago	NE-3	C-3	16-Jun-2011	16-Jun-2011	11.00
		NE-4	C-4	18-Jul-2011	19-Jul-2011	11.00
NC	Marathon	NC-1	C-5	31-May-2011	13-Jun-2011	9.00
	Wood	NC-2	C-4	22-Aug-2011	29-Aug-2011	10.00
SW	Dane	SW-1	C-6	21-May 2011; Jul-Sep 2011	04-Aug-2011	12.00
	Jefferson	SW-2		20-May-2011	03-Jun-2011	9.00
	Sauk	SW-3	C-1	09-Jun-2011	13-Jun-2011	10.00
SE	Milwaukee	SE-1	C-3	09-Jun-2011	19-Aug-2011	11.00
	Waukesha	SE-2	C-6	17-Jun-2011	17-Jun-2011	8.50

*NW: North West, NE: North East, NC: North Central, SW: South West, SE: South East

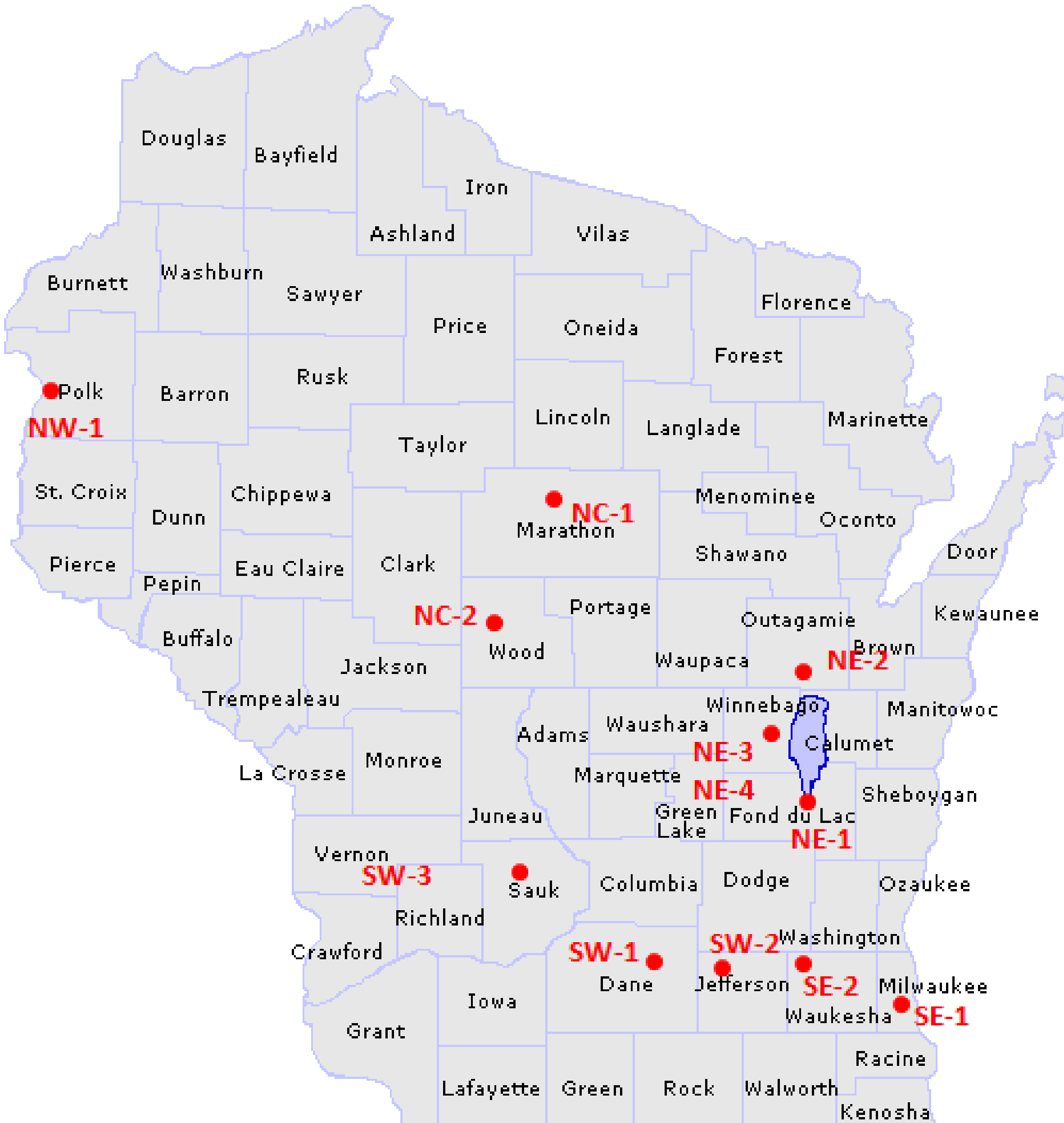

Figure 4. Location of paving projects selected for study.

The final experimental matrix used for this study is presented in table 2. As mentioned earlier, the major variables considered are: coarse aggregate type, AEA type, concrete plant and paving machine.

Table 2. Final experimental matrix.

Region	Batch Plant	Contractor	Vinsol Resin		Non-Vinsol Resin	
			Gravel	Limestone	Gravel	Limestone
North West	BP-1	P-1			NW-1	
		P-2				
		P-3				
		P-4				
	BP-2	P-1				
		P-2				
		P-3				
		P-4				
North East	BP-1	P-1				
		P-2		NE-1 NE-2		
		P-3				NE-3
		P-4				NE-4
	BP-2	P-1				
		P-2				
		P-3				
		P-4				
North Central	BP-1	P-1			NC-1 NC-2	
		P-2				
		P-3				
		P-4				
	BP-2	P-1				
		P-2				
		P-3				
		P-4				
South West	BP-1	P-1				
		P-2				
		P-3				SW-2 SW-3
		P-4				
	BP-2	P-1				
		P-2				
		P-3				SW-1
		P-4				
South East	BP-1	P-1				
		P-2				
		P-3				SE-1
		P-4				
	BP-2	P-1				
		P-2				
		P-3				SE-2
		P-4				

The concrete mix designs for each project included in the study is shown in table 3.

Table 3. Concrete mixture designs.

	Project ID					
	NW-1	NE-1	NE-2	NE-3	NE-4	NC-1
Cement (Type), lbs/yd^3	480 (I/II)	455 (Unk.)	455 (Unk.)	395 (Unk.)	395 (I/II)	452 (I)
Fly Ash (Type), lbs/yd^3	85 (C)	110 (C)	110 (C)	170 (C)	170 (C)	113 (Unk.)
Total Cementitious Content, lbs/yd^3	565	565	565	565	565	565
w/cm	0.40	0.40	0.38	0.38	0.37	0.41
Coarse Aggregate, lbs/yd^3	1814	1942	1928	1943	1944	1823
Fine Aggregate, lbs/yd^3	1211	1296	1281	1291	1294	1310
Air Entraining Type	Non Vinsol Resin	Vinson Resin	Vinsol Resin	Non Vinsol Resin	Non Vinsol Resin	Non Vinsol Resin
AEA Dosage (oz. / 100 wt.)	4.00	10.20	9.60	4.50	3.40	0.8
WRA Dosage (oz. / 100 wt.)	17.00	19.80	19.80	17.00	18.10	3.01
Target Air Content (%)	7.00%	7.00%	7.00%	7.00%	6.50%	Unk.
	NC-2	SW-1	SW-2	SW-3	SE-1	SE-2
Cement (Type), lbs/yd^3	395 (I/II)	396 (I)	395 (Unk.)	395 (I/II)	395 (I/II)	395 (I)
Fly Ash (Type), lbs/yd^3	170 (C)	170 (C)	170 (C)	170 (C)	170 (C)	170 (C)
Total Cementitious Content, lbs/yd^3	565	566	565	565	565	565
w/cm	0.37	0.37	0.41	0.41	0.37	0.41
Coarse Aggregate, lbs/yd^3	2045	1950	1889	1848	1910	1942
Fine Aggregate, lbs/yd^3	1256	1386	1237	1282	1262	1202
Air Entraining Type	Non Vinsol Resin	Non Vinsol Resin	Non Vinsol Resin	Non Vinsol Resin	Non Vinsol Resin	Non Vinsol Resin
AEA Dosage (oz. / 100 wt.)	0.80	6.00	7.00	4.00	6.80	5.00
WRA Dosage (oz. / 100 wt.)	3.00	23.00	17.00	17.00	17.00	18.00
Target Air Content (%)	6.00%	7.00%	7.00%	7.00%	7.00%	6.00%

Note: Information of some mix design details (like cement type and fly ash type) were not available and hence they are reported as "Unk." in table 3.

Field Sampling and Data Collection Program

During construction, a Wisconsin Highway Technician Certification Program (HTCP) PCC Tech I certified technician was present on site to test the fresh properties of the concrete and prepare cylindrical specimens (4-in by 8-in) for laboratory analysis. The technician coordinated all activities with the contractor, ensuring safety and minimal disruption to the paving operation. Testing commenced only after initial start-up and once the concrete supply and paving process were operating smoothly. Within each project, a minimum of three sampling sites were selected along the length of the project.

The fresh concrete properties measured included the air content (obtained in accordance with AASHTO T 152, *Air Content of Freshly Mixed Concrete by the Pressure Method*) and the unit weight (in accordance with AASHTO T 121, *Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*). Consistent with the standards and common practice, the concrete was consolidated for all fresh concrete testing and cylinder preparation through the use of an inserted vibrator. Sampling and testing of fresh concrete was conducted on concrete placed on grade directly in front of the paver and directly behind the paver after placement. The latter item was retrieved in the center portions of the slab to avoid edge effects and at locations away from any embedded steel. The sampling of the concrete behind the paver required sampling from a freshly placed paving lane, disturbing the surface, and requiring extra work to repair and finish the surface. These testing activities were closely coordinated with the contractor and WisDOT field personnel to ensure smooth operations.

In addition to the AASHTO T 152 and T 121 testing, the field technician cast two cylindrical specimens (4-in diameter by 8-in length) at each site, one from concrete in front of the paver and one from concrete behind the paver (see figure 5). A minimum of three sampling sites were selected within each project, thus yielding a total of at least six cylindrical specimens cast for each of the twelve projects. These specimens were used in the laboratory testing to analyze the air-void system parameters of hardened concrete, as described in Chapter 4.

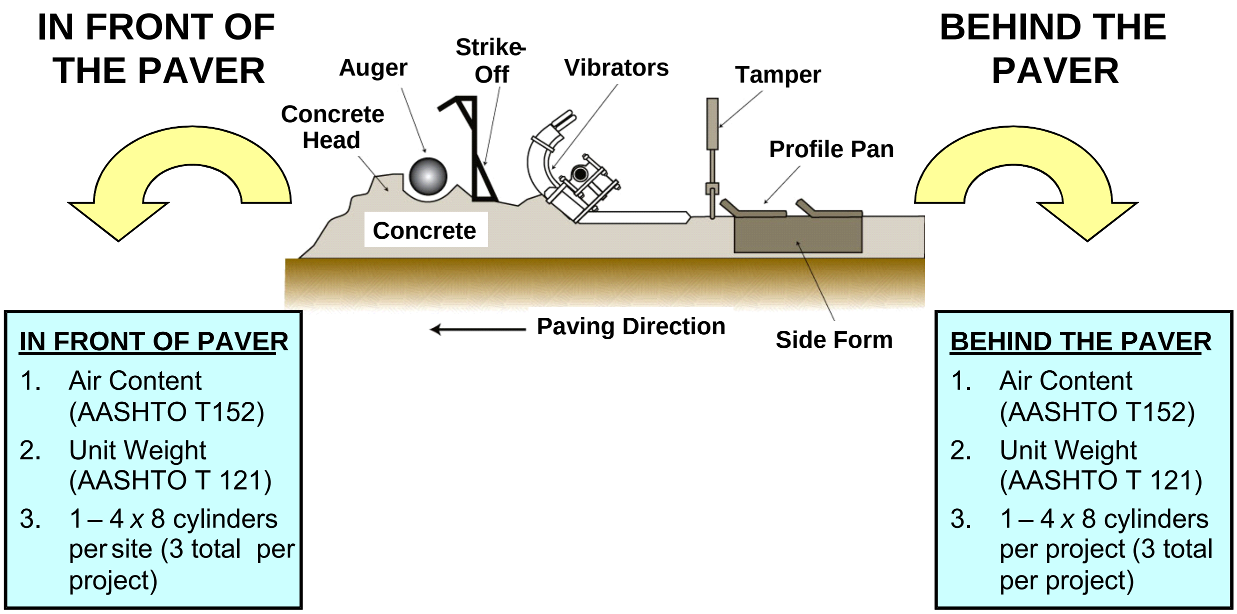

Figure 5. Fresh concrete sampling at each sampling site within a project.

The raw data collected during the field testing of each project is presented in Appendix B, while Appendix C presents a summary portfolio of each tested project.

The air-void system of the hardened concrete is often affected in non-uniform ways by the paving operation, and the only way to capture this is through examination of extracted concrete specimens. After construction and prior to opening the pavement to traffic, three cores were extracted from each project, one from each of three sampling sites. To minimize the impact of the coring on pavement performance, the cores were extracted from the interior of the slab. The cylindrical specimens and extracted cores were delivered to Michigan Technological University (MTU) and tested as described in Chapter 4.

Summary

This chapter discussed details on the field projects and the data collection program. The final testing matrix and concrete mix designs for each paving job included in this study were also discussed. The next chapter discusses the results of the field and laboratory testing.

CHAPTER 4. LABORATORY TESTING AND DATA ANALYSIS

Introduction

This chapter presents the results of the field and laboratory testing conducted to study the fresh and hardened concrete properties, specifically focused on air content and air-void system parameters. As discussed in the previous chapter, the fresh concrete properties measured were: air content in accordance with AASHTO T 152, *Air Content of Freshly Mixed Concrete by the Pressure Method* (AASHTO 2011b) and unit weight in accordance with AASHTO T 121, *Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete* (AASHTO 2011a). The laboratory testing involved the analysis of air-void system parameters of the field specimens in accordance with ASTM C457, *Standard Test Method for Microscopical Determination of the Parameters of the Air-Void System in Hardened Concrete: Procedure B, the Modified Point-Count Method*. In addition to the ASTM C457 manual method, an automated method of analyzing air-void parameters using a flatbed scanner was also performed; that method was supported in its development by WisDOT and is described by Sutter, Van Dam, and Thomas (2007). Those tests were performed on one set of samples (one cylinder cast from concrete before the paver, one cylinder cast from concrete after the paver, and one core extracted from the pavement) that were retrieved from each of the twelve projects. Additional laboratory testing was performed on one additional set of samples from two projects (NE-1 and NC-2).

Fresh Concrete Properties

The air content of the fresh concrete behind and in front of the paver from each site were examined to determine if there were any obvious changes in these properties due to the paving operation. Figure 6 summarizes the air contents of the fresh concrete as measured by the pressure meter.

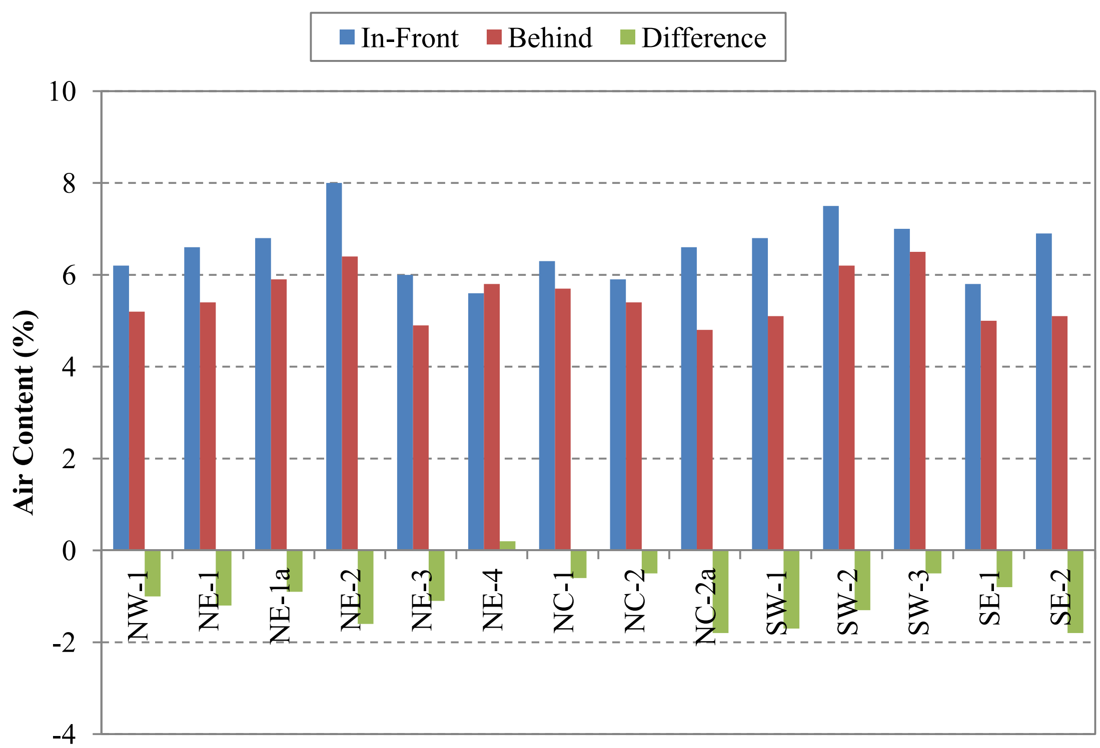

Figure 6. Air content of fresh concrete as measured by pressure meter.

The air content measured in front of the paver was consistently higher than the air content measured behind the paver (with the exception of NE-4). For the projects included in this study, the target fresh concrete air content was between 6 and 7 percent, with the average being approximately 6.8 percent. The average air content measured in front of the paver was approximately **6.6 percent** and the average air content measured behind the paver was approximately **5.5 percent**. Thus, the average air loss measured in the fresh concrete was approximately **1 percent** as it passed through the paver. Based on this testing, the air contents of the fresh concrete were generally within acceptable limits.

It is noted that the concrete behind the paver that was used in the air content testing was consolidated twice, first by the paver and then again by the use of the inserted vibrator (in accordance with the standards and common practice) in the air-pot during the air content testing. The concrete sample taken in front of the paver had been consolidated only once, by the use of an inserted internal vibrator. From that perspective, it is reasonable to expect the air content to decline. Yet the additional consolidation through vibration makes it impossible to separate the extent of air loss (if any) that is due exclusively to the paving process from that incurred as a result of the use of the inserted vibrator during testing. Air content testing on hardened concrete discussed in the following section sheds more light on this topic.

Hardened Concrete Properties

As mentioned earlier, the air-void system parameters of hardened concrete were analyzed in the laboratory using both the automated and ASTM C457 manual methods. This testing was done on the cylinders cast from concrete obtained in front of and behind the paver from each project, as well as on the extracted cores. Initially, thirty-six samples were tested in the laboratory, one set of three specimens obtained from each project (one cylinder before the paver, one cylinder after the paver, and one core sample from the finished project). All three samples tested were from the same testing site within the project, with efforts made to ensure the core was not extracted through the exact area where the concrete was disturbed during testing of the fresh concrete. Additional laboratory testing was performed on two projects (NE-1 and NC-2), with field cylinders and cores from another location within the same project site.

The laboratory testing report (Appendix D) provides detailed data on the testing performed along with micrographs of the cylinders and cores tested. The key findings from the laboratory testing are summarized in this section.

Issues Identified During Laboratory Testing

A number of specimens (again, representing cylinders before the paver, cylinders after the paver, and core samples) tested in the laboratory exhibited segregation and consolidation issues. For example, a large number of specimens cast in the field exhibited accumulation of air voids around the aggregates and the paste was also observed to be unusually porous in places where the vibrator was inserted, with significant coalescence of entrained air voids imparting a foamy appearance. However, even some of the cored specimens extracted from the in-place concrete demonstrated issues with the air-void system. A summary of the specimens exhibiting those issues is provided in table 4.

Table 4. Summary of issues uncovered during laboratory testing.

Project ID	AEA Type	Seggregation, Vibrator Insertion Marks			Air Void Accummulation Around Aggregates			Unusually Porous, Significant Coalescence of Air Voids		
		In-Front	Behind	Core	In-Front	Behind	Core	In-Front	Behind	Core
NW-1	Non VR				✓	✓				
NE-1	VR								✓	
NE-1a	VR							✓		
NE-2	VR				✓	✓	✓			
NE-3	Non VR				✓					
NE-4	Non VR	✓				✓		✓	✓	✓
NC-1	Non VR				✓		✓	✓	✓	
NC-2	Non VR		✓						✓	✓
NC-2a	Non VR	✓				✓				
SW-1	Non VR				✓	✓	✓			
SW-2	Non VR				✓	✓			✓	
SW-3	Non VR		✓		✓				✓	✓
SE-1	Non VR				✓	✓				
SE-2	Non VR	✓	✓					✓	✓	

This issues related to the cast specimens are largely believed to be due to the internal vibration used to consolidate them, producing noticeable segregation due to the insertion of the vibrator into specimens from the following sites: NE-4 (in front of the paver), NC-2 (behind the paver), NC-2a (in front of the paver), SW-3 (behind the paver), and SE-2 (in front of and behind the paver). The practice of using an internal vibrator for consolidation of cylindrical specimens is allowable under ASTM C31, *Standard Practice for Making and Curing Concrete Test Specimens in the Field*, section 9.4.2, and is commonly used by certified field technicians. Unfortunately this practice is not ideal when evaluating the effects of mix parameters and construction practices on the entrained air-void system in concrete. According to ASTM C231, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method,* section 8.1.1, concretes with slumps of greater than 3 inches must be consolidated by rodding. Concretes with slumps in the range of 1 to 3 inches may be consolidated either by rodding or vibration. Concretes with slump less than 1 inch must be consolidated by vibration. Based on these guidelines, there is little wonder why a vibrator was used for consolidation of these paving mixtures. Figures 7 (a) through (f) show micrographs of specimens prepared using the cylinders cast in the field exhibiting segregation due to internal vibration.

Interestingly, issues with the air-void system were also observed in some of the extracted cores. Figures 8 (a) through (f) show micrographs and scanned images of several extracted core specimens (from projects NE-2, NC-1, and SW-1) that exhibited accumulation of air voids around the aggregates. Figures 9 (a) through (f) show micrographs and scanned images of extracted core specimens (from projects: NE-4, NC-2, and SW-3) that were unusually porous with significant coalescence of entrained air voids. As these core specimens represent the concrete as-placed, there is some concern regarding the uniformity of the air-void system in newly constructed pavements.

It should be noted that no quantitative analysis was conducted to investigate how widespread these observations were. Rather, a qualitative assessment was performed to highlight the general issues and tendencies uncovered during the laboratory testing.

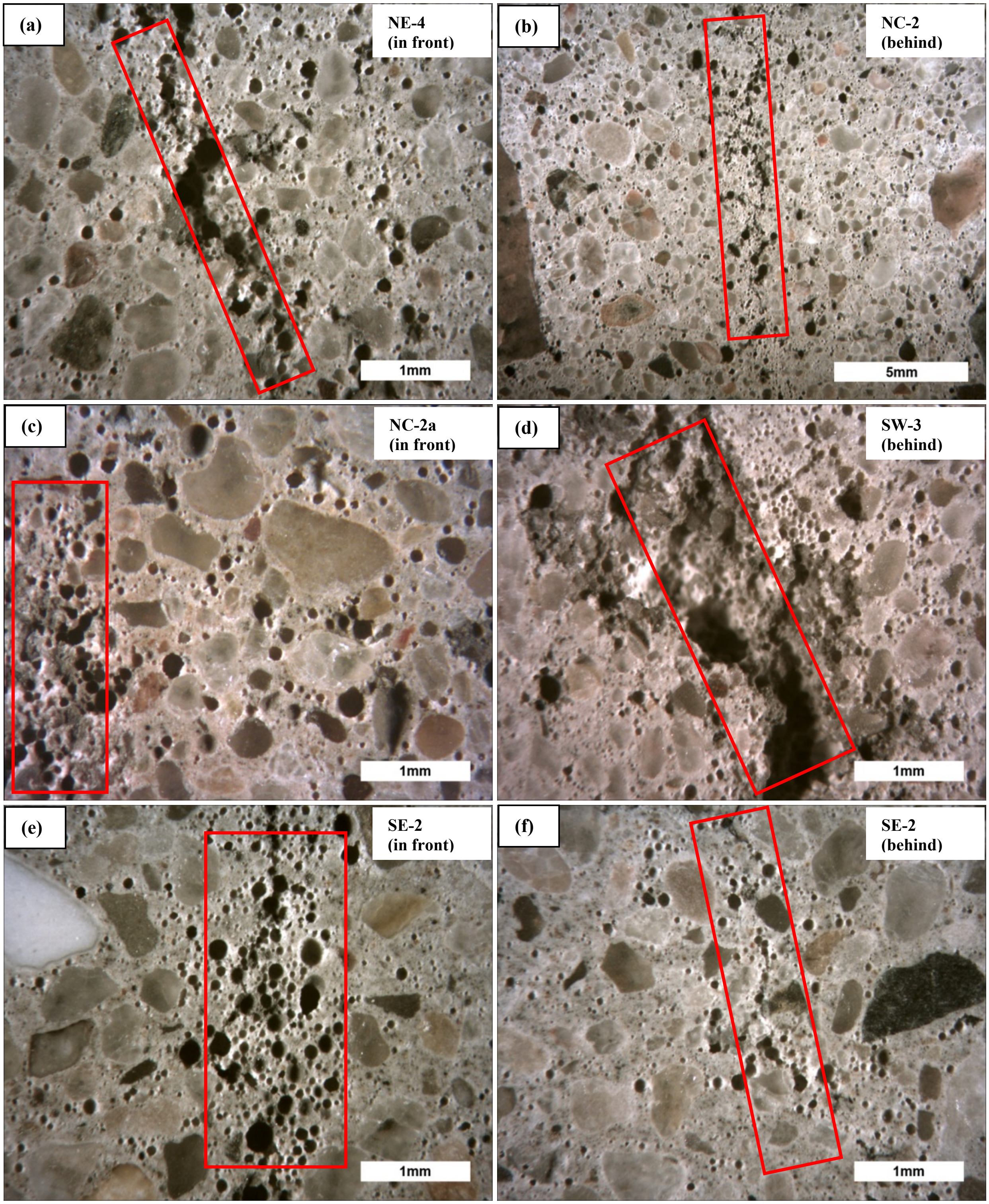

Figure 7. Micrographs of field-cast cylinder specimens exhibiting segregation due to internal vibration.

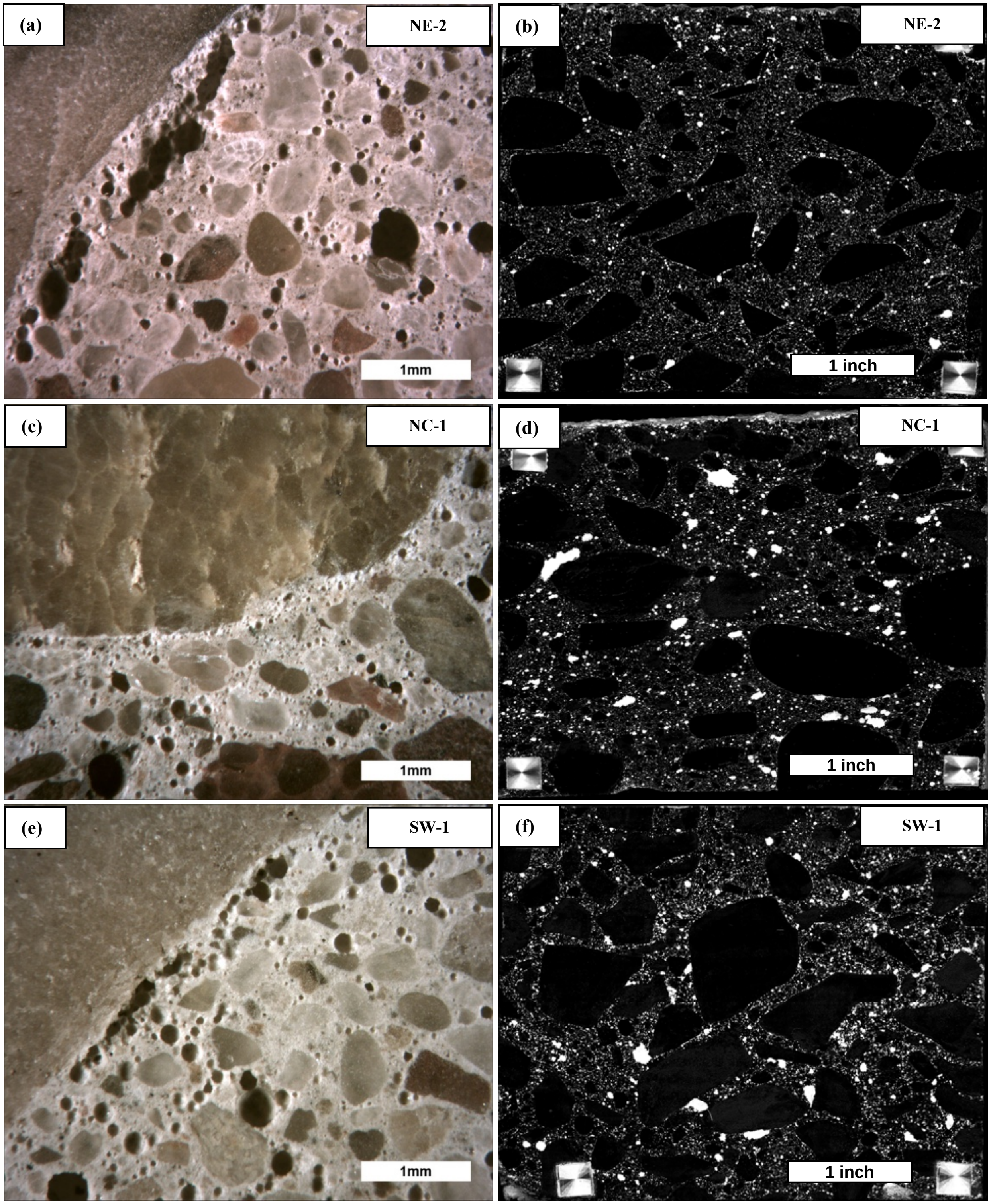

Figure 8. Micrographs and scanned images of core specimens exhibiting accumulation of air voids around aggregates.

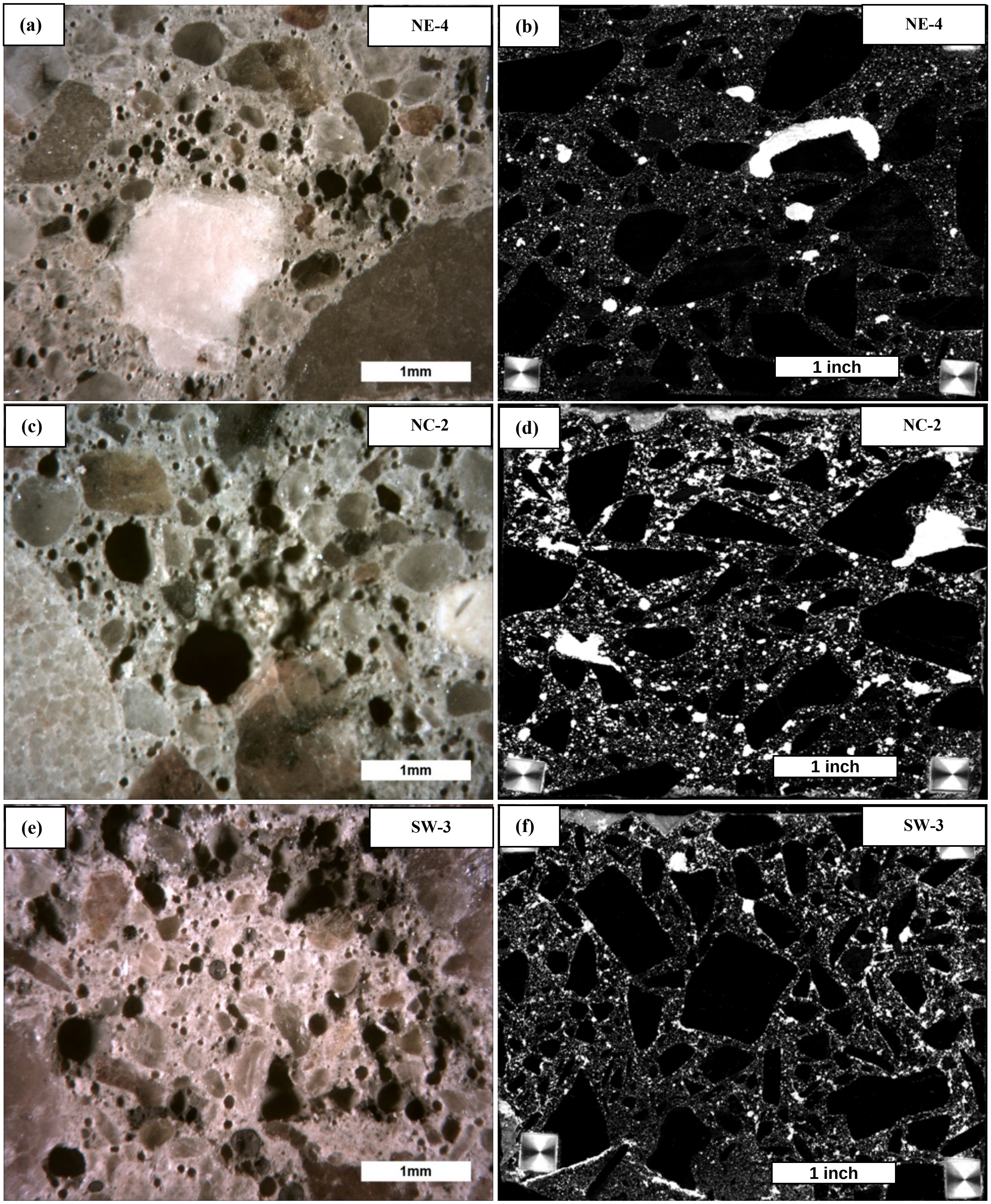

Figure 9. Micrographs and scanned images of unusually porous core specimens exhibiting coalescence of entrained air voids.

Comparison of Air Contents Before and After Slipform Paving

Figures 10 through 13 show the comparison of the air contents measured on the cylinders cast from the concrete obtained before and after the slipform paving process and on the cores extracted from the concrete pavement. Both the automated and the ASTM C457 manual analysis protocols were used in measuring the hardened air contents.

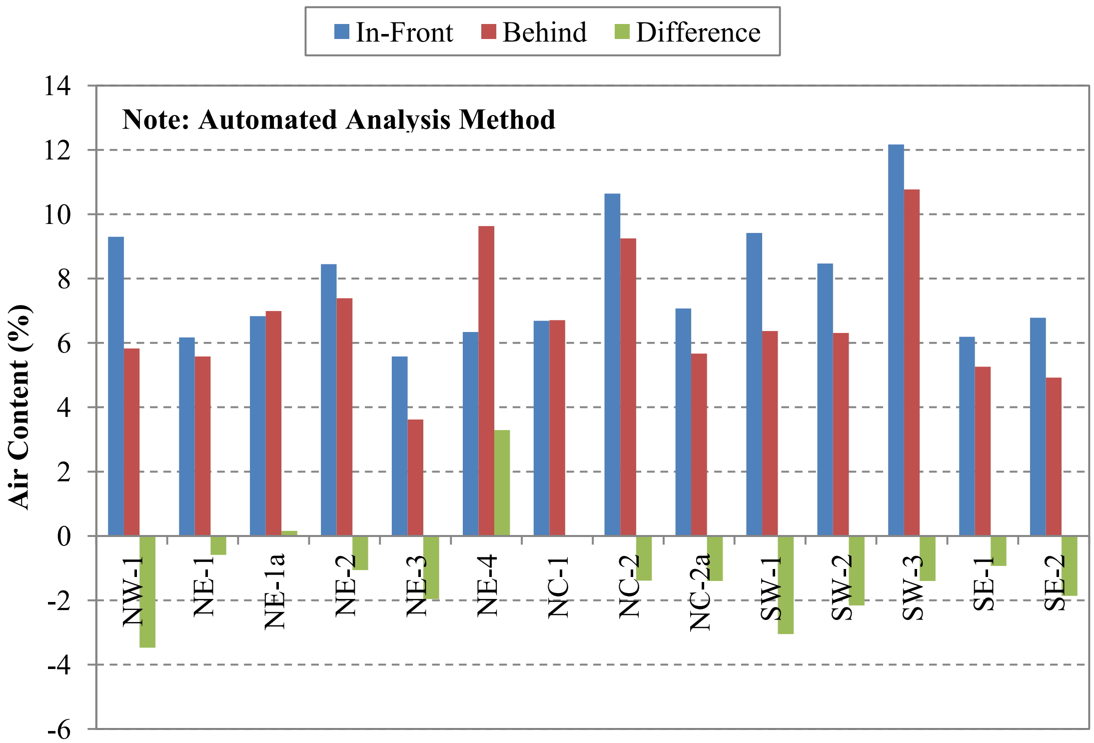

Figure 10. Comparison of air contents before and after slipform paving (field-cast cylinders) – Automated Method.

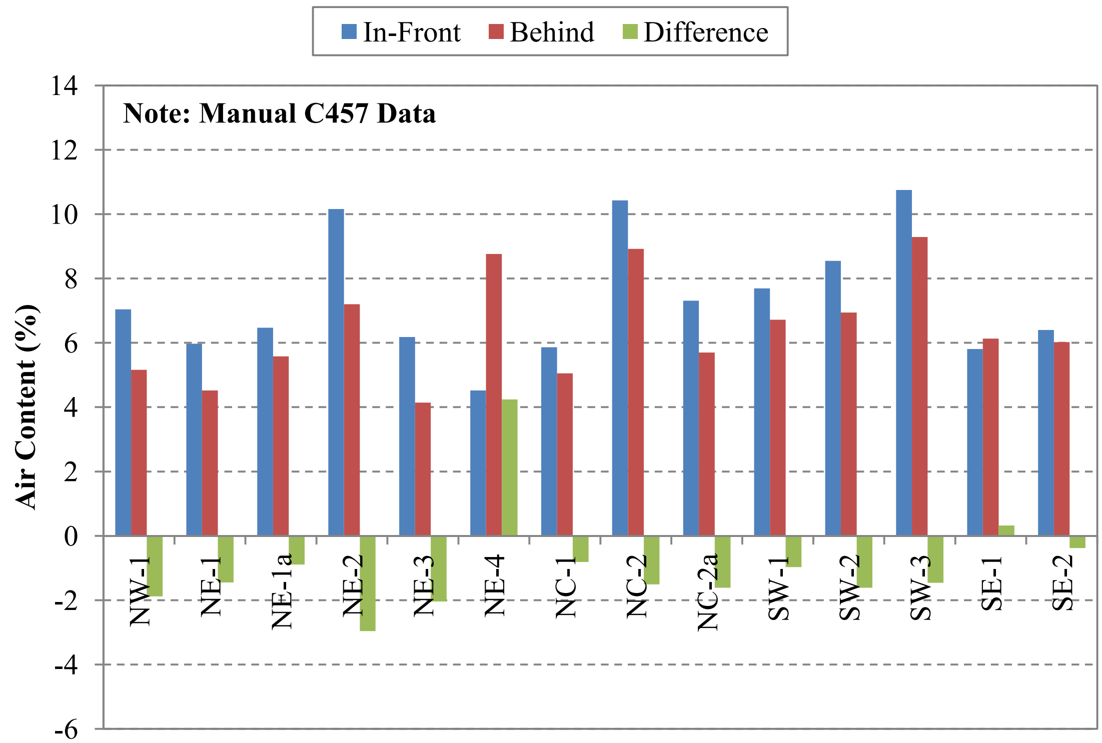

Figure 11. Comparison of air contents before and after slipform paving (field-cast cylinders) – ASTM C457 Manual Method.

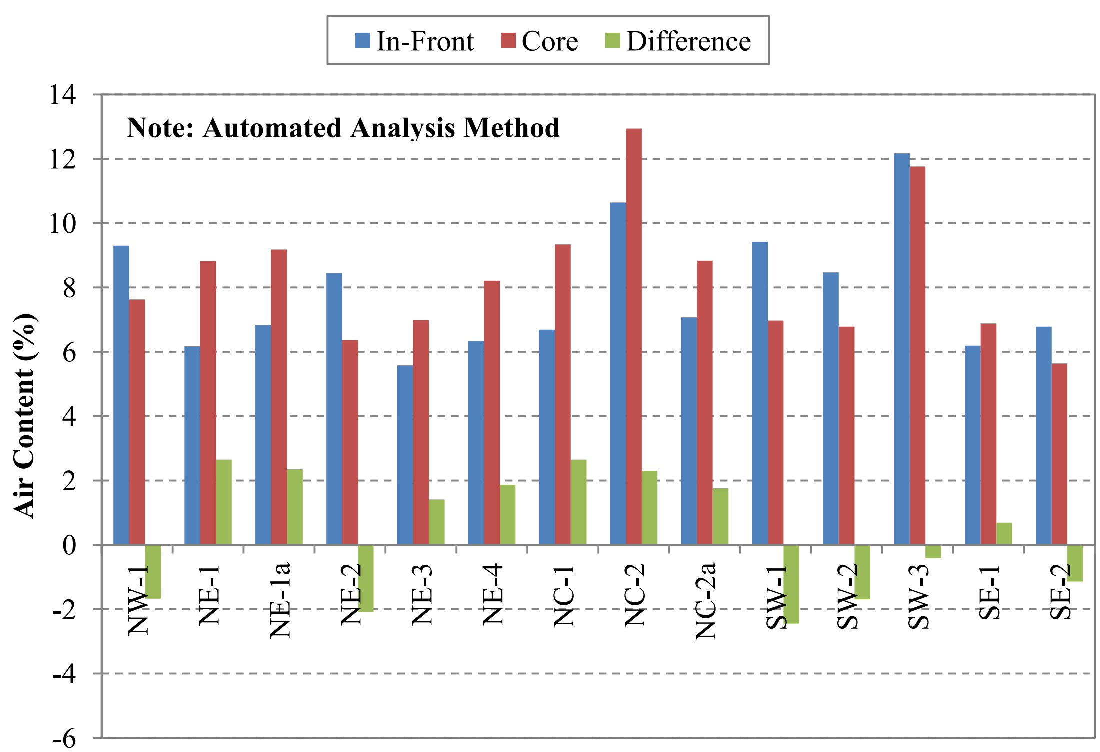

Figure 12. Comparison of air contents before (field-cast cylinders) and after slipform paving (extracted core specimen) – Automated Method.

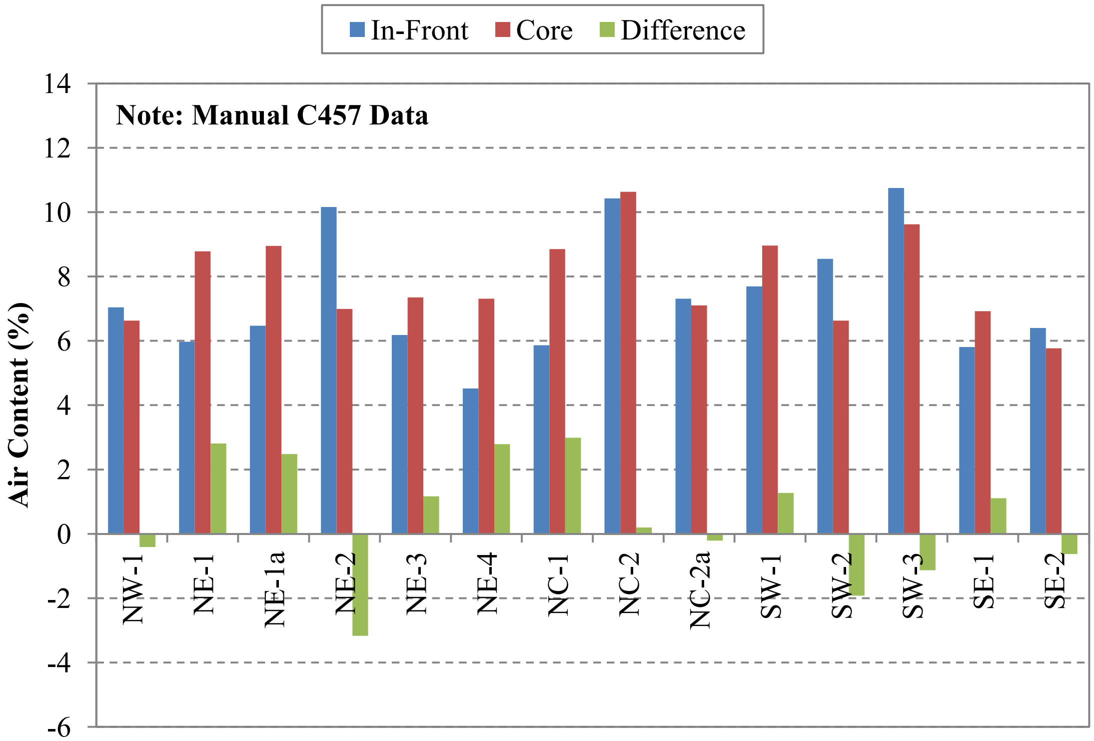

Figure 13. Comparison of air contents before (field-cast cylinders) and after slipform paving (extracted core sample) – ASTM C457 Manual Method.

When comparing the difference in air contents before and after the slipform paving operation using the air contents measured in the fresh concrete (see figure 6) and the field-cast cylinder specimens (see figures 10 and 11), a decline in the air content is evident. However, when comparing the air content measured in the field-cast specimens before the paving process and the core samples extracted from the pavement (see figures 12 and 13), there is no conclusive evidence to support the hypothesis that there is a decline in the air content due to the slipform paving process.

These conflicting results are likely the product of the differing methods of consolidation and its impact on the air-void system. As previously mentioned, the field-cast cylinders were consolidated using an internal vibrator; as a result, the segregation resulting from the vibrator is evident in many of the cylinder specimens, including the cast cylinder specimens collected after slipform paving (see figure 4). Concrete in these specimens has been worked and consolidated twice (first by the paver and then by the internal vibration during preparation of the cylinder specimens), so it is reasonable to expect that the air content would be lower and this is indeed the case.

Table 5 summarizes the type of admixtures (air-entraining agent and water reducer) used in the concrete mixtures and results of the field and laboratory air content testing. Figures 14 and 15 show the air void spacing factors from the cylinder and core specimens.

Table 5. Summary of field and laboratory air content testing results.

Project ID	AEA Type	Field			Laboratory (Automated)					Laboratory (Manual)				
		Air Content (%)			Average Air Content (%)					Average Air Content (%)				
		In-Front	Behind	Difference[1]	In-Front	Behind	Difference[2]	Core	Difference[3]	In-Front	Behind	Difference[2]	Core	Difference[3]
NW-1	Non VR	6.20	5.20	-1.00	9.3	5.83	-3.47	7.63	-1.67	7.04	5.16	-1.88	6.63	-0.41
NE-1	VR	6.60	5.40	-1.20	6.17	5.58	-0.59	8.82	2.65	5.97	4.52	-1.45	8.78	2.81
NE-1a	VR	6.80	5.90	-0.90	6.83	6.99	0.16	9.18	2.35	6.47	5.58	-0.89	8.95	2.48
NE-2	VR	8.00	6.40	-1.60	8.45	7.39	-1.06	6.37	-2.08	10.16	7.2	-2.96	6.99	-3.17
NE-3	Non VR	6.00	4.90	-1.10	5.58	3.62	-1.96	6.99	1.41	6.18	4.14	-2.04	7.35	1.17
NE-4	Non VR	5.60	5.80	0.20	6.34	9.63	3.29	8.21	1.87	4.52	8.76	4.24	7.31	2.79
NC-1	Non VR	6.30	5.70	-0.60	6.69	6.71	0.02	9.34	2.65	5.86	5.05	-0.81	8.85	2.99
NC-2	Non VR	5.90	5.40	-0.50	10.64	9.25	-1.39	12.94	2.3	10.43	8.92	-1.51	10.63	0.2
NC-2a	Non VR	6.60	4.80	-1.80	7.07	5.67	-1.4	8.83	1.76	7.31	5.7	-1.61	7.1	-0.21
SW-1	Non VR	6.80	5.10	-1.70	9.42	6.37	-3.05	6.97	-2.45	7.69	6.72	-0.97	8.96	1.27
SW-2	Non VR	7.50	6.20	-1.30	8.47	6.31	-2.16	6.78	-1.69	8.55	6.94	-1.61	6.63	-1.92
SW-3	Non VR	7.00	6.50	-0.50	12.17	10.77	-1.4	11.76	-0.41	10.75	9.29	-1.46	9.62	-1.13
SE-1	Non VR	5.80	5.00	-0.80	6.19	5.26	-0.93	6.88	0.69	5.81	6.13	0.32	6.92	1.11
SE-2	Non VR	6.90	5.10	-1.80	6.78	4.92	-1.86	5.64	-1.14	6.4	6.02	-0.38	5.77	-0.63

Notes:

[1]: Difference between air contents measured in fresh concrete in front of and behind the paver.

[2]: Difference between air contents measured in field cylinders cast using concrete in front of and behind the paver.

[3]: Difference between air contents measured in field cylinders cast using concrete in front of paver and extracted core samples.

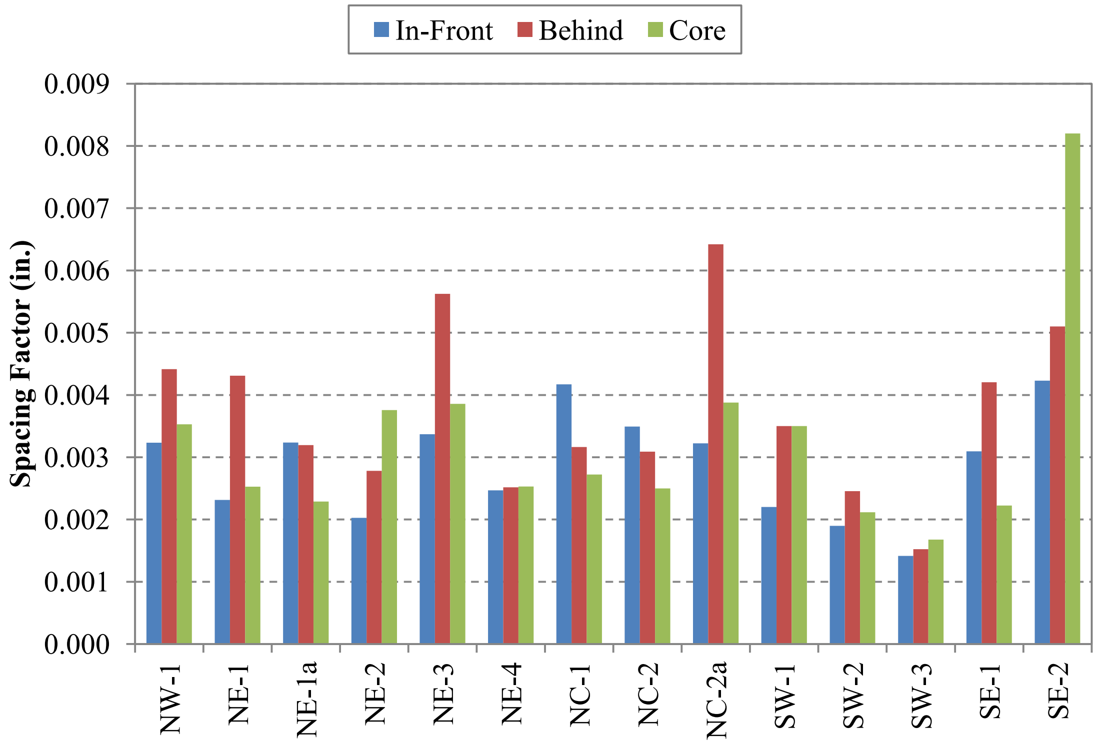

Figure 14. Air void spacing factor in cylinder and core specimens (Automated Method).

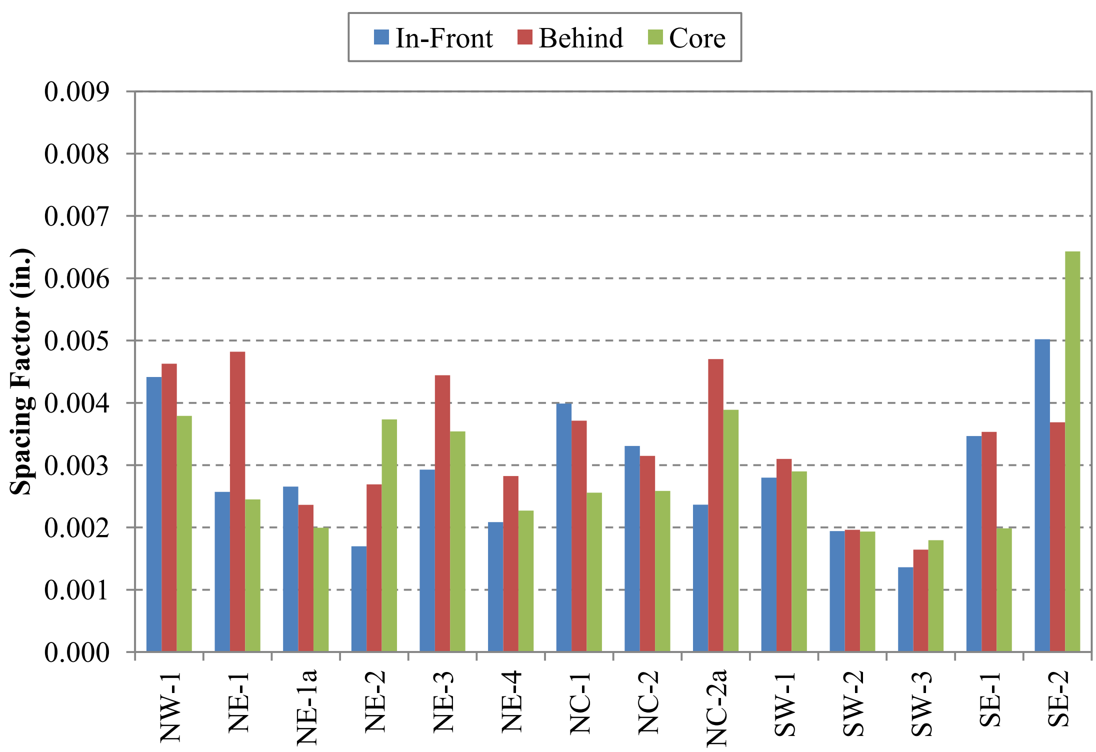

Figure 15. Air void spacing factor in cylinder and core specimens (ASTM C457 Manual Method).

From figures 14 and 15, it is seen that all of the tested specimens (with the exception of the core sample from SE-2, which was analyzed using the automated method) exhibited spacing factors of less than 0.008 in; that value is widely regarded as the acceptable threshold value to ensure good durability with respect to freezing and thawing.

Table 6 shows the variation of the average air content in the cores by depth. Significant variations in the air content by depth were observed in some of the core samples. Some samples exhibited increasing air contents with depth, some show decreasing air contents with depth, and some show no apparent difference. These results suggest that some mixtures may have been more difficult to consolidate than others. It should be noted that the air content values by depth provide reasonable estimates that can be used for comparative purposes.

Table 6. Variation in air content by depth in core samples (Automated Method).

Project ID	Air Content (%)			General Trend
	Top	Mid	Bottom	
NW-1	7.32	7.94	7.65	⇔
NE-1	6.34	9.53	10.58	⇧
NE-1a	6.64	10.07	9.82	⇧
NE-2	7.32	4.59	7.18	⇔
NE-3	5.87	8.59	6.49	⇔
NE-4	8.7	8.95	6.98	⇩
NC-1	7.87	8.45	11.62	⇧
NC-2	17.24	10.85	10.7	⇩
NC-2a	8.2		9.4	⇧
SW-1	5.53	6.7	8.68	⇧
SW-2	5.27	6.7	8.3	⇧
SW-3	12.6		10.87	⇩
SE-1	8.82	6.68	5.22	⇩
SE-2	5.97	4.43	6.48	⇔

⇧: Increasing Air Content with Depth ⇩: Decreasing Air Content with Depth ⇔: No Apparent Change

Comparison of Air Content Measured in Fresh Concrete, Field Cylinders, and Cores

This section presents some relative comparisons between the air content values measured in fresh concrete, field cylinders, and the extracted cores. Tables 7 and 8 presents various combinations of the ratios of air contents between the fresh concrete and cylinders, between the fresh concrete and cores, and the cylinders to cores. The primary intent of this analysis was to determine which of the air content measurements compared most closely with the air content values measured in the extracted cores.

Table 7. Comparison of air content ratios (Automated Method).

Project ID	Automated Method					
	Fresh : Cylinders		Fresh : Core		Cylinders : Core	
	In-Front	Behind	In-Front	Behind	In-Front	Behind
NW-1	0.67	0.89	0.81	0.68	1.22	0.76
NE-1	1.07	0.97	0.75	0.61	0.70	0.63
NE-1a	1.00	0.84	0.74	0.64	0.74	0.76
NE-2	0.95	0.87	1.26	1.00	1.33	1.16
NE-3	1.08	1.35	0.86	0.70	0.80	0.52
NE-4	0.88	0.60	0.68	0.71	0.77	1.17
NC-1	0.94	0.85	0.67	0.61	0.72	0.72
NC-2	0.55	0.58	0.46	0.42	0.82	0.71
NC-2a	0.93	0.85	0.75	0.54	0.80	0.64
SW-1	0.72	0.80	0.98	0.73	1.35	0.91
SW-2	0.89	0.98	1.11	0.91	1.25	0.93
SW-3	0.58	0.60	0.60	0.55	1.03	0.92
SE-1	0.94	0.95	0.84	0.73	0.90	0.76
SE-2	1.02	1.04	1.22	0.90	1.20	0.87
# Projects with Ratios < 1.00	11	12	11	13	8	12
Average	0.87	0.87	0.84	0.70	0.97	0.82
SD	0.17	0.20	0.23	0.16	0.25	0.19
COV	0.20	0.23	0.28	0.23	0.25	0.23

Table 8. Comparison of air content ratios (ASTM C457 Manual Method).

Project ID	Manual Method					
	Fresh : Cylinders		Fresh : Core		Cylinders : Core	
	In-Front	Behind	In-Front	Behind	In-Front	Behind
NW-1	0.88	1.01	0.94	0.78	1.06	0.78
NE-1	1.11	1.19	0.75	0.62	0.68	0.51
NE-1a	1.05	1.06	0.76	0.66	0.72	0.62
NE-2	0.79	0.89	1.14	0.92	1.45	1.03
NE-3	0.97	1.18	0.82	0.67	0.84	0.56
NE-4	1.24	0.66	0.77	0.79	0.62	1.20
NC-1	1.08	1.13	0.71	0.64	0.66	0.57
NC-2	0.57	0.61	0.56	0.51	0.98	0.84
NC-2a	0.90	0.84	0.93	0.68	1.03	0.80
SW-1	0.88	0.76	0.76	0.57	0.86	0.75
SW-2	0.88	0.89	1.13	0.94	1.29	1.05
SW-3	0.65	0.70	0.73	0.68	1.12	0.97
SE-1	1.00	0.82	0.84	0.72	0.84	0.89
SE-2	1.08	0.85	1.20	0.88	1.11	1.04
# Projects with Ratios < 1.00	9	9	11	14	8	10
Average	0.93	0.90	0.86	0.72	0.95	0.83
SD	0.18	0.19	0.19	0.13	0.25	0.21
COV	0.19	0.21	0.22	0.18	0.26	0.25

SD: Standard Deviation; COV: Coefficient of Variation

From tables 7 and 8, it is seen that the ratios computed using the air content measurements determined using both the automated and the ASTM C457 manual method are very similar. Although several key factors can affect these values, the data shown in tables 7 and 8 suggest the following:

- Comparing the ratios between the air content values measured in the fresh concrete and the field-cast cylinders, it was observed that, on average, the air content measured in the fresh concrete was approximately 10 percent lower than the air content measured in the field cylinders. The biggest differences were in NC-2 and SW-3, both of which had fresh air contents within the specification range, but air contents well above specification in the cast cylinders. It is noted that the air contents in the extracted cores were also the highest in the data set, being well above the specification limits.
- The ratios between air content measured in the fresh concrete (in front of the paver) and the core specimens are, on average, also less than 1.00, and to a greater degree than the ratio of fresh concrete and the cast cylinders. This indicates that the amount of air measured in the in-place concrete is higher than the air content measured in the fresh concrete, both in front of and behind the paver. This suggests that the air content testing on fresh concrete is underestimating the air content of the concrete placed with a slipform paver.
- As discussed earlier, the air content of the fresh concrete measured behind the paver is reduced due to the additional consolidation effort imparted by the paver. Hence, the ratio of fresh concrete sampled behind the paver to the core specimen (approximately 0.70) is significantly smaller than the ratio of fresh concrete sampled in front of the paver to the core specimen (approximately 0.85).
- The ratios between the air content values measured in the field cylinders (cast from concrete in front of the paver) and the air content measured in the core samples are very close to 1.00 (0.95 for the ASTM C457 Manual Method and 0.97 for the automated method). This suggests that the air content of the in-place concrete pavement placed by a slipform paver may be better represented by the air content values of the hardened concrete measured using cylinders cast from concrete from in front of the paver when that concrete is consolidated with an inserted vibrator. It should be noted that these conclusions are based on a very limited data set and thus cannot be supported statistically. A rigorous experiment should be designed to more fully investigate this observation.
- As expected, the ratios between the air content measured in the field cylinder cast using concrete behind the paver and the air content of the core specimens are lower than the ratios between the air content measured in field cylinders cast from concrete obtained in front of the paver and the air content measured in the core specimens.

Figures 16 through 21 summarize the air content measured in the fresh concrete, field-cast cylinders, and the core samples extracted from the pavement. The horizontal dashed lines in each plot show WisDOT's current specification for air content of fresh concrete measured in front of the paver (5.5 to 8.5 percent). These figures clearly show the trends discussed above, as well as the project-to-project variation.

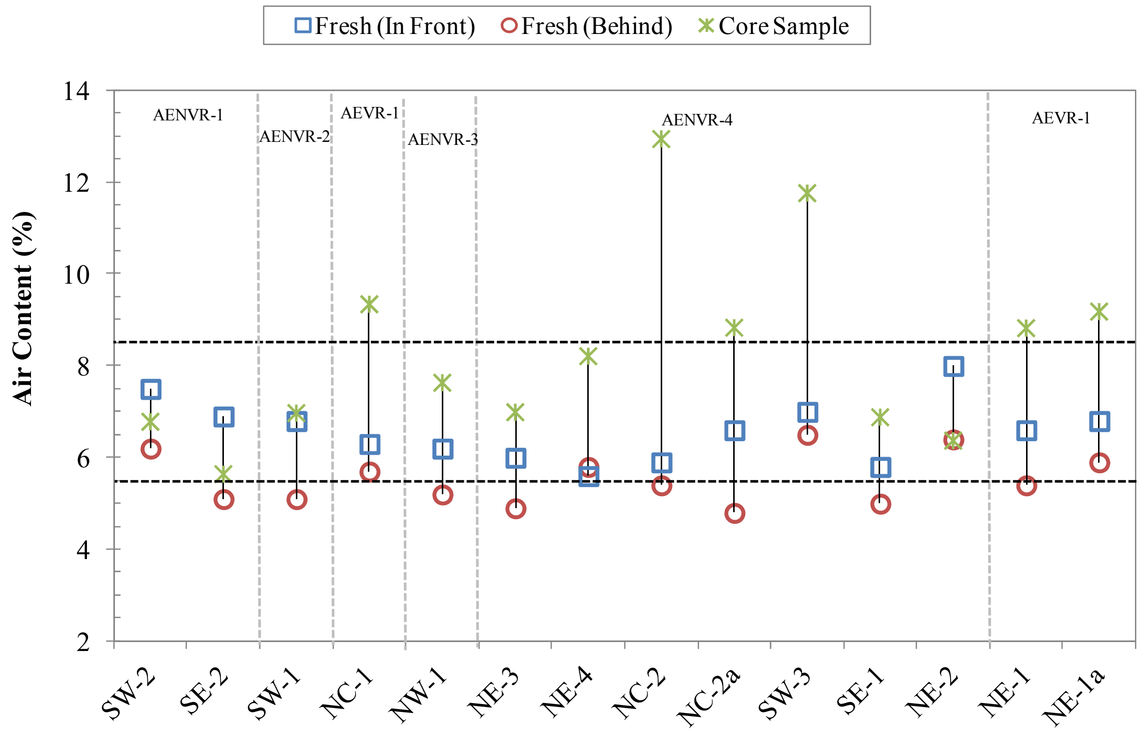

Figure 16. Comparison of fresh and hardened concrete (cores) air contents (Automated Method).

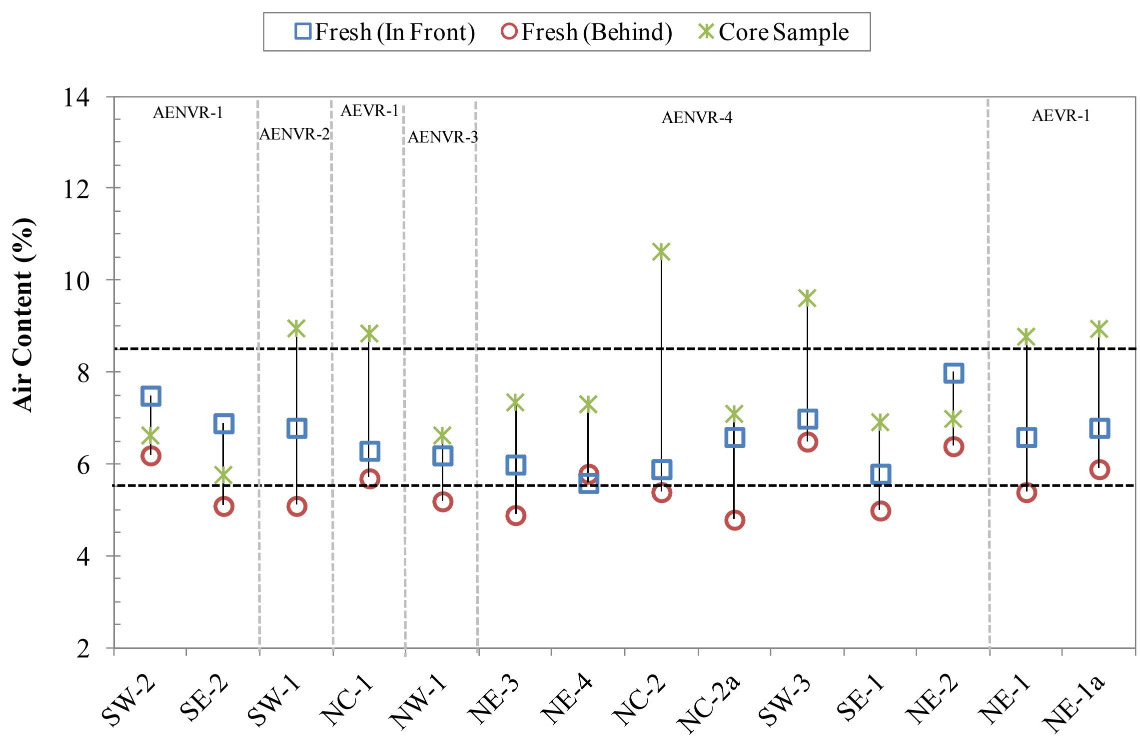

Figure 17. Comparison of fresh and hardened concrete (cores) air contents (ASTM C457 Manual Method).

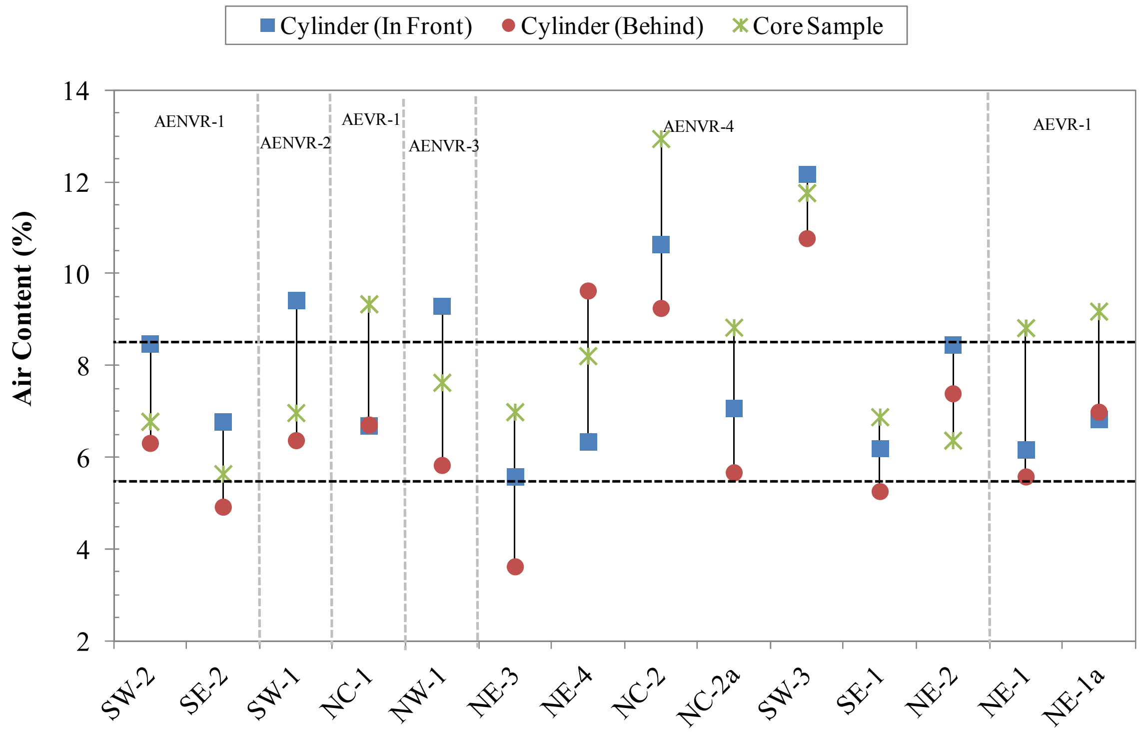

Figure 18. Comparison of air contents in cylinders and cores (Automated Method).

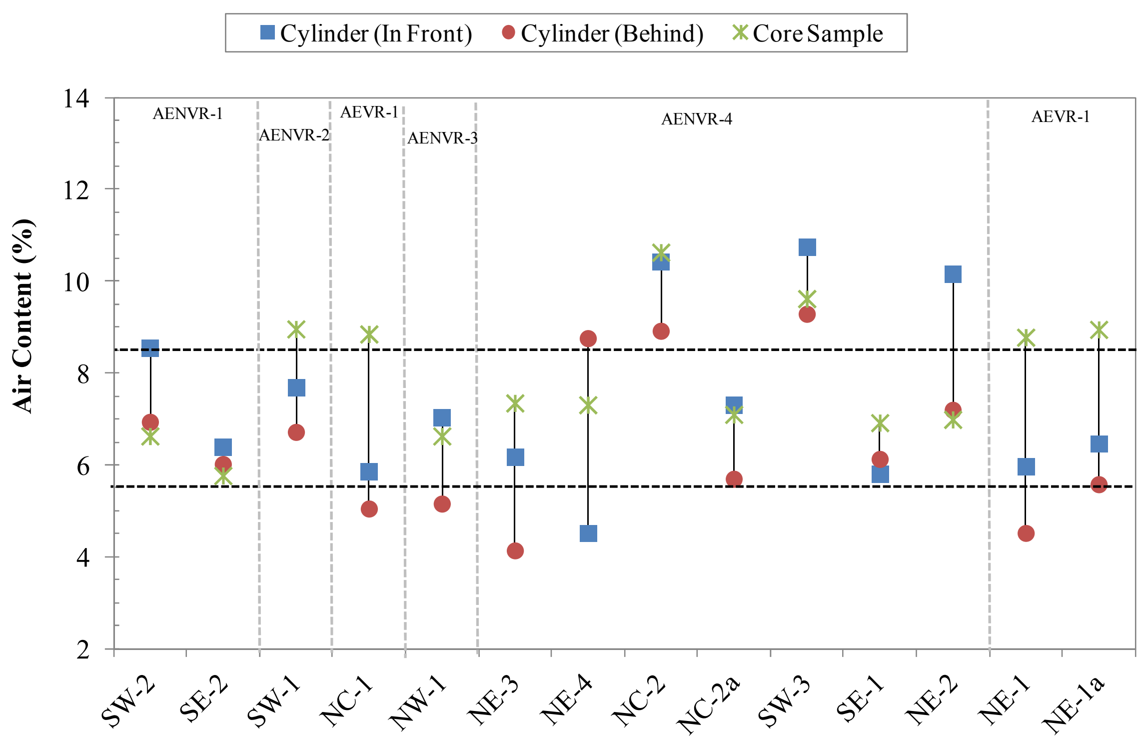

Figure 19. Comparison of air contents in cylinders and cores (ASTM C457 Manual Method).

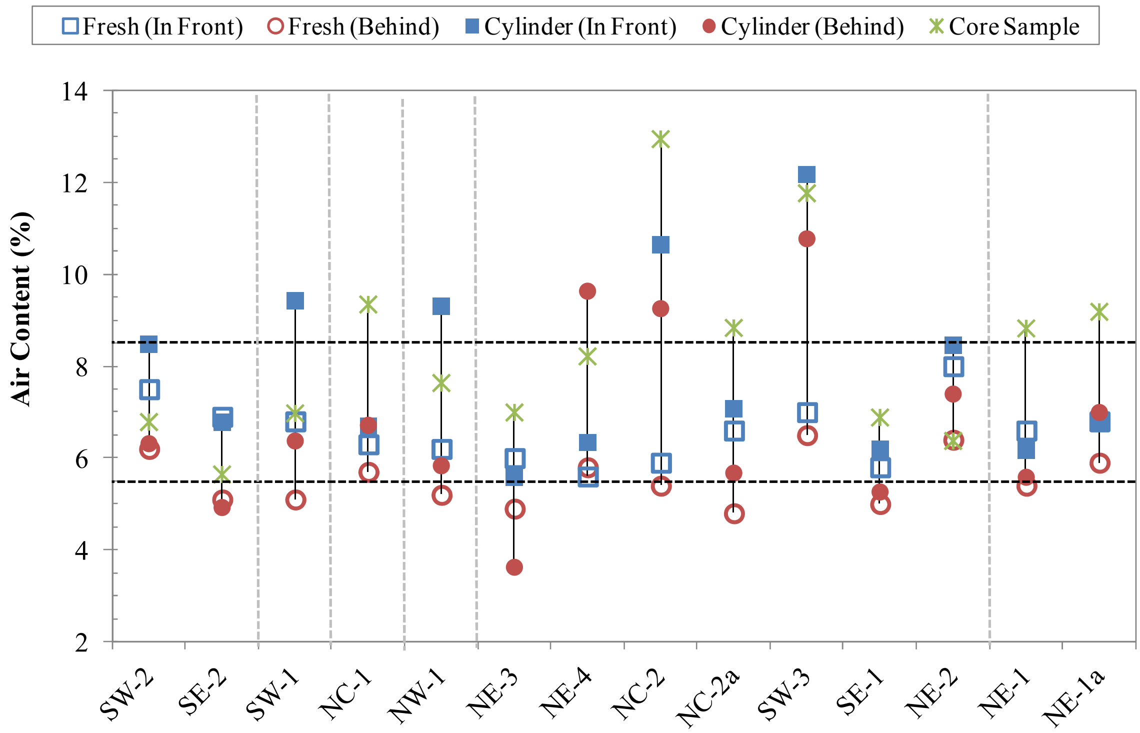

Figure 20. Summary of air contents measured in the field and laboratory (Automated Method).

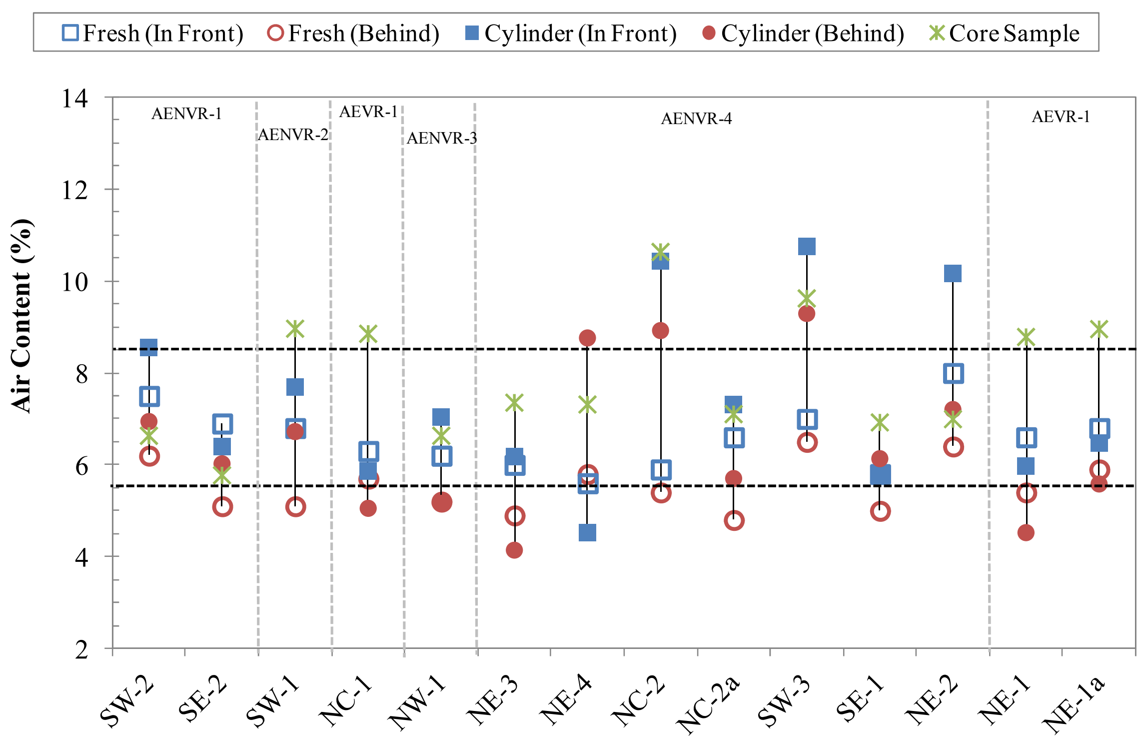

Figure 21. Summary of air contents measured in the field and laboratory (ASTM C457 Manual Method).

From figures 16 through 21, the following general observations are made:

- For all the projects, the air contents of the fresh concrete measured by the pressure meter in front of the paver were within the specification limits of 5.5 to 8.5 percent. Only 2 of the 14 sites tested had fresh air contents in front of the paver of 7.5 percent or greater (NE-2 and SW-2) and none were greater than 8.0 percent.
- Comparing the air contents measured in the fresh concrete and the field cylinders cast with concrete in front of the paver:
  - The air contents measured in the field cylinders are greater than the fresh concrete air contents in 11 out of the 14 sites per the automated analysis protocol.
  - The air contents measured in the field cylinders are greater than the fresh concrete air contents in 9 out of the 14 sites per the ASTM C457 manual analysis protocol.

  These results suggest that the air content testing of fresh concrete in general yields lower values than the air content testing on hardened concrete.
- Comparing the air contents measured in the fresh concrete and the core samples extracted from the pavement:
  - The air contents measured in the core samples are greater than the fresh concrete air contents in 11 out of the 14 sites (as per both the automated and ASTM C457 manual analysis protocols).
  - The data indicate that the air content measured using the pressure meter results, on average, in a lower air content value in the majority of cases. Even though the experiment in this study was not designed to be statistically representative, a general conclusion can be drawn that the air content measured using the pressure meter is not representative of the air content measured microscopically on the in-place concrete pavement. In a majority of the cases, the in-place pavement has higher air contents than the project specifications, which are based on the fresh concrete properties. The higher air contents of the in-place pavement could potentially lead to increased permeability and reduced strength, which can have a significant impact on the long-term durability of the concrete pavement. Although it is known that the pressure meter (AASHTO T 152/ASTM C231) will measure less air than ASTM C457 at relatively high air contents, the air content measurements of the fresh concrete before the paver all fell within project specifications (and 12 of the 14 were less than 7.5 percent). Thus, it appears that the discrepancy between the air content in the fresh and hardened concrete is real, and should be addressed through further research.
- Comparing the air contents measured in the field cylinder cast using the concrete in front of the paver and the core samples extracted from the pavement:
  - The air contents measured in the core samples are greater than the air contents measured in the field cylinders in 8 out of the 14 sites (per both the automated and ASTM C457 manual analysis protocols), which is just over 50 percent of the sites included in this study. This result suggests that in about 50 percent of the cases, the air contents of the field cylinders (cast using concrete in front of the paver) are higher than the air contents of the extracted cores.

It is recognized that comparing the average air content values of all the project sites has limited value as each site condition is different and there are several factors impacting the fresh and hardened concrete properties. However, the concrete mix designs for each of these projects were developed in order to achieve an average target air content of approximately 7 percent. Table 9 shows statistics on the average air content values of the fresh concrete, field cylinders, and the extracted core specimens.

Table 9. Summary of average air content values.

Statistics	Fresh Concrete Air Content (%)				
	In Front		Behind		Difference
Average	6.57		5.53		-1.04
SD	0.67		0.56		0.58
Statistics	**Laboratory Air Content (%, Automated Method)**				
	In Front[1]	**Behind[2]**	**Difference[3]**	**Core**	**Difference[4]**
Average	7.86	6.74	-1.13	8.31	0.45
SD	1.94	1.97	1.63	2.06	1.93
Statistics	**Laboratory Air Content (%, Manual Method)**				
	In Front[1]	**Behind[2]**	**Difference[3]**	**Core**	**Difference[4]**
Average	7.37	6.44	-0.93	7.89	0.53
SD	1.92	1.63	1.68	1.39	1.90

[1,2]: Field cylinders; [3]: Difference between air contents measures in cylinders (In front - Behind)
[4]: Difference between air contents measures in cylinder and core (Cylinder In front - Core)

From the data summarized in table 9, it can be inferred that the difference between the air content of the extracted core samples and the fresh concrete (in front of the paver) is between 1.32 and 1.74 percent. The difference between the air content of the field cylinders (in front of the paver) and the core samples is between 0.45 and 0.53 percent, with the core samples always having higher air contents. Noting that the fresh concrete air specimens and cast cylinders were compacted similarly, these data suggest that the air content testing using the pressure meter (ASTM C231) is, on average, underestimating the air content values. The average air content of the cylinders cast using the concrete in front of the paver is much more comparable to the air content measured in the core samples, possibly as a result of the internal vibration used to consolidate the cylinders simulating the consolidation that occurs through the paver.

The result of the air content testing on the fresh concrete and the field cylinders suggests that there is a loss of air (approximately 1 percent) as the concrete passes through the paver. However, in considering this finding, two issues must be noted:

- The multi-operator precision of the air meter (according to ASTM C231) is 0.8 percent, which is very close to the observed air loss in the fresh concrete.
- The specimens prepared using the concrete behind the paver has been consolidated twice—first by the paver and then by the internal vibration applied during specimen preparation.

Table 10 summarizes the air content test results and the air-void system parameters for the core samples retrieved from the pavement.

Table 10. Summary of air contents and air-void system parameters for core samples.

Project ID	AEA Type	Air Content (%)		Void Frequency (voids/in.)		Spacing Factor (in.)	
		Automated	Manual	Automated	Manual	Automated	Manual
NW-1	Non VR	7.63	6.63	12.88	11.99	0.0035	0.0038
NE-1	VR	8.82	8.78	13.87	14.30	0.0025	0.0025
NE-1a	VR	9.18	8.95	14.93	17.12	0.0023	0.0020
NE-2	VR	6.37	6.99	11.79	11.86	0.0038	0.0037
NE-3	Non VR	6.99	7.35	11.02	12.01	0.0039	0.0035
NE-4	Non VR	8.21	7.31	13.25	14.76	0.0025	0.0023
NC-1	Non VR	9.34	8.85	14.29	15.20	0.0027	0.0026
NC-2	Non VR	12.94	10.63	15.26	14.74	0.0025	0.0026
NC-2a	Non VR	8.83	7.10	11.51	11.48	0.0039	0.0039
SW-1	Non VR	6.97	8.96	11.60	14.23	0.0035	0.0029
SW-2	Non VR	6.78	6.63	13.71	14.99	0.0021	0.0019
SW-3	Non VR	11.76	9.62	17.81	16.63	0.0017	0.0018
SE-1	Non VR	6.88	6.92	12.76	14.30	0.0022	0.0020
SE-2	Non VR	5.64	5.77	7.00	8.93	0.0082	0.0064

Based on the data summarized in table 10, the following qualitative assessments on the measured air contents and the air-void system parameters can be made:

- In many cases, the spacing factor requirements were comfortably met (NE-1, NE-1a, NE-4, NC-1, and NC-2a). For several projects (NC-2 and SW-3), the air contents were exceptionally high (>10 percent, on average). These high air content values can result in reduced strength and increased permeability, which can detrimentally impact the long-term durability of the pavement. This is of even greater concern because the fresh air content measurements before the paver for NC-2 and SW-3 were 5.90 and 7.00 percent, respectively, which are comfortably within the range of the specification. In these two extreme cases, the measurement of the fresh concrete air content gave no indication that a potential high air issue existed.
- The target air content (fresh concrete, specified per ASTM C231) for most of the projects is around 7 percent. More than 50 percent of the projects sampled have hardened air contents outside the 7±1 percent range, and six projects have hardened air contents that are greater than the upper specification limit of 8.5 percent (but none had values below the lower specification limit of 5.5 percent). The air void spacing factors are all within the acceptable threshold limits and hence this is not expected to impact the long-term freeze-thaw durability of the concrete. However, in cases where the air contents are too high, the reduced strength and increased permeability could be a potential issue.

Air Content and Compressive Strength

This section presents some relative comparisons between the air content values measured in fresh concrete and the cores and the compressive strength data obtained from the quality assurance (QA) testing. This is an attempt to see whether there are any relationships between these variables, although on a very broad level. It should be noted that the cylinders used to determine the compressive strengths were not cast using the concrete from the exact same location as the air content testing, but the air content measurement and the strength testing locations were within 500 feet of each other. Table 11 summarizes the air contents and the compressive strength testing (QA) results.

Table 11. Summary of air contents and compressive strength test results.

Project ID	AEA Type	Average Air Content (%)					Compressive Strength (psi) (QA)
		Fresh Concrete			Core		
		In-Front	In-Front (QA)	Behind	Automated	Manual	
NW-1	Non VR	6.20	6.50	5.20	7.63	6.63	4,827
NE-1	VR	6.60	6.10	5.40	8.82	8.78	6,985
NE-1a	VR	6.80		5.90	9.18	8.95	
NE-2	VR	8.00	6.90	6.40	6.37	6.99	6,211
NE-3	Non VR	6.00	6.90	4.90	6.99	7.35	6,060
NE-4	Non VR	5.60	6.70	5.80	8.21	7.31	5,236
NC-1	Non VR	6.30	6.30	5.70	9.34	8.85	4,621
NC-2	Non VR	5.90	6.30	5.40	12.94	10.63	5,565
NC-2a	Non VR	6.60		4.80	8.83	7.10	
SW-1	Non VR	6.80	8.80	5.10	6.97	8.96	4,367
SW-2	Non VR	7.50	7.00	6.20	6.78	6.63	4,782
SW-3	Non VR	7.00	7.90	6.50	11.76	9.62	3,835
SE-1	Non VR	5.80		5.00	6.88	6.92	
SE-2	Non VR	6.90	6.30	5.10	5.64	5.77	5,970

Based on the reports on the WisDOT GIS portal, all the projects met the project-specified compressive strength requirements. The data summarized in table 11 do not exhibit any particular trends that would suggest that higher air content values (seen in projects NC-1, NC-2, SW-1, and SW-3) resulted in lower than specified compressive strength values. As these are different mixes sampled from around the state, no relationship between strength and air content would be expected.

The air content data from the pressure meter testing were compared to the QA test data with good agreement. In addition, this testing was conducted over the course of the entire construction season. Hence, there is no belief that there was a problem with the calibration of a given air pressure meter during field testing.

Summary

This chapter presents the results of the laboratory and the field testing performed in this study. A summary of the primary findings and observations from the data analysis is presented below:

- The results of the air content testing on fresh concrete and the concrete cylinder specimens cast in the field suggested that there is a loss of air (approximately 1 percent) as the concrete passes through the paver. However, laboratory testing performed on cores extracted from the pavement did not provide conclusive evidence that air was lost during the slipform paving process.

- The air content values from the as-placed hardened samples measured in extracted cores are high in many cases, and the relative values of the air contents taken from the cylinders (before and after the paver) and from the cores do not always follow expected trends.
- The cylinders cast from the concrete were subjected to internal vibration during consolidation. As a result, the air contents from these specimens are likely not representative of the concrete as delivered and placed. Furthermore, the internal vibration may have led to the accumulation of air voids around the aggregates as observed in many of the cylinder specimens that were cast in the field. An alternative method of consolidation, such as a vibration table or rodding, may provide a better consolidation method for a study on air content.
- Many of the extracted cores had measured air content values that exceeded the upper limit of WisDOT specifications (8.5 percent). This could result in increased permeability and low strength. However, an investigation of the field QC/QA compressive strength data did not indicate any strength values below the project specifications. It was observed that the spacing factor requirements were easily met on all of the field projects investigated in the study.
- Some extracted cores exhibited segregation issues, accumulation of air voids around the aggregates, and coalescence of air voids thereby imparting a foamy appearance to the specimens. The majority of the extracted cores also showed significant variation in the air content through the depth of the specimen.
- Although sufficient data for a rigorous statistical analysis were not available, the results suggest that the air content testing using the pressure meter (ASTM C231) on fresh concrete is not measuring all the air present in the concrete placed with a slipform paver. The fresh concrete air content is generally lower than the air content measured on the core samples.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Summary

This project investigated the impact of slipform paving on the air content and the air-void system parameters of portland cement concrete pavements in Wisconsin through limited laboratory and field testing. Twelve projects, the selection of which was based on the desire to include a range of aggregate types, batch plants, paver types, and geographical locations, were included in the study.

An evaluation of the results of the air content testing performed on fresh concrete and the cylinder specimens cast in the field suggested that there is loss of air (approximately 1 percent) as the concrete passes through the paver. However, analysis of hardened air on cores extracted from the pavement did not provide conclusive evidence that air is lost during the slipform paving process. These conflicting results can be partially attributed to the method of consolidation for the fresh concrete, whether for the air content testing or cylinder preparation. With the data collected in this study, it is not possible to separate out the air loss due to specimen consolidation from that incurred due to the slipform paving process. The significant findings from this study are summarized below.

- Due to the small number of projects, the small sample size, and overall variability, the impact of individual variables included in the study (concrete plant, paver, coarse aggregate type, and air entraining admixture type) on the as-constructed air-void structure and air content could not be discerned.
- The fresh total air content of the concrete measured before the paver using the pressure meter was consistently less (approximately 1 percent) than that measured after the paver. A similar difference of roughly the same magnitude was also observed in hardened concrete from the cylinders cast in the field.
- In the projects evaluated, current WisDOT standards provide that the ability to produce concrete with acceptable strength and air-void system parameters. Hence, durability or strength-related issues are not expected.
- In every instance, the total air content (based on the pressure meter) measured on the fresh concrete obtained behind the paver was less than that measured in a core extracted from the concrete in the same location. Overall, the air content of the hardened concrete cores extracted from the constructed pavements was high (averaging 7.9 percent), which was, on average, 2.3 percent higher than that measured in the fresh concrete obtained behind the paver. In the two projects where two cores were evaluated (i.e. NE-1 and NC-2), the air content exceeded 7.0 percent in all cases. Of the 14 extracted cores that were evaluated, only five had total air contents less than 7 percent.
- An examination of all the data strongly suggest that the pressure meter is not accounting for all the air that is present in the concrete mixtures; in fact, in two cases (NC-2 and SW-3), the differences between the measured fresh air content and the hardened air content of the extracted core were extreme. The air content test method using the pressure meter was developed when Vinsol resin-based air entraining admixtures were in widespread use. The air bubbles entrained by non-Vinsol resin-based air entraining admixtures are known to be finer than those produced by Vinsol resin-based AEA, and as a result the pressure meter may not be accounting for the finer bubbles. The air content data from the

pressure meter testing were compared to the QC/QA test data with good agreement. In addition, this testing was conducted over the course of the entire construction season. Hence, there is no belief that there was a problem with the calibration of a given pressure meter during field testing. Although it is noted that the QC/QA test data were not from the same location as the field testing in this project, the locations were within 500 feet of each other.

- The method used to consolidate the cylindrical specimens (as well as the concrete used in the determination of fresh concrete air content) clearly impacted the fabric of most of the concrete, creating segregation, clustering of air voids around the aggregates, and coalescence of air voids within the paste. This affected at least one cylindrical specimen from every project. In 9 of the 12 projects, the cylinders cast using concrete from in front of and behind the paver were affected. It is therefore recommended that other methods of consolidation (like rodding or the use of a mobile table vibrator) be considered for preparing specimens for air content determination. It should also be noted that 4 by 8 inch cylinders were used in this project and more energy is expected to be trapped and applied to the concrete during consolidation in the smaller specimens. WisDOT typically uses 6 by 12 inch cylinders for strength testing.
- Either air void clustering or coalescence was observed in the cores extracted from half the projects (i.e., 6 of the 12 projects) indicating that this phenomena might be widespread. Of the six projects having air void clustering and coalescence, the average total hardened air content of the as-placed concrete was 8.7 percent (versus 7.3 percent for those projects in which air void clustering and coalescence was not observed). Although there is variability in these data, it appears that the opportunity for irregularities in the air void system increases as air content increases.

Suggestions for Future Research

Based on the results of this work, recommendations for future work activities are presented below:

- The field and laboratory investigations performed in this study suggest that the use of internal vibration to create concrete specimens for studies of air void systems may be problematic, which is evident from the vibrator insertion marks seen in many of the field-cast specimens. Due to these observations, a study to investigate the influence of internal vibration on strength development, air content, air-void system parameters, permeability, and freeze-thaw durability is suggested. These can be compared to specimens consolidated using hand rodding (this, however, may not be practical for some stiff paving mixtures that have slumps of less than 1 in) and a vibrator table.
- In order to get a better understanding on the impact of the paving process and other concrete mix design parameters on the air content and the air-void system parameters of concrete pavements, a rigorous experiment should be designed where multiple locations within a single project site are tested. Laboratory investigations should be followed by periodic field investigations to monitor and understand the long-term impacts.
- The high amount of air and the incidence of air void irregularities observed in the extracted core specimens suggests that WisDOT is not getting the air-void system desired. An additional study should be initiated to understand why this is occurring, to establish better field test methods, and to determine the effect that such irregularities

might have on long-term pavement performance. In particular, the efficacy of the pressure meter (ASTM C231) should be evaluated.

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APPENDIX A. ANNOTATED BIBLIOGRAPHY

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This guide describes specific types of concrete deterioration. Each chapter contains a discussion of the mechanisms involved and the recommended requirements for individual components of concrete, quality considerations for concrete mixtures, construction procedures, and influences of the exposure environment, which are all important considerations to ensure concrete durability. This guide was developed for conventional concrete but is generally applicable to specialty concretes; however, specialty concretes, such as roller-compacted or pervious concrete, may have unique durability-related issues that deserve further attention that are not addressed herein. Readers should consult other ACI documents for more detailed information on special concretes of interest.

Bloem, D. L. (1950). *Air Entrainment in Concrete,* National Sand and Gravel Association and National Ready Mixed Concrete Association, Silver Spring, MD.

Abstract not available.

Cross. W., E. Duke, J. Keller, and D. Johnston. 2000. *Investigation of Low Compressive Strengths of Concrete Paving, Precast, and Structural Concrete*. SD98-03-F. South Dakota Department of Transportation, Pierre, SD.

This research examines the causes for a high incidence of catastrophically low compressive strengths, primarily on structural concrete, during the 1997 construction season. The source for the low strengths was poor aggregate/paste bond associated with air void clusters and poorly formed cement paste in the interfacial region adjacent to the aggregate. An interaction between the synthetic air entraining admixtures, used as substitutes for vinsol resin, and low alkali cements was directly tied the problem with high summertime temperatures also contributing to the problem.

The synthetics appear to be more hydrophobic, form thinner-walled air bubbles and develop rapid draining bubble flocculations more readily than vinsol resin, all of which can lead to significant reductions in strength. As an interim measure, the Department specified the sole use of vinsol resin air entraining agents along with water reducers, as needed, in April, 1998 and these measures have minimized the incidence of low strengths. Petrographic analysis of cores taken from low strength concretes failed to reveal the causes of the low strength problem but SEM microscopy clearly showed the failure mechanism. Laboratory testing of concrete mixes with various air entraining admixtures demonstrated an interaction was taking place with one cement and petrographic and chemical analysis of the cements used in the testing implicated alkali sulfates as a potential source of the interaction. Testing of the 3synthetic4 air entraining admixtures showed they have substantially different properties compared to vinsol resins. Mixtures of the synthetics and vinsol resin with 50% or more vinsol resin behaved similarly to vinsol alone.

Dubovoy, V. S., S. H. Gebler, and P. Klieger. 2002. *Cement-Alkali Level as It Affects Air-Void Stability, Freeze-Thaw Resistance, and Deicer Scaling Resistance of Concrete*. RD128. Portland Cement Association, Skokie, IL.

This research report documents the effect of cement alkali content on the behavior of entrained air voids in concrete with four types of air-entraining admixtures, neutralized Vinsol resin, salts of fatty acids, sulfonated hydrocarbons, and alkylbenzylsulfonates. Air-void stability in fresh concrete was evaluated. Results of freeze-thaw testing and deicer scaling tests on hardened concrete are reported. This report is also found on DVD021.

Parameters of air-void systems in freshly-mixed and hardened air-entrained concretes, with cement-alkali levels of 0.21%, 0.60%, and 1.20% as Na2O by mass of cement, were compared. Additionally, four different generic types of air-entraining admixtures were utilized to investigate the effects these admixtures have on the air-void system at various cement-alkali levels. These air-entraining admixtures were salts of fatty acids, sulfonated hydrocarbons, alkylbenzylsulfonates, and neutralized Vinsol resin (NVR). Concretes with cement-alkali contents greater than or equal to 0.60% and containing air-entraining admixture neutralized Vinsol resin or based on salts of fatty acids produced reasonably stable air-void systems, whereas sulfonated hydrocarbon-based and alkylbenzylsulfonate-based air-entraining admixtures produced relatively unstable air-void systems as the cement-alkali level increased. Deicer scaling and freeze-thaw tests were conducted. Concretes prepared with an air-entraining admixture based on salts of wood resins (NVR) showed a tendency for less severe scaling at the highest cement-alkali content. With regard to freezing and thawing, our tests indicated that the impact on the air-void systems of increased alkali in cement and periodic agitation had little, if any, effect on the durability factor of these concretes. However, mass change and visual examination revealed some surface deterioration, especially for those subjected to salt solution.

Eickschen, E. 2004. *Factors Affecting the Formation of Air Voids in Road Concrete*. Concrete Technology Reports 2001-2003. German Cement Works Association, Düsseldorf.

Damage as a result of attack by freeze-thaw with de-icing salt has practically ceased since concretes for carriageway pavements have contained artificially introduced air voids. Respective specifications for composition and production of concrete with high resistance to freeze-thaw with de-icing salt have been fixed in the regulations and have been proved successful in the past. However, a greatly increased air void content in the hardened concrete has been found in recent years in some contract sections of concrete pavement, especially with high fresh concrete temperatures. Investigations were carried out at the Research Institute of the Cement Industry on road concretes in order to determine the reason for this excessively high content. The test results show that a substantial increase in air content can only occur if the air-entraining agent in the fresh concrete is not adequately broken down during production, due to too short a mixing time, and has therefore been insufficiently activated. The air content can then rise if mixing energy is introduced into the fresh concrete later during production of the pavement. Practical recommendations for future concrete production are given to avoid excessive air void formation during the placement of concrete.

Ghafoori, N. and M. Barfield. 2009. "Effects of Admixture Type on Air-Entrained Self-Consolidating Concrete." *Concrete Solutions.* Grantham, Majorana & Salomoni (Eds). Taylor and Francis Group. London.

Self-consolidating concrete (SCC) is a highly flowable construction material well-suited for repair applications that require thin overlays of concrete. In this investigation, mixtures were developed with a 635mm slump flow utilizing admixtures from two sources in order to study the effects if admixture type on the air void characteristics of air-entrained self-consolidating concrete. The mixtures had a constant water-to-cementitious materials ratio of 0.30 and constant

mixture proportions with the exception of admixture dosages. The main objective of this study was to compare different types of air-entrainment admixtures (AEA) and high range water reducers (HRWR) from two commonly available manufacturers. The air void characteristics (specific surface and spacing factor) were measured on the fresh concrete using an Air Void Analyzer. The additional properties measured were: slump flow, J-Ring passing ability, rate of flowability, resistance to dynamic segregation and compressive strength.

Kozikowski Jr. Ronald L., D. B. Vollmer, P. C. Taylor, and S. H. Gebler. 2005. *Factors Affecting the Origin of Air-Void Clustering.* PCA R&D Serial No. 2789. Portland Cement Association, Skokie, IL.

Air-void clustering is a phenomenon in which entrained air-voids abnormally cluster around coarse aggregate particles. Numerous cases of low strength concrete have been attributed to this phenomenon and this study investigated the possible causes of the problem. There are many opinions as to why air-void clustering occurs, but to our knowledge, no study has ever been conducted and published to determine the specific cause(s) of the phenomenon. Therefore, various parameters were obtained through a literature search and interviews with industry experts to evaluate their potential influence on air-void clustering.

A visual petrographic rating system was developed to establish a standardized method for determining the severity of clustering. A correlation was found between this rating system and compressive strength loss and was used to evaluate which parameters had the most influence on air-void clustering. Problematic air-void clustering was found to coincide with late additions of water to the concrete mixture. The type of air-entraining admixture used in the concrete was found to have a major influence on clustering. It was noted that longer mixing times exacerbated the condition and that air-void clustering tended to occur in relatively finer air-void systems.

Kosmatka, S., B. Kerkhoff, and W. Panarese. 2002. *Design and Control of Concrete Mixtures.* Fourteenth Edition. Engineering Bulletin 001. Portland Cement Association. Skokie. IL.

This book presents the properties of concrete as needed in concrete construction, including strength and durability. All concrete ingredients (cementing materials, water, aggregates, chemical admixtures, and fibers) are reviewed for their optimal use in designing and proportioning concrete mixtures. The use of concrete from design to batching, mixing, transporting, placing, consolidating, finishing, and curing is addressed. Besides presenting a 30% increase in new information over the prior edition within the previous chapters, this edition has added four new chapters on concrete sustainability, reinforcement, properties of concrete, and durability.

Mehta, P. and P. Monteiro. 2005. *Concrete: Microstructure, Properties, and Materials*. McGraw-Hill Publishing, New York, NY.

Abstract not available.

Nagi, M., P. Okamoto, R. Kozikowski, and K. Hover. 2007. *Evaluating Air-Entraining Admixtures for Highway Concrete.* NCHRP Report 578. Transportation Research Board, Washington, DC.

This report presents a recommended procedure for evaluating air-entraining admixtures used in highway concrete. The procedure involves the testing of non-air-entrained concrete and concrete

containing the air-entraining admixture under simulated field conditions. Criteria are proposed for acceptance of admixtures for use in either highway pavements or structures. The recommended procedure and acceptance criteria will guide materials engineers in evaluating and selecting air-entraining admixtures that should contribute to appropriate freeze-thaw durability and thus to good performance and long service life. The content of the report will be of immediate interest to materials engineers, researchers, and others concerned with the design of concrete mixtures for use in highway pavements and structures.

Ozyildirim, C. 1990. *Comparison of Air Void Content Measurements in Fresh Versus Hardened Concrete.* FHWA/VA-R23. Virginia Transportation Report Council. Charlottesville, VA.

This study compares the air content of freshly mixed and hardened concretes. At the fresh stage, pressure meters (Types A and B) and a volumetric meter were used to determine the air content. At the hardened stage, the air content was calculated using the linear traverse method described in ASTM C 457, which is a microscopical procedure. The unit weight and compressive strength of the concretes were also determined.

The results show that, at the ranges commonly used in the construction of pavements and bridges, the air content of fresh concrete measured by pressure meters and that determined by the microscopical method for essentially the same concrete after hardening are, for practical purposes, the same. The air content obtained by a volumetric meter as normally run in the field is generally lower than that obtained for the same hardened concretes by the microscopical method. The unit weight and compressive strength correlate well with the air content. It was also shown that adding water to concrete can significantly increase the air content, as well as the slump. Thus, a higher air content in hardened concretes than that indicated by initial measurements with a pressure meter is likely to be present if water is added during placement.

Schell, H. and J. Konecny. 2003. "Development of an End-Result Specification For Air Void Parameters of Hardened Concrete in Ontario's Highway Structures." TRB 2003 Annual Meeting CD-ROM. Transportation Research Board, Washington, DC.

In 1997, Ontario Ministry of Transportation introduced an end-result specification for concrete quality including requirements for air void parameters of the hardened concrete. This was intended to introduce a more significant durability component into the ministry's acceptance process for concrete, to ensure long-term performance and extend the service life of concrete highway structures in the province. Limits for air content and air void spacing factor were specified, which would be measured on cores removed from the completed structure, using a standard ASTM test procedure. Experience gained to date with this specification, applied to both conventional and high performance concrete, and refinements in the first generation specification, are discussed. Means of addressing industry concerns with increased risk, and providing for prequalification of private sector testing laboratories to carry out the testing, are presented. Development of a conformance testing process to verify accuracy of test results, currently underway, is described. Review of test results to date indicates a high level of compliance with the specification requirements. Future work will concentrate on ensuring that financial penalties applied to deficient work reflect the severity of the long term impact, and on improvements in systems to verify proper conduct of testing.

Snyder, K., K. Natesaiyer, and K. Hover. 2001. "The Stereological and Statistical Properties of Entrained Air-Voids in Concrete: A Mathematical Basis for Air-Void System

Characterization." *Materials Science in Concrete VI*, American Ceramic Society, Westerville, OH.

To understand the freeze-thaw properties of hardened concrete, the air void system must be characterized. Studies of the stereological and statistical properties of entrained air voids in concrete have often involved a number of steps: sample preparation and air void identification, linear and planar analyses of a polished surface, uncertainty analysis of the recorded data, parametric and non-parametric estimates of the air void diameter distribution, and analysis of the air void system spatial statistics. Each of these steps has been discussed in detail by a number of engineering fields. For the civil engineering researcher, a comprehensive study of these properties requires consulting many varied texts, each addressing these steps individually. This Chapter attempts to consolidate these topics into a single desk reference. The researcher can then realize the interdependencies of these topics, learn to accurately characterize the air void system microstructure, and develop an understanding of the basis for standardized test methods such as ASTM C 457.

Stutzman, P. 1999. *Deterioration of Iowa Highway Concrete Pavements: A Petrographic Study*. NISTIR 6399. National Institute of Standards and Technology, Gaithersburg, MD.

Major highway concrete pavements in Iowa have exhibited premature deterioration attributed to effects of ettringite formation, alkali-silica expansive reactions, and to frost attack, or some combination of them. These pavements were constructed in the mid-1980s as non-reinforced, dual-lane, roads ranging in thickness between 200 mm and 300 mm, with skewed joints reinforced with dowels. Deterioration was initially recognized with a darkening of joint regions, which occurred for some pavements as soon as four years after construction. Pavement condition ranges from severe damage to none, and there appeared to be no unequivocal materials or processing variables correlated with failure.

Based upon visual examinations, petrographic evaluation, and application of materials models, the deterioration of concrete highway pavements in Iowa appear related to a freeze-thaw failure of the coarse aggregate and the mortar. Crack patterns sub-parallel to the concrete surface transecting the mortar fraction and the coarse aggregate are indicative of freeze-thaw damage of both the mortar and aggregate. The entrained air void system was marginal to substandard, and filling of some of the finer-sized voids by ettringite appears to have further degraded the air void system. The formation of secondary ettringite within the entrained air voids probably reflects a relatively high degree of concrete saturation causing the smaller voids to be filled with pore solution when the concrete freezes. Alkali-silica reaction (ASR) affects some quartz and shale in the fine aggregate, but is not considered to be a significant cause of the deterioration. Delayed ettringite formation was not deemed likely as no evidence of a uniform paste expansion was observed. The lack of field-observed expansion is also evidence against the ASR and DEF modes of deterioration. The utilization of fly ash does not appear to have affected the deterioration as all pavements with or without fly ash exhibiting substantial damage also exhibit significant filling of the entrained air void system, and specimens containing fly ash from sound pavements do not have significant filling.

The influence of the mixture design, mixing, and placing must be evaluated with respect to development of an adequate entrained air void system, concrete homogeneity, long-term drying shrinkage, and microcracking. A high-sand mix may have contributed to the difficult mixture characteristics noted upon placement and exacerbate concrete heterogeneity problems, difficulty in developing an adequate entrained air void system, poor consolidation potential, and increased drying shrinkage and cracking. Finally, the availability of moisture must also be considered, as the secondary precipitation of ettringite in entrained air voids indicates they were at least partially filled with pore solution at times. Water availability at the base of the slabs, in joints, and cracks may have provided a means for absorbing water to a point of critical saturation.

Sutter, L., T. Van Dam, and M. Thomas. 2007. *Evaluation of Methods for Characterizing Air-Void Systems in Wisconsin Paving Concrete*. WHRP-07-05. Wisconsin Department of Transportation, Madison, WI.

This research investigated primarily two methods of determining the air-void system parameters of hardened concrete. The methods investigated were the use of a flat-bed scanner and the use of a CT x-ray scanner. The flat-bed scanner proved to be an effective means of performing the analysis at a relatively low cost. The CT scanner proved to be technically feasible but not ready for general implementation outside of controlled laboratory conditions. The research also investigated the freeze-thaw performance of Wisconsin paving concrete mixtures prepared with vinsol resin air-entraining admixtures (AEA) and with non-vinsol (synthetic) AEAs. The mixtures prepared with vinsol resin based AEA performed in accordance with what has been historically reported in the literature. The mixtures prepared with synthetic AEAs performed better than the vinsol based AEA when the admixtures were used in low dosages (i.e. low air content). The results indicate that mixtures prepared with synthetic AEA could possibly be prepared with lower target air contents and a satisfactory level of freeze-thaw performance could be expected

Tanesi, J. and R. Meininger. 2006. *Freeze-Thaw Resistance of Concrete With Marginal Air Content*. FHWA-HRT-06-117. Federal Highway Administration, McLean, VA.

Freeze-thaw resistance is a key durability factor for concrete pavements. Recommendations for the air void system parameters are normally: 6 ± 1 percent total air, and spacing factor less than 0.20 millimeters. However, it was observed that some concretes that did not possess these commonly accepted thresholds presented good freeze-thaw resistance in laboratory studies.

This study evaluated the freeze-thaw resistance of several "marginal" air void mixes, with two different types of air-entraining admixtures (AEA)-a Vinsol resin and a synthetic admixture. This study used rapid cycles of freezing and thawing in plain water, in the absence of deicing salts.

For the specific materials and concrete mixture proportions used in this project, the marginal air mixes (concretes with fresh air contents of 3.5 percent or higher) presented an adequate freeze-thaw performance when Vinsol resin based air-entraining admixture was used. The synthetic admixture used in this study did not show the same good performance as the Vinsol resin admixture.

Taylor, P. C., S. H. Kosmatka, G. F. Voigt, M. E. Ayers, A. Davis, G. J. Fick, J. Gajda, J. Grove, D. Harrington, B. Kerkhoff, C. Ozyildirim, J. M. Shilstone, K. Smith, S. M. Tarr, P. D. Tennis, T. J. Van Dam, and S. Waalkes. 2007. *Integrated Materials and Construction Practices for Concrete Pavement.* FHWA-HIF-07-004. Federal Highway Administration, Washington, DC.

At the heart of all concrete pavement projects is the concrete itself. This manual is intended as both a training tool and a reference to help concrete paving engineers, quality control personnel, specifiers, contractors, suppliers, technicians, and tradespeople bridge the gap between recent research and practice regarding optimizing the performance of concrete for pavements. Specifically, it will help readers do the following:

- Understand concrete pavement construction as a complex, integrated system involving several discrete practices that interrelate and affect one another in various ways.
- Understand and implement technologies, tests, and best practices to identify materials, concrete properties, and construction practices that are known to optimize concrete performance.
- Recognize factors that lead to premature distress in concrete, and learn how to avoid or reduce those factors.
- Quickly access how-to and troubleshooting information.

Tymkowicz, S. and R. Steffes. 1999. *Vibration Study for Consolidation of Portland Cement Concrete*. MLR-95-4. Iowa Department of Transportation, Ames, IA.

The Iowa Department of Transportation has discovered an increase in the occurrence of excessively vibrated portland cement concrete (PCC) pavements. The overconsolidation of PCC pavements has been observed in several projects across the state. Overconsolidation is also believed to be a factor in acceleration of premature deterioration of at least two pavement projects in Iowa.
To address the problem, a research project in 1995 documented the vibratory practices of PCC slipform paving in Iowa in order to determine the effect of vibration on consolidation and air content of pavement. Paver speed, vibrator frequency, and air content relative to the location of the vibrator were studied. The study concluded that the Iowa Department of Transportation specification of 5,000 to 8,000 vibrations per minute (vpm) for slipform pavers is effective for normal paver speeds on the three projects that were examined. Excessive vibration was clearly identified on one project where a vibrator frequency of 12,000 vpm was discovered. When the paver speed was reduced to half the normal speed, hard air contents indicate that excessive vibration was beginning to occur in the localized area immediately surrounding the vibrator at a frequency of 8,000 vpm. The study also indicates that the radius of influence of the vibrators is smaller than has been claimed.

Walker, S. and Bloem, D.L. (1955). *Design and Control of Air Entrained Concrete,* Publication No. 60, National Ready Mixed Concrete Association, Silver Spring, MD.

Abstract not available.

Whiting, D. and M. Nagi. 1998. *Manual on Control of Air Content in Concrete.* Engineering Bulletin (EB) 116. Portland Cement Association, Skokie, IL.

Abstract not available.

APPENDIX B. FIELD DATA

Project ID: NW-1

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
187+80	6'	10:15	70	69	—	6.2	44.83	8.14	36.69	0.250	146.76	1	1A	
187+80	6'	10:22	70	70	—	5.2	45.37	"	37.23	0.250	148.92	1	1B	
189+05	5'	10:41	73	69	—	5.5	45.12	"	36.98	0.250	147.92	2	2A	
189+05	5'	10:55	73	69	—	5.5	45.16	"	37.02	0.250	148.08	2	2B	
									5		143.06			
191+10	10'	11:18	75	69	—	8.9	43.905	"	37.765	0.250	~~151.46~~	3	3A	Reviewed by [signature] 6-27-2011
191+10	10'	11:37	75	69	—	~~7.5~~ 7.3	44.59	"	36.45	0.250	145.8	3	3B	

Remarks: Aggregate Correction: 0.2

Offsets are the distance from left edge (north edge) Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): Air Content Range (%): Concrete Temp Range: Air Temp Range:

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: partly cloudy 70 - 75°

Total No. of Cylinders Made: 6

Equipment: Air Meter: #2 Slump Cone: Therm.:

Technician: T. Portman Time Started: Ended:

Site/Travel Hrs F4010: Mileage G8001:

Project ID: NE-1

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
105+50	6'	825	49	60	—	6.6	46.43	9.31	37.12	.25	148.48	1	A	
105+50	6'	830	49	61	–	5.4	47.08	↓	37.77	↓	151.08	1	B	
107+75	3'	910	51	59	–	7.3	46.21		36.90		147.60	2	A	
107+75	3'	920	51	59	–	5.1	47.27		37.96		151.84	2	B	
110+50	10'	1010	52	59	–	8.2	45.95		36.64		146.56	3	A	
110+50	10'	1020	52	60	–	7.0	46.52		37.21		148.84	3	B	
112+25	5'	1035	52	57	–	6.8	46.90		37.59		150.36	4	A	
112+75	5'	1045	52	58	–	5.9	47.14		37.83		151.32	4	B	

Remarks: Aggregate Correction: 0.3 Offsets are the distance from WEST EDGE OF CENTER LANE Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): — Air Content Range (%): 5.1 - 8.2 Concrete Temp Range: 57-61 Air Temp Range: 49-52

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: CLOUDY, WINDY Total No. of Cylinders Made: 8

Equipment: Air Meter: 30-120 Slump Cone: 30-102 Therm. 34-270 #8

Technician: JOHNSON, JOSH Time Started: 615 Ended: 1330 Site/Travel Hrs F4010: Mileage G8001: 162

Project ID: NE-1

Summary of technical and/or engineering services performed, including field test data. Locations, elevations and depth are estimated

PICKED UP CYLINDERS THAT WERE MADE 5/26/11. ALSO WENT TO PLANT TO PICK UP CEMENT, FLYASH, AND ADMIXTURES

Technician: JOSH JOHNSON Title: ENGINEERING TECHNICIAN	Equipment Rental ______ Mileage 162 Project Preparation Time: —	Arrive Job 9:00 Depart Job 9:15 Total Hours on Job .25 Travel Time 2.0	TOTAL CHARGEABLE HOURS 2.25

Project ID: NE-2

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
304+50	3.0	740	55	–	–	6.7	46.48	9.33	37.15	.25	148.60	1	A	
304+50	3.0	745	57	–	–	6.7	46.40	↓	37.07	↓	148.28	1	B	
301+50	5.0	845	55	–	–	7.4	46.02		36.69		146.76	2	A	
301+50	5.0	850	55	–	–	6.2	46.60		37.27		149.08	2	B	
299+00	10.0	925	54	–	–	8.0	45.74		36.41		145.64	3	A	
299+00	10.0	935	54	–	–	6.4	46.48		37.15		148.60	3	B	
294+50	19.0	1050	55	–	–	7.1	46.09		36.76		147.04	4	A	
294+50	19.0	1100	55	–	–	6.2	46.48		37.15		148.60	4	B	
291+00	4.0	1155	55	–	–	7.9	45.83		36.50		146.00	5	A	
291+00	4.0	1200	55	–	–	6.3	46.49	↓	37.16	↓	148.64	5	B	

Remarks: Aggregate Correction: .2

Offsets are the distance from CENTERLINE Cylinder ID A=Front of Paver, B= Behind Paver

* DROVE TO PLANT TO PICKUP AIR ENTRAINMENT & WATER REDUCER

INSPECTION INFORMATION:

Slump Range (in): — Air Content Range (%): 6.2 - 8.0 Concrete Temp Range: — Air Temp Range: 55-57

GENERAL INFORMATION: **Cylinder Type: 4 x 8**

Weather: CLOUDY Total No. of Cylinders Made: 10

Equipment: Air Meter: 30-120 Slump Cone: 30-102 Therm.: 34-270

Technician: JOSH JOHNSON Time Started: 615 Ended: 1345 Site/Travel Hrs F4010: 7.5 Mileage G8001: 65

Project ID: NE-2

Summary of technical and/or engineering services performed, including field test data. Locations, elevations and depth are estimated

PICKED UP CYLINDERS THAT WERE MADE ON 5/24/11

Technician: JOSH JOHNSON Title: ENGINEERING TECHNICIAN	Equipment Rental — Mileage 46 Project Preparation Time: —	Arrive Job 1245 Depart Job 1300 Total Hours on Job .25 Travel Time .75	TOTAL CHARGEABLE HOURS 1.0

Project ID: NE-3

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
703+00	22'	830	54	71	—	5.9	46.64	9.36	37.34	.25	149.36	1	A	
703+00	22'	840	54	73	—	4.7	47.18		37.88		151.52	1	B	
704+75	4'	915	59	74	—	5.2	47.09		37.79		151.16	2	A	
704+75	4'	925	59	75	—	4.6	47.59		38.29		153.16	2	B	
707+25	20'	950	61	74	—	6.0	46.85		37.55		150.20	3	A	
707+25	20'	1000	61	74	—	4.9	47.14		37.84		151.36	3	B	
709+25	6'	1020	63	74	—	5.8	46.88		37.58		150.32	4	A	
709+25	6'	1030	65	73	—	5.2	47.03		37.73		150.92	4	B	

Remarks: Aggregate Correction: 0.2 Offsets are the distance from EAST EDGE OF SOUTHBOUND LANE Cylinder ID A=Front of Paver, B= Behind Paver

T NORTH TO 66 LEFT, DRIVEWAY PAST NRA ON LEFT

INSPECTION INFORMATION:

Slump Range (in): — Air Content Range (%): 4.6 - 6.0 Concrete Temp Range: 71-75 Air Temp Range: 54-65

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: CLOUDY Total No. of Cylinders Made: 8

Equipment: Air Meter: 30-120 Slump Cone: 30-102 Therm.: 34-270 #B

Technician: Josh Johnson Time Started: 0700 Ended: 12:30 Site/Travel Hrs F4010: 5.5 Mileage G8001: 95

Project ID: NE-4

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
376+30	3'	5:30	73	83	–	5.6	46.51	9.34	37.17	0.250	148.68	1	A	
376+30	3'	5:40	73	82	–	5.8	46.72	↓	37.38	↓	149.52	1	B	
378+55	3'	6:15	73	84	–	6.2	46.97		37.63		150.52	2	A	
378+55	3'	6:25	75	84	–	5.8	47.10		37.76		151.04	2	B	
381+00	3'	7:00	75	85	–	5.8	47.12		37.78		151.12	3	A	
381+00	3'	7:08	75	84	–	6.4	46.73		37.39		149.56	3	B	
384+00	3'	7:55	75	85	–	5.5	47.23		37.89		151.56	4	A	
384+00	3'	8:00	75	86	–	5.5	47.38		38.04		152.16	4	B	

Remarks: Aggregate Correction: 0.2 Offsets are the distance from east edge of North bound lane Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): – Air Content Range (%): 5.5 - 6.4 Concrete Temp Range: 82 - 86 Air Temp Range: 73-75

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: Fog/Cloudy

Total No. of Cylinders Made: 8

Equipment Air Meter: 30-120 Slump Cone: 30-101 Therm.: 220#6

Technician: S. Humphrey Time Started: 4:00 Ended: 10:00 Site/Travel Hrs F4010: 6.0 Mileage G8001: 110

Reviewed by: [signature] 7-19-2011

Project ID: NC-1

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
74+77R	5'	8:21	65°	67°	–	6.3	43.900	7.935	35.965	.249	144.4		1A	
74+77R	5'	8:55	65°	67°	–	5.7	44.205	7.935	36.270	.249	145.7		1B	
76+68R	10'	9:50	70°	67°	–	7.1	43.735	7.935	35.800	.249	143.8		2A	
76+68R	10'	10:15	70°	71°	–	6.3	44.030	7.935	36.095	.249	145.0		2B	
79+61R	15'	11:15	74°	70°	–	6.4	43.895	7.935	35.960	.249	144.4		3A	
79+61R	15'	11:55	75°	75°	–	5.5	44.645	7.935	36.710	.249	147.4		3B	
79+93R	20'	11:40	75°	72°	–	6.2	43.995	7.935	36.060	.249	144.8		4A	
79+93R	20'	12:05	75°	75°	–	5.6	44.355	7.935	36.420	.249	146.3		4B	

Remarks: Aggregate Correction: 0.3 Offsets are the distance from South Side of pavement lane Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): – Air Content Range (%): 5.5 - 7.1 % Concrete Temp Range: 67° - 75° Air Temp Range: 65° - 75°

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: Sunny Total No. of Cylinders Made: 8

Equipment: Air Meter: 12-111 Slump Cone: – Therm.:

Technician: Eric Dobbe Time Started: 6:30 Ended: 12:30 Site/Travel Hrs F4010: 6.0 Mileage G8001: 20

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Project ID: NC-2

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
189+57	3ft	11:30	74°	83°	–	5.7	43.56	7.61	35.95	.249	144.38		1A	
189+57	3ft	11:42	↓	84°	–	5.4	44.01	7.61	36.40	.249	146.18		1B	
192+60	4ft	11:52	↓	82°	–	6.6	42.85	7.61	35.24	.249	141.53		2A	
192+60	4ft	12:04	↓	82°	–	4.8	43.98	7.61	36.37	.249	146.06		2B	
195+03	2ft	12:15	↓	79°	–	5.9	43.52	7.61	35.91	.249	144.22		3A	
195+03	2ft	12:23	↓	80°	–	5.4	43.67	7.61	36.06	.249	144.82		3B	

Remarks: Aggregate Correction: −0.3 Offsets are the distance from North edge West bound lane Cylinder ID A=Front of Paver, B= Behind Paver

Air values recorded are corrected for 0.3%

INSPECTION INFORMATION:

Slump Range (in): — Air Content Range (%): 5.1 - 6.9 Concrete Temp Range: 79° - 84° Air Temp Range: 74°

GENERAL INFORMATION: Cylinder Type: (4 x 8)

Weather: Clear-breezy Total No. of Cylinders Made: 12

Equipment: Air Meter: 12-122 Slump Cone: 12-117 Therm.:

Technician: Marilyn Hein Time Started: 10:30 Ended: 3:00 Site/Travel Hrs F4010: 4.5 Mileage G8001: 92 miles

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Reviewed By: [signature] 8-31-2011

Project ID: SW-1

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
448+75	3'	9:36	70	80	-	6.8	45.07	9.33	35.74	0.250	142.96	1	A	
448+75	3'	8:50	70	85	-	5.1	45.91		36.58		146.32	1	B	
445+85	6'	9:20	72	85	-	8.0	44.67		35.34		141.36	2	A	
445+85	6'	9:27	72	85	-	5.6	46.16		36.83		147.32	2	B	
443+10	9'	9:55	75	82	-	6.6	45.67		36.34		145.36	3	A	
443+10	9'	10:05	75	84	-	5.6	46.01		36.68		146.72	3	B	
440+15	12'	10:25	75	85	-	6.0	45.55		36.22		144.88	4	A	
440+15	12'	10:35	75	84	-	4.5	46.47		37.14		148.56	4	B	

Remarks: Aggregate Correction: 0.8 Offsets are the distance from north side of east bound shoulder Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): - Air Content Range (%): 4.5- 8.0 Concrete Temp Range: 85- 90 Air Temp Range: 70-75

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: Sunny Total No. of Cylinders Made: 8

Equipment: Air Meter: 22-17 Slump Cone: 33-01 Therm.: 33-06

Technician: J. Humphrey Time Started: 6:00 Ended: 14:00 Site/Travel Hrs F4010: Mileage G8001: 320

Reviewed By [signature] 8-8-2011

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Project ID: SW-2

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
257+75	41'	1005	74	72	—	6.9	46.46	9.30	37.16	.25	148.64	1	A	
257+75	41'	1015	74	74	—	6.1	46.65	↓	37.35	↓	149.40	1	B	
254+75	22'	1045	76	77	—	8.1	45.57		36.27		145.08	2	A	
254+75	22'	1055	76	77	—	6.2	46.35		37.05		148.20	2	B	
252+00	13'	1120	77	77	—	7.5	46.06		36.76		147.04	3	A	
252+00	13'	1130	78	77	—	6.2	46.60		37.30		149.20	3	B	

Remarks: Aggregate Correction: 0.3 ______ Offsets are the distance from EAST EDGE SOUTH BOUND LANE Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): — Air Content Range (%): 6.1 - 8.1 Concrete Temp Range: 72-77 Air Temp Range: 74-78

GENERAL INFORMATION: **Cylinder Type: 4 x 8**

Weather: SUNNY, HOT Total No. of Cylinders Made: 6

Equipment Air Meter: 30-120 Slump Cone: 30-102 Therm.: 34-270

Technician: JACK JOHN Time Started: 630 Ended: 1430 Site/Travel Hrs F4010: 5 Mileage G8001: 275

Project ID: SW-3

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
256+00	10ft	11:25	72	76		6.4	—						1A	
256+00	10ft	11:40	72	76		6.1	43.4	7.779	35.621	.249	143.1		1B	
252+00	5ft	12:10	72	76		6.7	43.4	7.779	35.621	.249	143.1		2A	
252+00	5ft	12:25	73	78		5.4	44.2	7.779	36.421	.249	146.3		2B	
249+00	8ft	12:55	73	79		5.2	44.0	7.779	36.221	.249	145.5		3A	
249+00	8ft	1:10	74	77		5.0	43.8	7.779	36.021	.249	144.7		3B	
246+00	3ft	1:25	74	77		7.0	44.0	7.779	36.221	.249	145.5		4A	
246+00	3ft	1:40	74	75		6.5	43.8	7.779	36.021	.249	144.7		4B	
242+00	5ft	1:55	74	77		7.5	42.6	7.779	34.821	.249	139.8		5A	
242+00	5ft	2:10	74	78		6.5	43.0	7.779	35.221	.249	141.4		5B	

Remarks: Aggregate Correction: .3 Offsets are the distance from east Edge of paving Cylinder ID A=Front of Paver, B= Behind Paver

9.5ft/min - paver speed.

INSPECTION INFORMATION:

Slump Range (in): — Air Content Range (%): 5.0 - 7.5 Concrete Temp Range: 75 - 78 Air Temp Range: 72 - 74

GENERAL INFORMATION: Cylinder Type: 4 x 8

Weather: clear - breezy 5-10mph Total No. of Cylinders Made: 10

Equipment: Air Meter: 122 Slump Cone: 117 Therm.:

Technician: [illegible] Time Started: 6:30am Ended: 5:30pm Site/Travel Hrs F4010: 11hrs Mileage G8001: 250 miles

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Project ID: SE-1

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
476+00	3'	8:55	70	80	–	7.0	45.23	9.32	35.91	0.250	143.64	1	A	
476+00	3'	9:05	70	80	–	5.1	46.29	↓	36.97	↓	147.88	1	B	
477+50	5'	9:30	70	80	–	5.8	46.14	↓	36.82	↓	147.28	2	A	
477+50	5'	9:40	70	80	–	5.0	46.32	↓	37.00	↓	148.00	2	B	
479+00	6'	10:05	75	82	–	5.8	46.25	↓	36.93	↓	147.72	3	A	
479+00	7'	10:10	75	83	–	5.1	46.30	↓	36.98	↓	147.92	3	B	

Remarks: Aggregate Correction: 0.4 ____ Offsets are the distance from east side of shoulder Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): – Air Content Range (%): 7.0-5.0 Concrete Temp Range: 83-80 Air Temp Range: 75-70

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: Sunny

Total No. of Cylinders Made: 6

Equipment: Air Meter: 30-120 Slump Cone: 30-101 Therm.: 270#6

Technician: J. Humphrey Time Started: 6:00 Ended: 13:00

Site/Travel Hrs F4010:

Mileage G8001: 255

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Reviewed By [signature] 8-24-2011

Project ID: SE-2

Station	Offset	Time Sampled	Air Temp (°F)	Conc Temp (°F)	Slump	% Air	Weight of Concrete & Tare	Tare Weights	Weight of Concrete	Volume	Unit Weight (W/V)	Conc Set No.	Cyl ID	Location/Remark
1050+00	3'	1005	66	74	—	6.7	46.29	9.35	36.94	.25	147.74	1	A	
1050+00	3'	1015	69	75	—	4.5	47.35	↓	38.00	|	152.00	1	B	
1048+00	18'	1050	68	75	—	6.9	46.17	↓	36.82	|	147.28	2	A	
1048+00	18'	1100	68	75	—	5.1	46.90	↓	37.55	|	150.20	2	B	
1045+00	8'	1120	69	75	—	6.3	46.44	↓	37.09	|	148.36	3	A	
1045+00	8'	1130	69	77	—	4.8	47.23	↓	37.88	|	151.52	3	B	

Remarks: Aggregate Correction: 0.2 Offsets are the distance from EAST EDGE OF SOUTH BOUND LANE Cylinder ID A=Front of Paver, B= Behind Paver

INSPECTION INFORMATION:

Slump Range (in): — Air Content Range (%): 4.5-6.7 | Concrete Temp Range: 74-77 | Air Temp Range: 66-69

GENERAL INFORMATION:

Cylinder Type: 4 x 8

Weather: SUNNY | Total No. of Cylinders Made: 6

Equipment: Air Meter: 30-120 Slump Cone: — Therm.: 34-170 #8

Technician: Josh Johnson Time Started: 645 Ended: 1500 | Site/Travel Hrs F4010: 8.25 | Mileage G8001: 314

APPENDIX C. PROJECT PORTFOLIOS

Project ID: NW-1

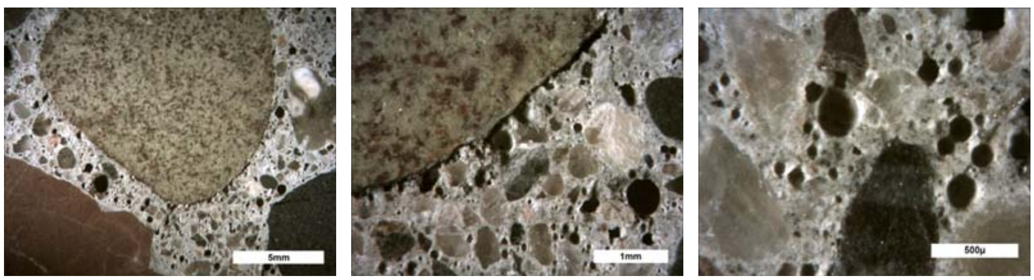
Region: NW |PCC Thickness: 9.50 inches

Paving Start Date: June 23, 2011	Field Testing Date : June 24, 2011

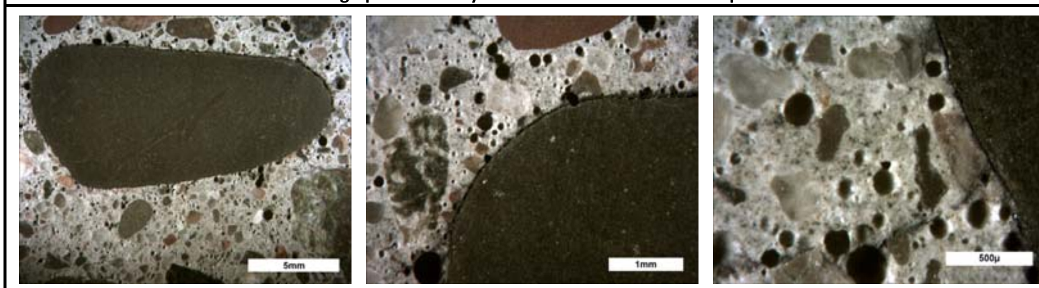
Concrete Mix Design		Other Project Details	
Cement (Type), lbs/yd³	480 (I/II)	Plant	BP-1
Fly Ash (Type), lbs/yd³	85 (C)	Paver	P-1
Total Cementitious Content, lbs/yd³	565	AEA Brand	AENVR-4
w/cm	0.40	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd³	1814, 1211	WRA Brand	WR-1
AEA, WRA Dosage (oz. / 100 wt.)	4.00, 17.00	Coarse Aggregate Type	Gravel

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.20	9.30	7.04		
Behind Paver (%)	5.20	5.83	5.16	7.63	6.63
Difference (%)	-1.00	-3.47	-1.88	-1.67	-0.41

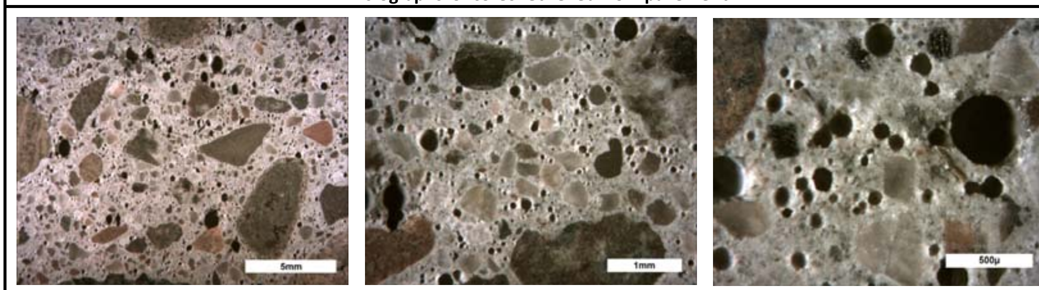
Micrographs of field cyclinders from concrete in front of paver



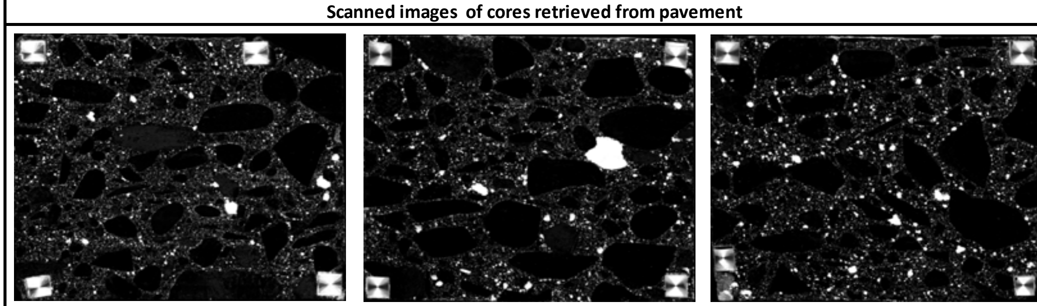
Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



Project ID: NE-1

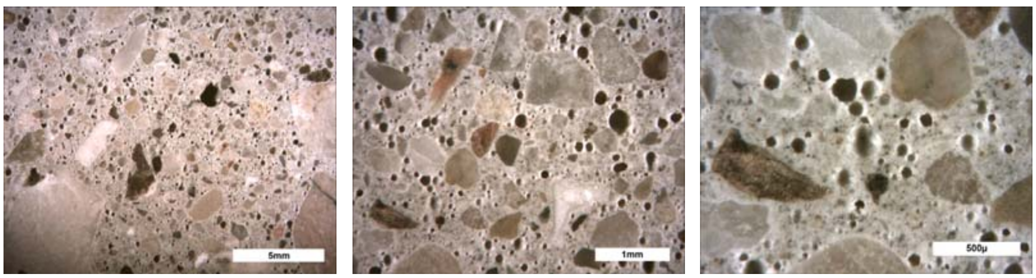
Region: NE |PCC Thickness: 9.00 inches

Paving Start Date: May 23, 2011	Field Testing Date : May 26, 2011

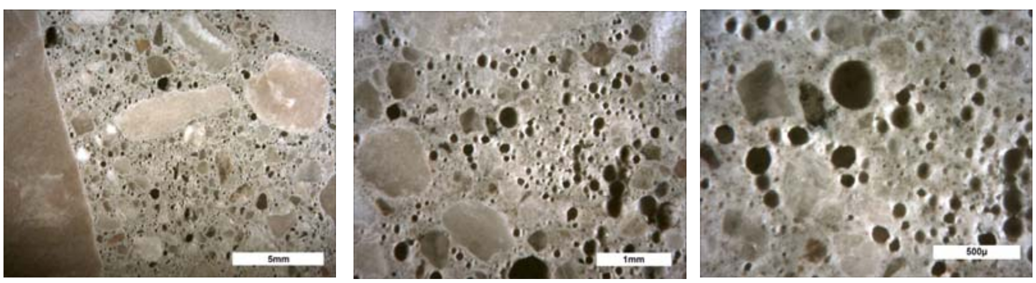
Concrete Mix Design		Other Project Details	
Cement (Type), lbs/yd^3	455 (Unknown)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	110 (C)	Paver	P-2
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AEVR-1
w/cm	0.40	AEA Type	Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1942, 1296	WRA Brand	WR-1
AEA, WRA Dosage (oz. / 100 wt.)	10.20, 19.80	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.60	6.17	5.97		
Behind Paver (%)	5.40	5.58	4.52	8.82	8.78
Difference (%)	-1.20	-0.59	-1.45	2.65	2.81

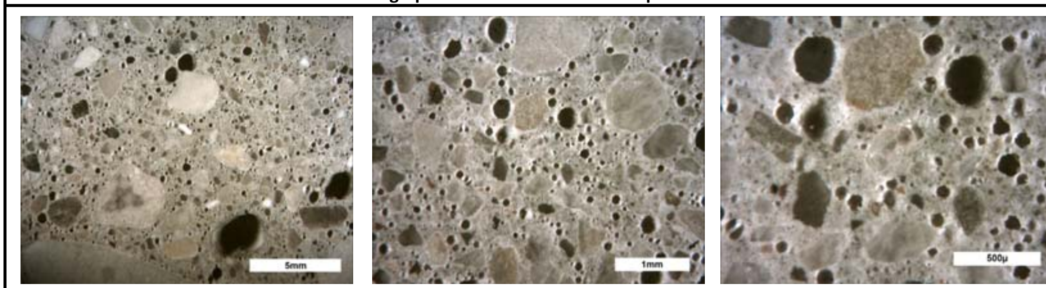
Micrographs of field cyclinders from concrete in front of paver



Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



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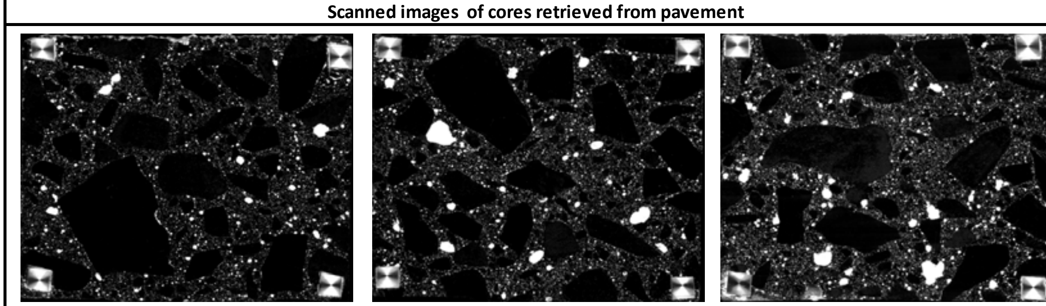


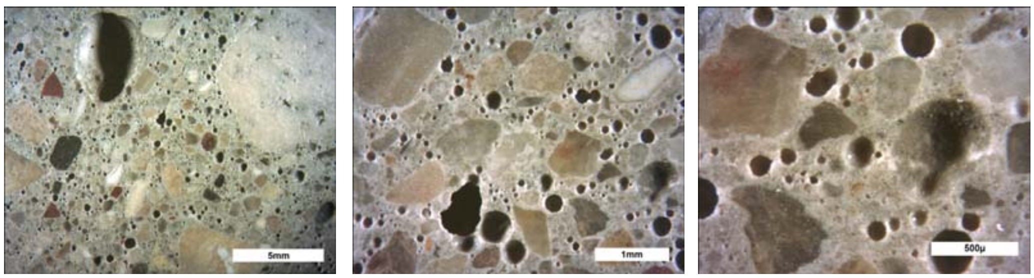
Project ID: NE-1a

Region: NE |PCC Thickness: 9.00 inches

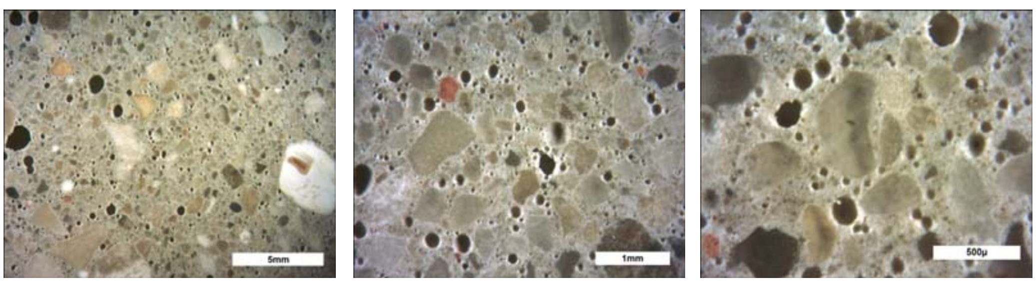
Paving Start Date: May 23, 2011		Field Testing Date : May 26, 2011	
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	455 (Unknown)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	110 (C)	Paver	P-2
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AEVR-1
w/cm	0.40	AEA Type	Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1942, 1296	WRA Brand	WR-1
AEA, WRA Dosage (oz. / 100 wt.)	10.20, 19.80	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.80	6.83	6.47		
Behind Paver (%)	5.90	6.99	5.58	9.18	8.95
Difference (%)	-0.90	0.16	-0.89	2.35	2.48

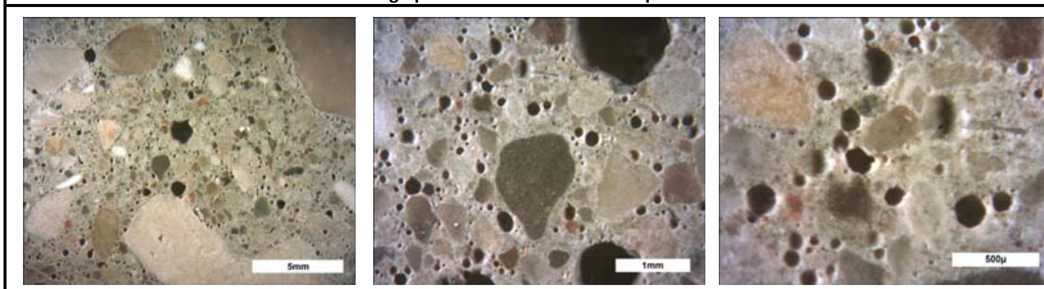
Micrographs of field cyclinders from concrete in front of paver



Micrographs of field cylinders from concrete behind paver



Micrographs of cores retrieved from pavement



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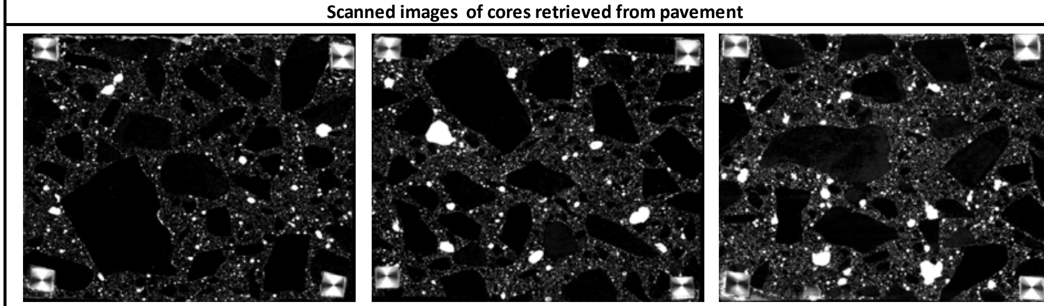


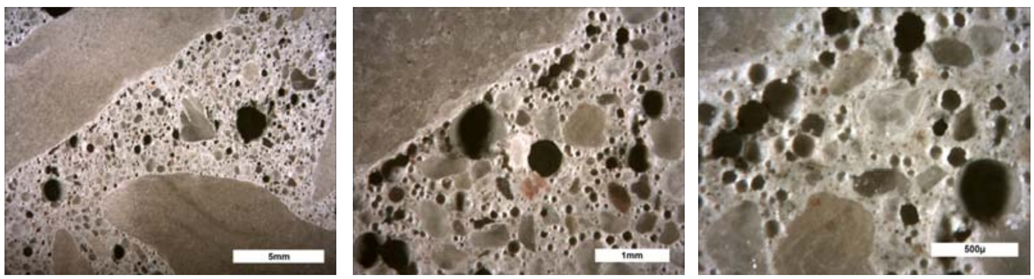
Project ID: NE-2

Region: NE |PCC Thickness: 8.50 inches	
Paving Start Date: May 24, 2011	Field Testing Date : May 24, 2011

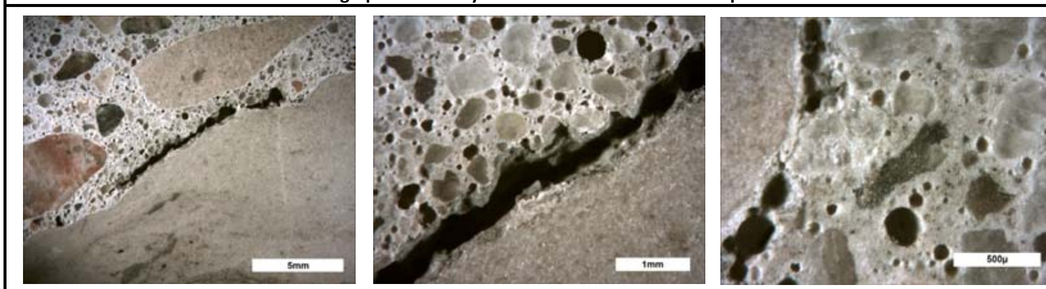
Concrete Mix Design		Other Project Details	
Cement (Type), lbs/yd^3	455 (Unknown)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	110 (C)	Paver	P-2
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AEVR-1
w/cm	0.38	AEA Type	Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1928, 1281	WRA Brand	WR-2
AEA, WRA Dosage (oz. / 100 wt.)	9.60, 19.80	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	8.00	8.45	10.16		
Behind Paver (%)	6.40	7.39	7.20	6.37	6.99
Difference (%)	-1.60	-1.06	-2.96	-2.08	-3.17

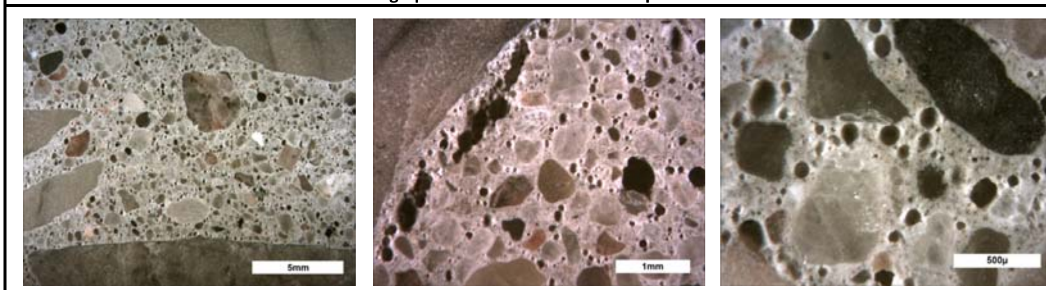
Micrographs of field cyclinders from concrete in front of paver



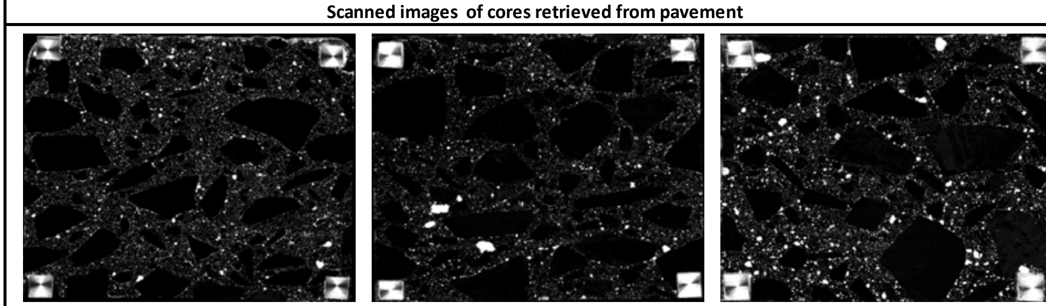
Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



Project ID: NE-3

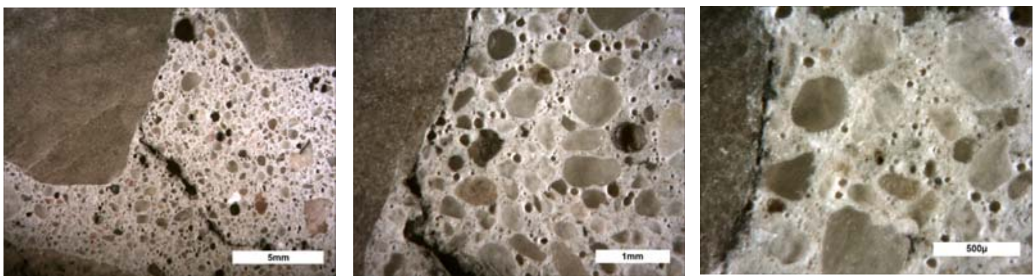
Region: NE |PCC Thickness: 11.00 inches

Paving Start Date: June 16, 2011	**Field Testing Date : June 16, 2011**

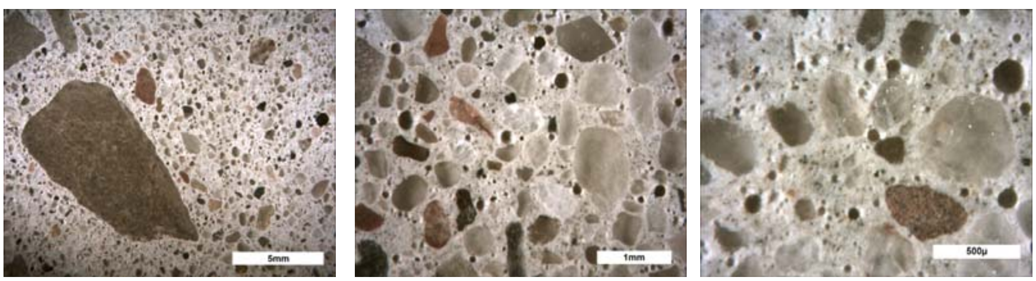
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	395 (Unknown)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-3
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-4
w/cm	0.38	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1943, 1291	WRA Brand	WR-1
AEA, WRA Dosage (oz. / 100 wt.)	4.50, 17.00	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.00	5.58	6.18		
Behind Paver (%)	4.90	3.62	4.14	6.99	7.35
Difference (%)	-1.10	-1.96	-2.04	1.41	1.17

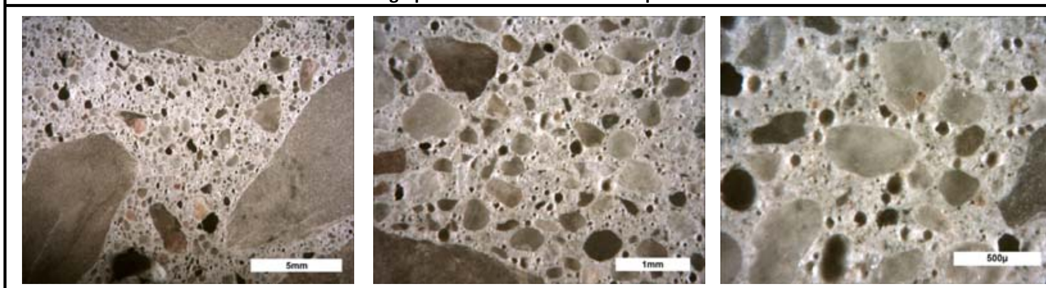
Micrographs of field cyclinders from concrete in front of paver



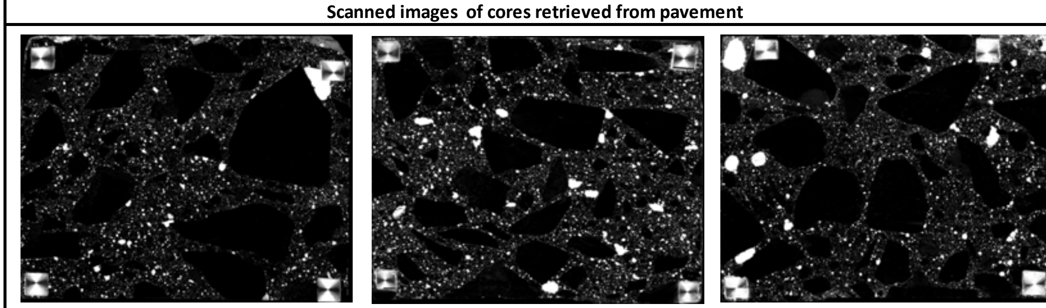
Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



Project ID: NE-4

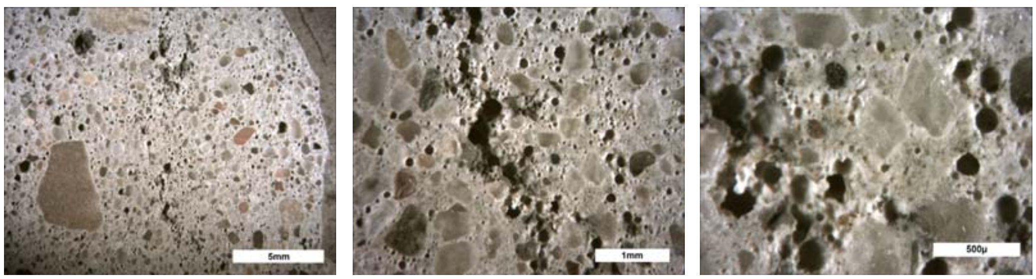
Region: NE |PCC Thickness: 11.00 inches

Paving Start Date: July 18, 2011	**Field Testing Date : July 19, 2011**

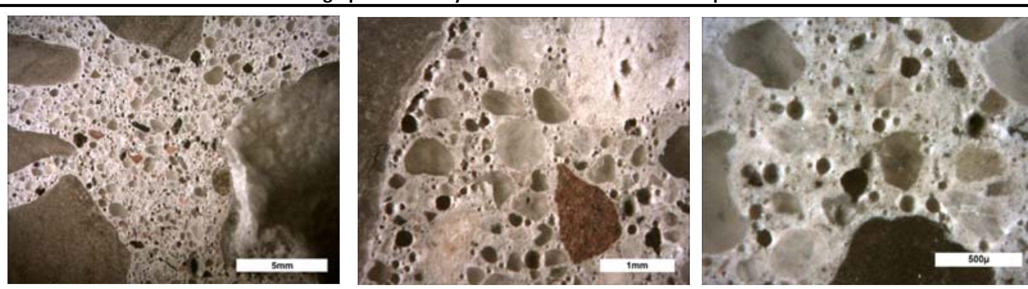
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	395 (I/II)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-4
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-4
w/cm	0.37	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1944, 1294	WRA Brand	WR-1
AEA, WRA Dosage (oz. / 100 wt.)	3.40, 18.10	Coarse Aggregate Type	Limestone

Air Content	**Fresh Concrete**	**Field Cylinders (Auto)**	**Field Cylinders (Manual)**	**Core (Auto)**	**Core (Manual)**
In front of Paver (%)	5.60	6.34	4.52		
Behind Paver (%)	5.80	9.63	8.76	8.21	7.31
Difference (%)	0.20	3.29	4.24	1.87	2.79

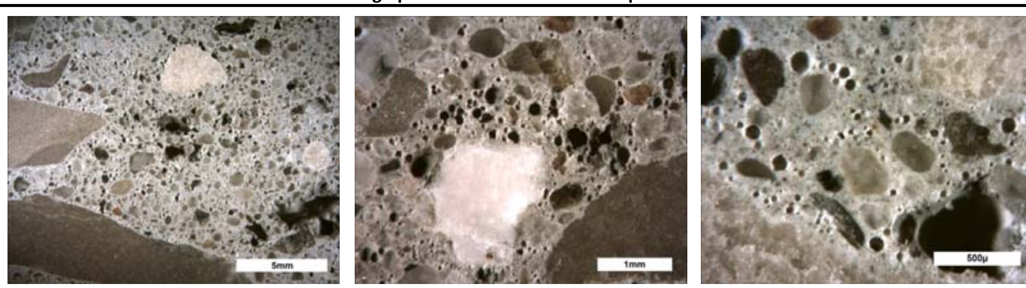
Micrographs of field cyclinders from concrete in front of paver



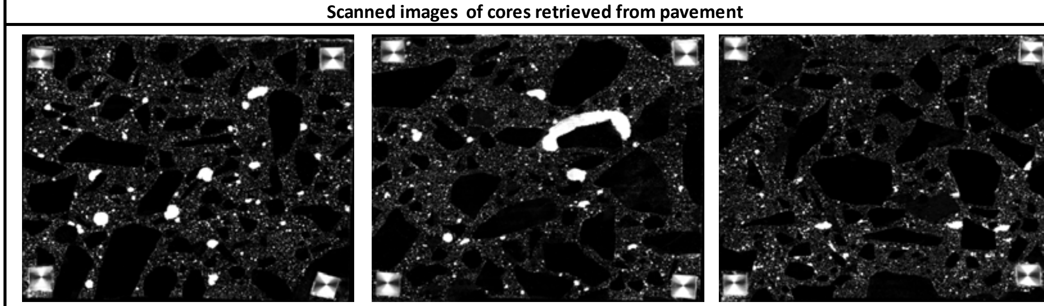
Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



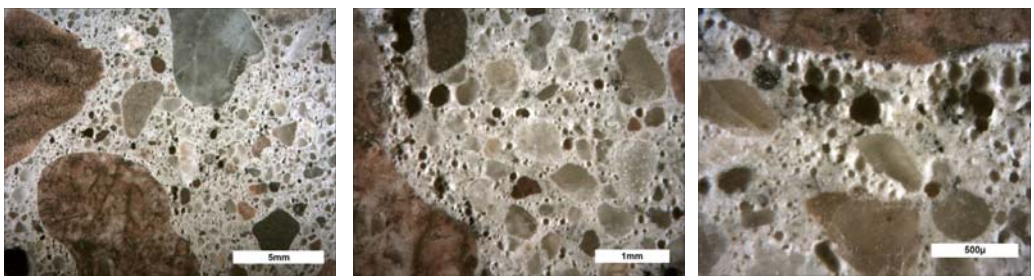
Project ID: NC-1

Region: NC |PCC Thickness: 9.00 inches

Paving Start Date: May 31, 2011		**Field Testing Date : June 13, 2011**	
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	452 (I)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	113 (Unknown)	Paver	P-1
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-3
w/cm	0.41	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1823, 1310	WRA Brand	WR-3
AEA, WRA Dosage (oz. / 100 wt.)	0.80, 3.01	Coarse Aggregate Type	Gravel

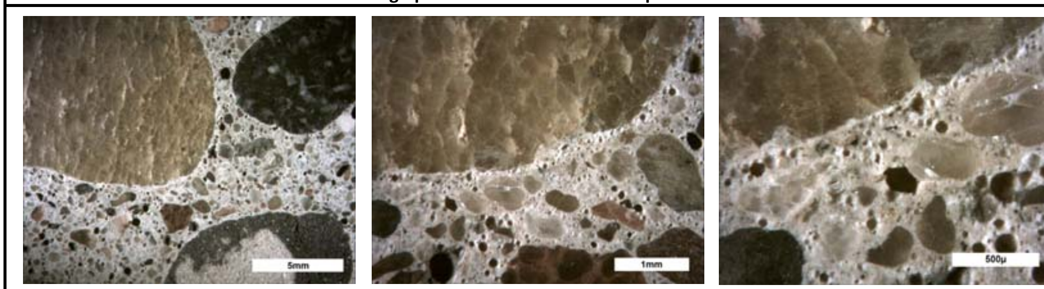
Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.30	6.69	5.86		
Behind Paver (%)	5.70	6.71	5.05	9.34	8.85
Difference (%)	-0.60	0.02	-0.81	2.65	2.99

Micrographs of field cyclinders from concrete in front of paver

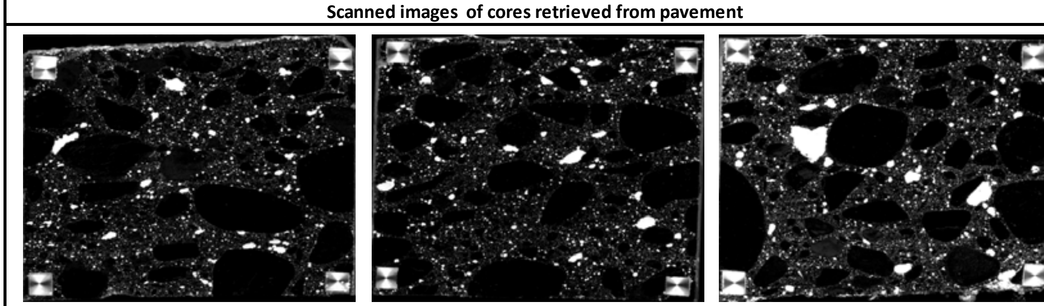


Micrographs of field cyclinders from concrete behind paver

Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



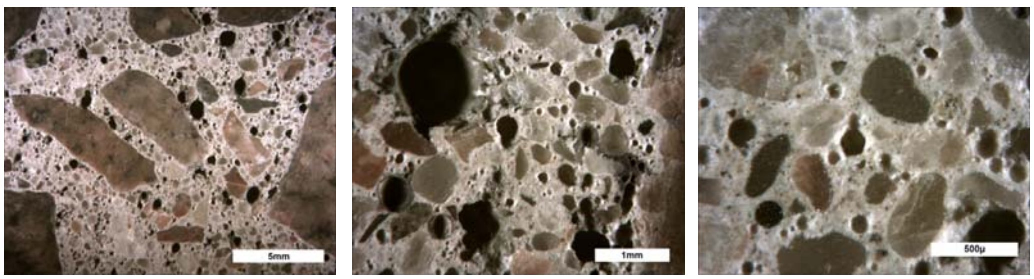
Project ID: NC-2

Region: NC |PCC Thickness: 10.00 inches

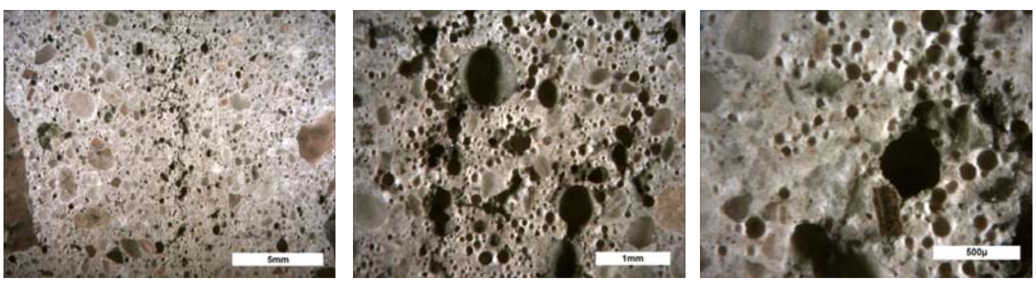
Paving Start Date: August 22, 2011		**Field Testing Date : August 29, 2011**	
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	395 (I/II)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-1
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-3
w/cm	0.37	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	2045, 1256	WRA Brand	WR-3
AEA, WRA Dosage (oz. / 100 wt.)	0.80, 3.00	Coarse Aggregate Type	Gravel

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	5.90	10.64	10.43		
Behind Paver (%)	5.40	9.25	8.92	12.94	10.63
Difference (%)	-0.50	-1.39	-1.51	2.30	0.20

Micrographs of field cyclinders from concrete in front of paver

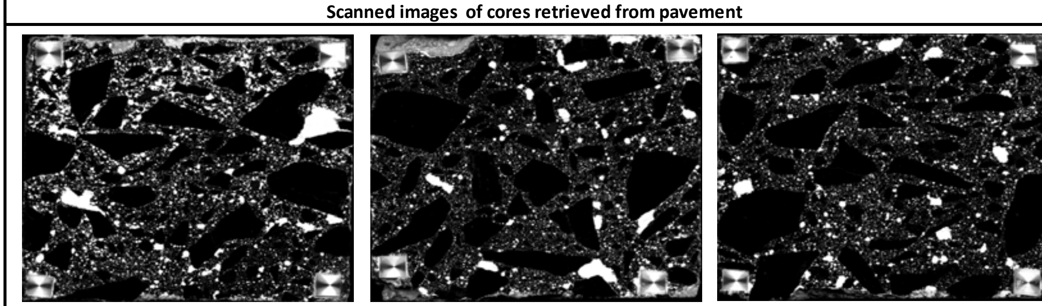


Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement

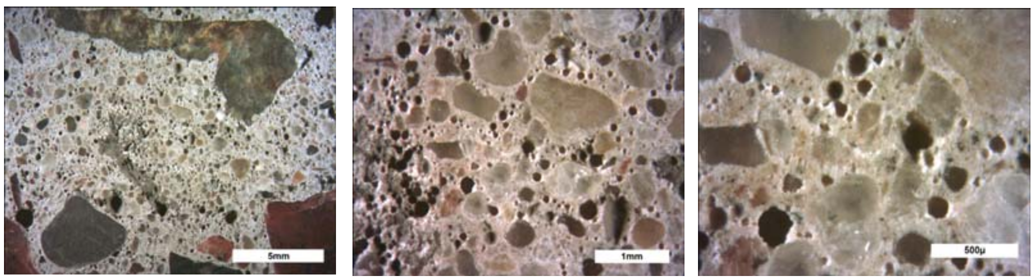
Scanned images of cores retrieved from pavement



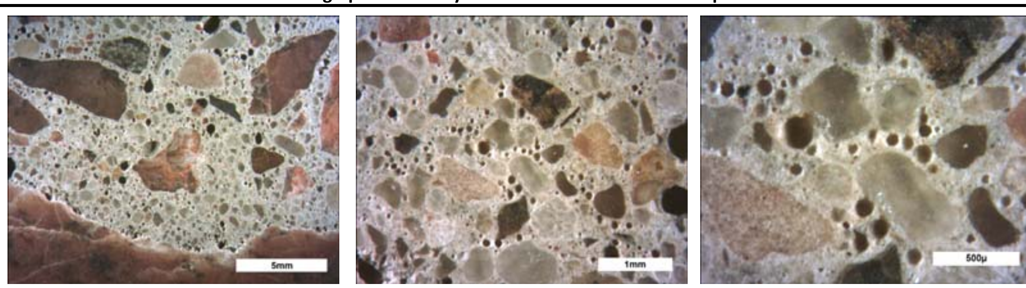
Project ID: NC-2a			
Region: NC |PCC Thickness: 10.00 inches			
Paving Start Date: August 22, 2011		Field Testing Date : August 29, 2011	
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	395 (I/II)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-1
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-3
w/cm	0.37	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	2045, 1256	WRA Brand	WR-3
AEA, WRA Dosage (oz. / 100 wt.)	0.80, 3.00	Coarse Aggregate Type	Gravel

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.60	7.07	7.31		
Behind Paver (%)	4.80	5.67	5.70	8.83	7.10
Difference (%)	-1.80	-1.40	-1.61	1.76	-0.21

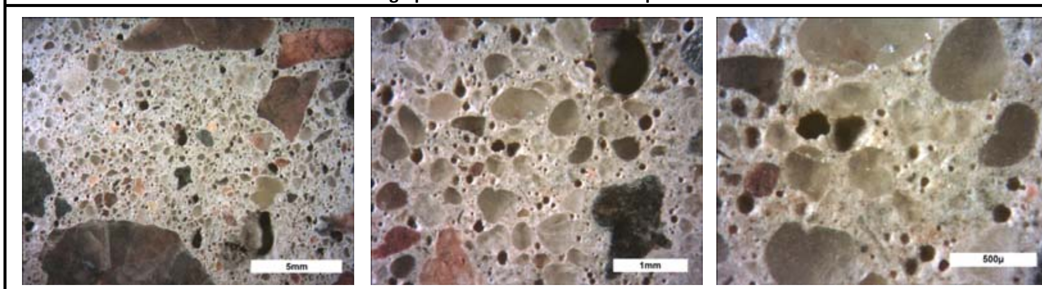
Micrographs of field cyclinders from concrete in front of paver



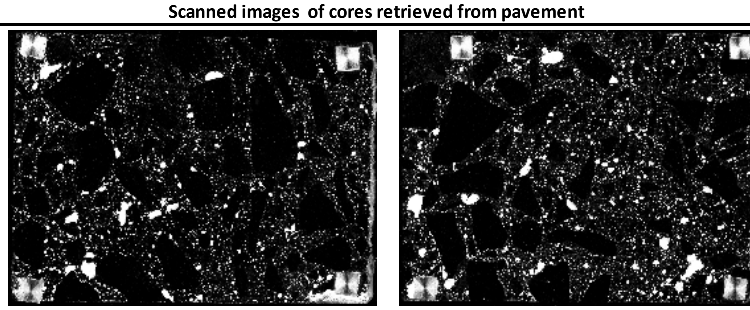
Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



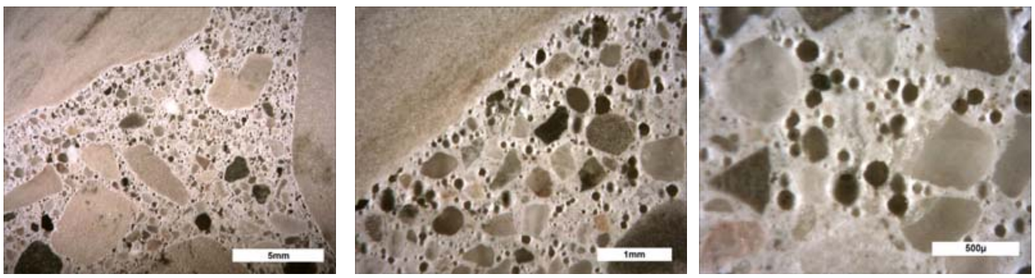
Project ID: SW-1

Region: SW |PCC Thickness: 12.00 inches

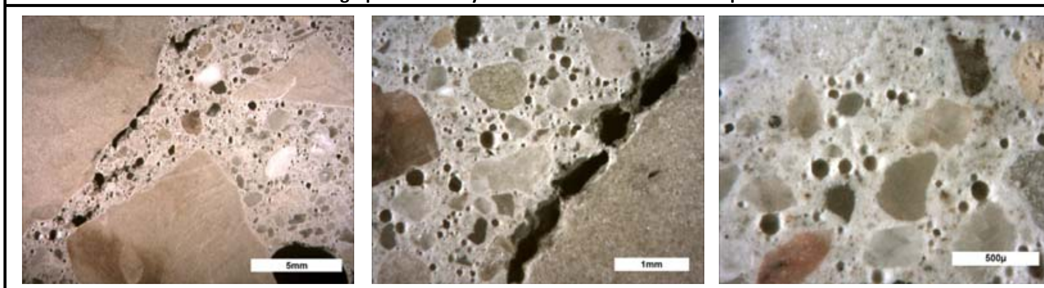
Paving Start Date: May 22; July to September, 2011		**Field Testing Date : August 4, 2011**	
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	395 (I/II)	Plant	BP-2
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-3
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-2
w/cm	0.37	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	2045, 1256	WRA Brand	WR-4
AEA, WRA Dosage (oz. / 100 wt.)	0.80, 3.00	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.80	9.42	7.69		
Behind Paver (%)	5.10	6.37	6.72	6.97	8.96
Difference (%)	-1.70	-3.05	-0.97	-2.45	1.27

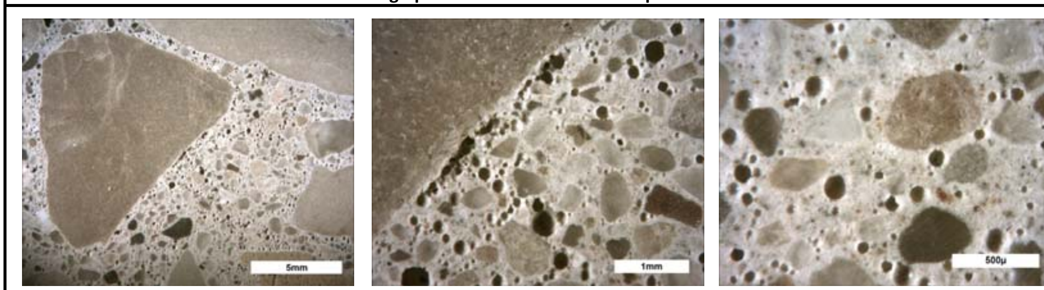
Micrographs of field cyclinders from concrete in front of paver



Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



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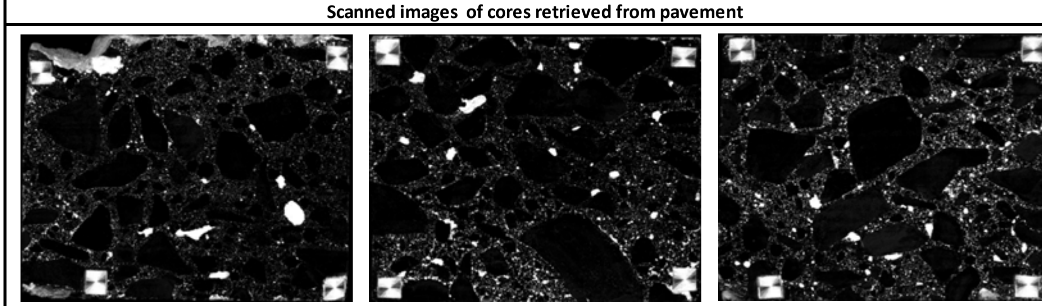


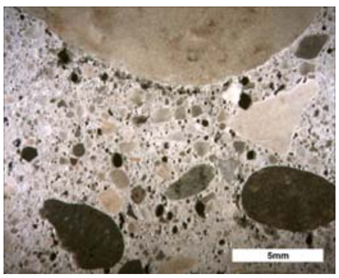
Project ID: SW-2

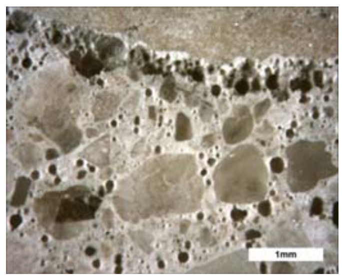
Region: SW |PCC Thickness: 9.00 inches

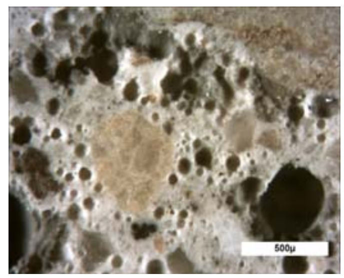
Paving Start Date: May 20, 2011		**Field Testing Date : June 3, 2011**	
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	395 (Unknown)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-3
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-1
w/cm	0.41	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1889, 1237	WRA Brand	WR-4
AEA, WRA Dosage (oz. / 100 wt.)	7.00, 17.00	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	7.50	8.47	8.55		
Behind Paver (%)	6.20	6.31	6.94	6.78	6.63
Difference (%)	-1.30	-2.16	-1.61	-1.69	-1.92

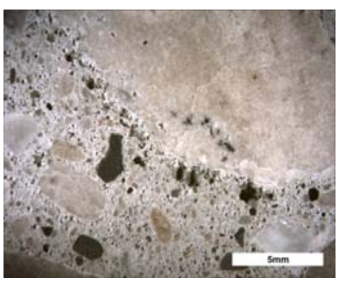
Micrographs of field cyclinders from concrete in front of paver

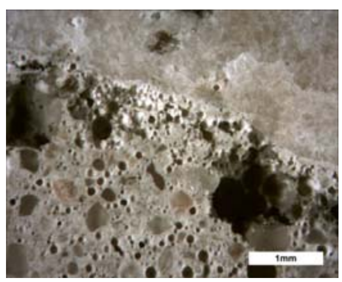


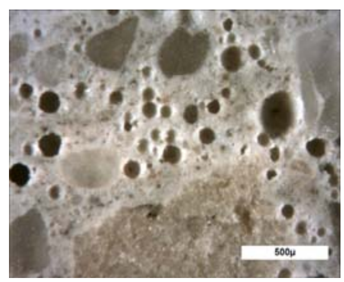




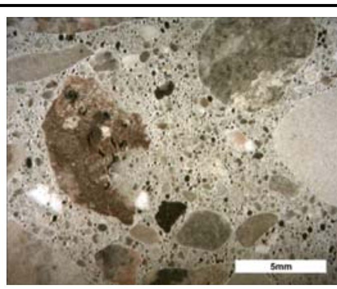
Micrographs of field cyclinders from concrete behind paver

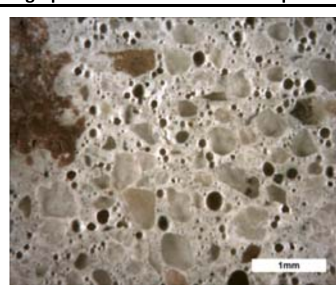


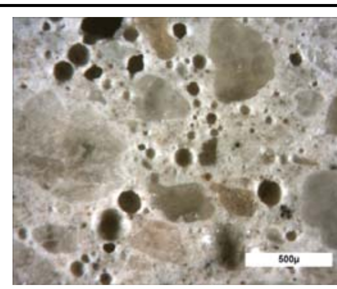




Micrographs of cores retrieved from pavement







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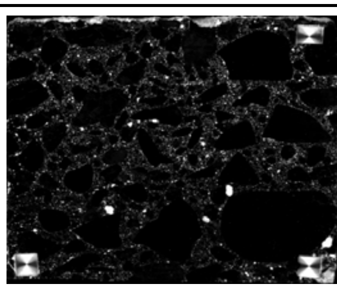
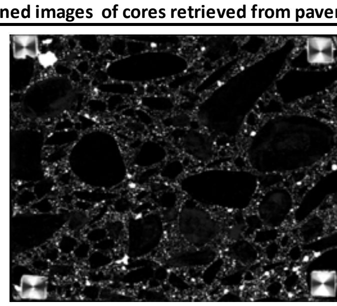
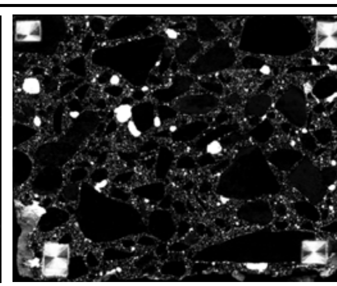




Project ID: SW-3

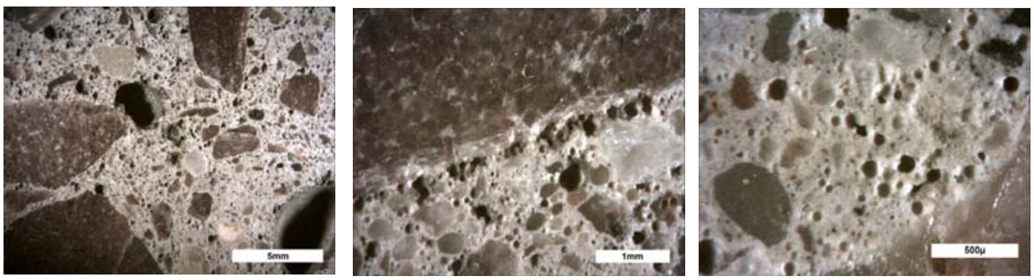
Region: SW |PCC Thickness: 10.00 inches

Paving Start Date: June 9, 2011	**Field Testing Date : June 13, 2011**

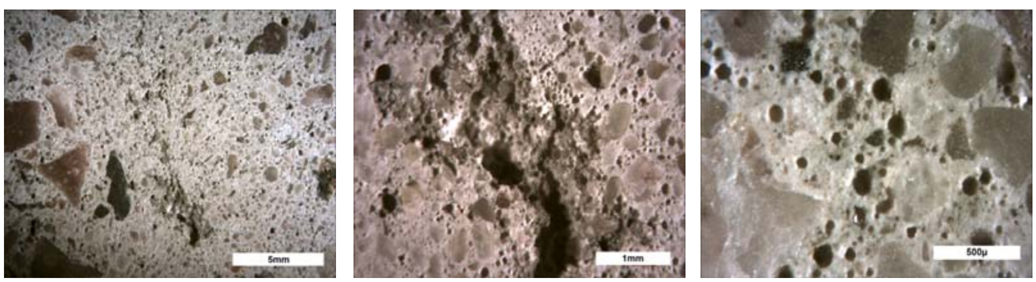
Concrete Mix Design		**Other Project Details**	
Cement (Type), lbs/yd^3	395 (I/II)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-3
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-4
w/cm	0.41	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1848, 1282	WRA Brand	WR-1
AEA, WRA Dosage (oz. / 100 wt.)	4.00, 17.00	Coarse Aggregate Type	Limestone

Air Content	**Fresh Concrete**	**Field Cylinders (Auto)**	**Field Cylinders (Manual)**	**Core (Auto)**	**Core (Manual)**
In front of Paver (%)	7.00	12.17	10.75		
Behind Paver (%)	6.50	10.77	9.29	11.76	9.62
Difference (%)	-0.50	-1.40	-1.46	-0.41	-1.13

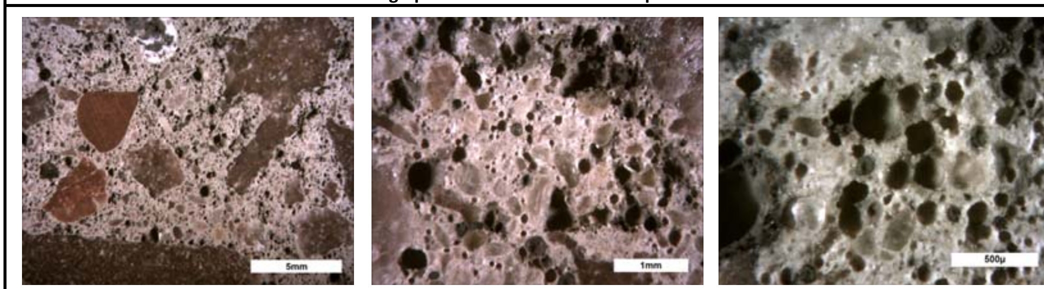
Micrographs of field cyclinders from concrete in front of paver



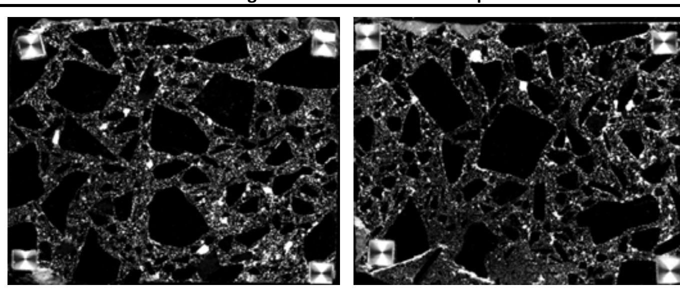
Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



Project ID: SE-1

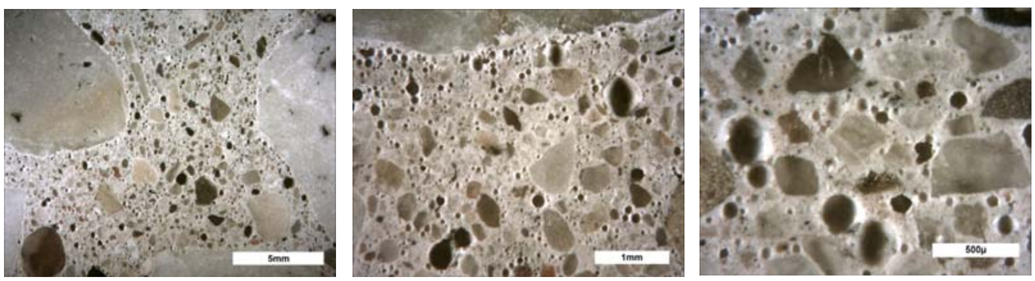
Region: SE |PCC Thickness: 11.00 inches

Paving Start Date: June 9, 2011	Field Testing Date : August 19, 2011

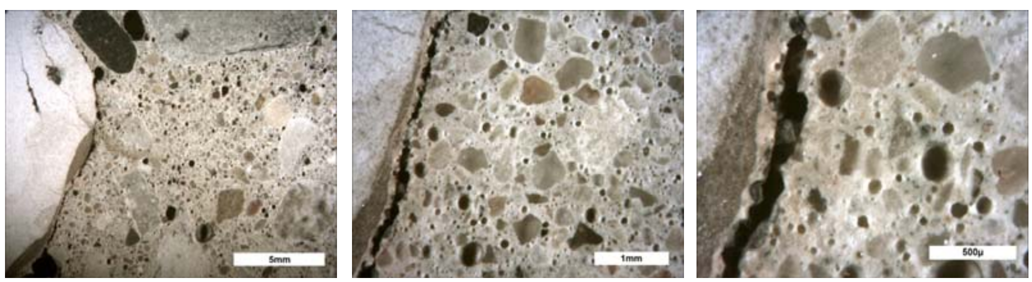
Concrete Mix Design		Other Project Details	
Cement (Type), lbs/yd^3	395 (I/II)	Plant	BP-1
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-3
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-4
w/cm	0.37	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1910, 1262	WRA Brand	WR-1
AEA, WRA Dosage (oz. / 100 wt.)	6.80, 17.00	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	5.80	6.19	5.81		
Behind Paver (%)	5.00	5.26	6.13	6.88	6.92
Difference (%)	-0.80	-0.93	0.32	0.69	1.11

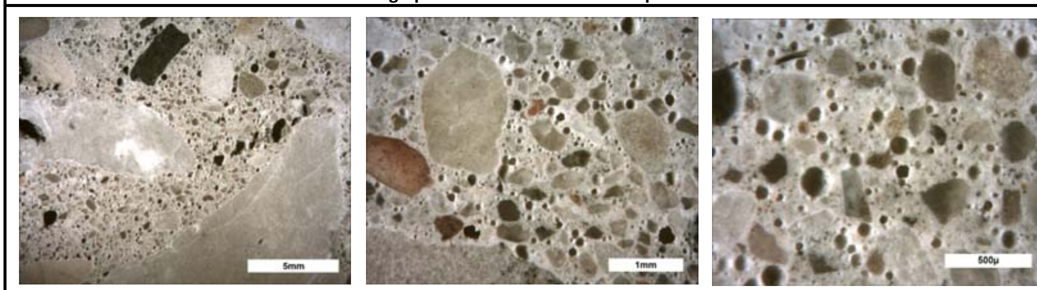
Micrographs of field cyclinders from concrete in front of paver



Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



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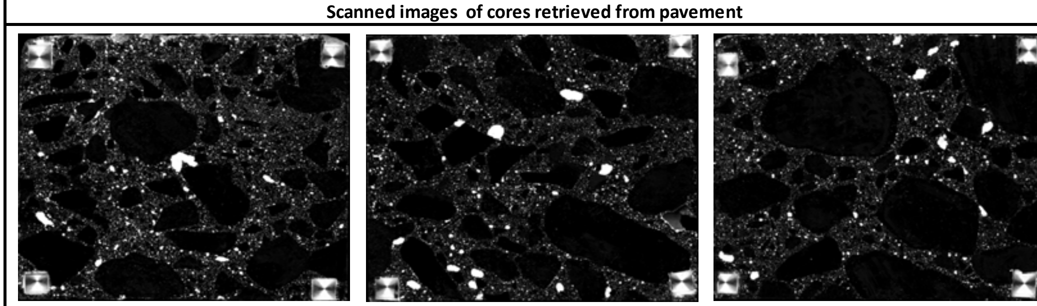


Project ID: SE-2

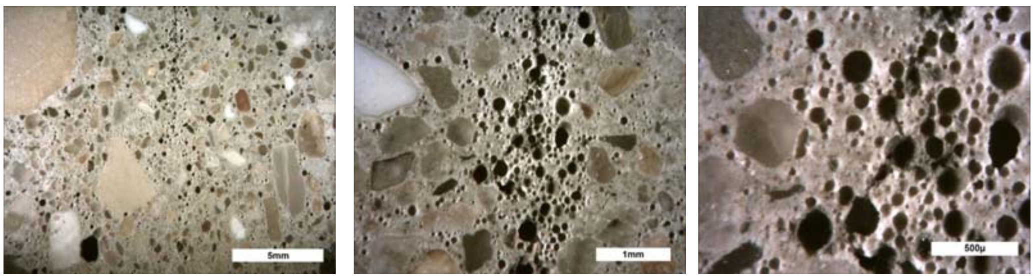
Region: SE |PCC Thickness: 8.50 inches

Paving Start Date: June 17, 2011	Field Testing Date : June 17, 2011

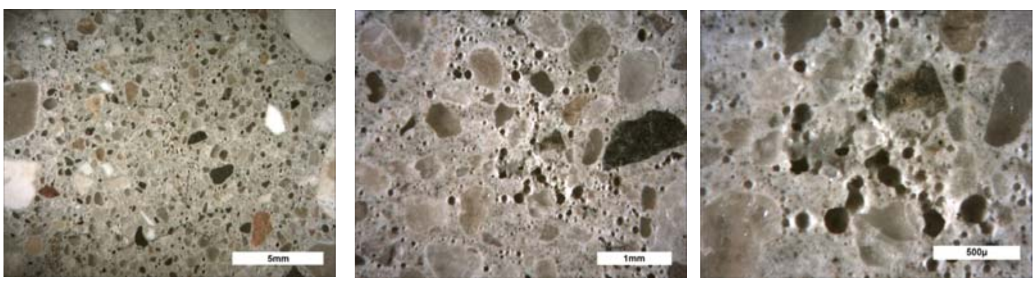
Concrete Mix Design		Other Project Details	
Cement (Type), lbs/yd^3	395 (I)	Plant	BP-2
Fly Ash (Type), lbs/yd^3	170 (C)	Paver	P-3
Total Cementitious Content, lbs/yd^3	565	AEA Brand	AENVR-1
w/cm	0.41	AEA Type	Non Vinsol Resin
Aggregate (Coarse, Fine), lbs/yd^3	1942, 1202	WRA Brand	WR-4
AEA, WRA Dosage (oz. / 100 wt.)	5.00, 18.00	Coarse Aggregate Type	Limestone

Air Content	Fresh Concrete	Field Cylinders (Auto)	Field Cylinders (Manual)	Core (Auto)	Core (Manual)
In front of Paver (%)	6.90	6.78	6.40		
Behind Paver (%)	5.10	4.92	6.02	5.64	5.77
Difference (%)	-1.80	-1.86	-0.38	-1.14	-0.63

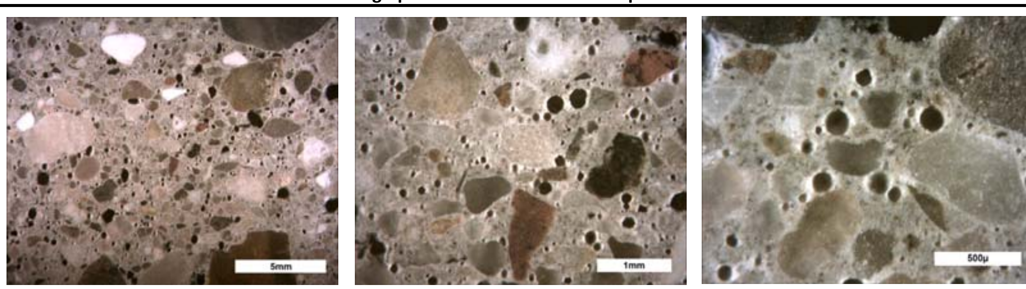
Micrographs of field cyclinders from concrete in front of paver



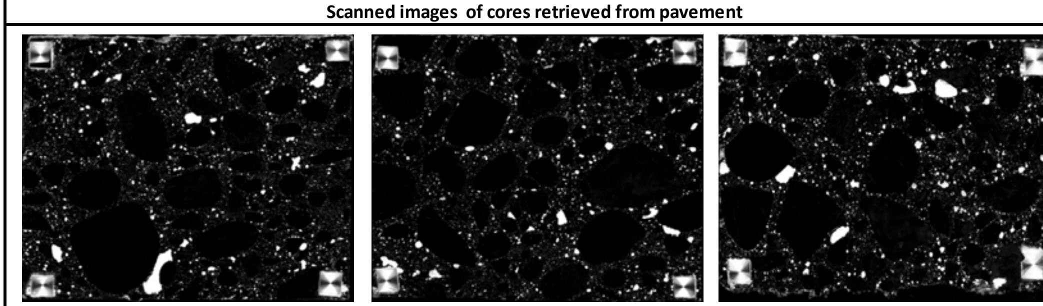
Micrographs of field cyclinders from concrete behind paver



Micrographs of cores retrieved from pavement



Scanned images of cores retrieved from pavement



APPENDIX D. LABORATORY TESTING REPORT

As Received Specimens

A total of 42 specimens were received and cataloged from 14 paving sites. Thirty six specimens were received in late 2011; six additional were received in mid 2012. Each construction site provided three specimens comprised of cylinders prepared from fresh concrete obtained before the slipform paver (A), behind the slipform paver (B) and cores retrieved after hardening (C). Images of the as-received specimens are shown in Figures 1, 2 and 3.

Sample Preparation

A precision cutoff saw was used to cut two ½ inch thick longitudinal slabs from the centers of each specimen. The large slabs were then cut down to 3 x 4 x ½ inch to accommodate the polishing equipment. One side of each slab was plane ground and then polished with #600 SiC compound on a LapMaster 12 lapping machine. The slab surface was thoroughly cleaned, the slab dried and a coat of 5:1 acetone:hardner solution was applied to stabilize the surface prior to final polishing. Final polishing was completed on fresh #600 SiC PSA-backed polishing paper. The slab was again thoroughly cleaned and dried prior to analysis.

Stereo micrographs of prepared slab surfaces from all of the specimens are shown in Figures 5 through 40

Manual Analysis

Analyses of prepared slabs were performed in accordance with ASTM C457 Method B: Modified Point Count Method. Results for each slab are presented in Table 1. Results for individual cores and cylinders are shown in Table 2.

A number of cylinder specimens exhibited segregation issues with several having vibrator trails, evident in slabs from SW-3B (Figure 12), SE-2A (Figure 20), SE-2B (Figure 21), NE-4A (Figure 26), NC-2B (Figure 39) and NC-2AA (Figure 44).

Accumulation of voids about aggregate grains is seen in all specimens from SW-1 (Figures 5 through 7), SE-1A and B (Figures 8 and 9), SW-3A (Figure 11), SW-2A and B (Figures 14 and 15), NC-1A and C (Figures 17 and 19), all specimens from NE-2 (Figures 23 through 25), NE-4B (Figure 27), NE-3A (Figure 29),NW-1A and B (Figures 35 and 36) and NC-2AB (Figure 45).

The core from SW-3 (SW-3C, Figure 13) was unusually porous with coalescence of entrained air voids imparting a foamy appearance. Coalescence of entrained air voids is also apparent in NE-4C (Figure 28), NE-1B (Figure 33) and NC-2C (Figure 40). Specimen NC-1B (Figure 18) contained a large irregularly shaped air void that may be related to the observation of air voids ringing aggregate particles in the other two specimens from that location (see Figures 17 and 19).

Automated Analysis

Following completion of manual air-void parameter determinations, slabs were treated to enhance the contrast between solid phases and voids and scanned for analysis on a flatbed scanner. Scanned images of prepared slabs are shown in Figures 47 through 82.

The presence of porous aggregate necessitated pre-inking of coarse aggregate faces prior to application of ink over the entire slab surface. Two ink applications were then completed on each slab. Ground wollastonite was pressed into the voids and porous aggregate was re-inked prior to scanning (pre-inking of coarse aggregate improves discrimination during this step). Scanning was done at 3,175 dpi to a grayscale TIFF format. While not shown in the scanned images, a white balance card was scanned simultaneously with each slab.

Poor consolidation is seen in slabs from SW-3B (Figure 54), SW-2B (Figure 57), NC-1A (Figure 59), NC-1B (Figure 60), SE-2A (Figure 62), SE-2B (Figure 63), NC-2B (Figure 69), NE-4A (Figure 71), NE-4B (Figure 72), NE-4C (Figure 73) and NE-1AA (Figure 83). What appear to be vibrator trails are apparent in many of these images.

What appear to be vibrator trails are seen in SW-1B (Figure 48), SW-cB (Figure 54), NC-1B (Figure 60), SE-2A (Figure 62), NC-2B (Figure 69), NE-4A (Figure 71) and NE-1AA (Figure 83).

Accumulation of air voids around coarse aggregate particles is present in many images of the slabs.

Analyses were performed with the newest software version written for Adobe Photoshop CS5. In addition to the original thresholding method where a single threshold operation is performed, the threshold applied being an average of the optimum thresholds found for 1) air content and 2) void frequency,four additional thresholding methods are available with this version:

1) Applying the void frequency-optimized threshold followed by expansion or contraction of chord lengths to calculate air content.
2) Applying just the void frequency-optimized threshold.
3) Applying just an air content-optimized threshold.
4) Applying a void frequency-optimized threshold for void frequency determination and a separate air content-optimized threshold for air content determination.

The two threshold method (#4) was employed for these analyses. Optimization of thresholds was completed with 25 randomly selected scanned images. Results of automatic analyses are presented for each slab in Table 3. Results for each specimen (cylinder or core) are shown in Table 4. Comparisons of automatic and manual air content, void frequency and spacing factor are shown in Figures 89, 90 and 91, respectively.

Air-void system parameters by depth were determined by extracting 200 traverses from each slab taken from the core specimens. Traverses were then split into groups of five consecutive traverses descending from the top of the slab to the bottom and analyses were performed on each of these groups. Plots of air content by relative depth for each specimen are shown in Figures 92 through 95. Plots of void frequency by relative depth are shown in Figures 96 through 99. Plots of spacing factor by relative depth are shown in Figures 100 through 103. Each point on these plots is the result of the analysis performed for the group of five traverses extracted at that depth in the specimen. Depths are relative due to the material removed when the slabs are cut and as a result of the area selected for analysis being deliberately chosen away from slab edges.

Air Content Before and After Slipform Paver

The difference in air content of hardened concrete determined using the automatic method is shown graphically in Figures 104 and 105. Figure 104 shows the measured difference in air content between cylinders cast with fresh concrete before and after the paver. Figure 105 shows the measured difference in air content between cylinders made with fresh concrete before the paver and cores later taken from the hardened pavement. Since the intent of this research is to ascertain the fate of entrained air, intercepts were filtered to remove entrapped air (intercepts having a chord length greater than 1mm). Blue bars indicate the difference in air content with all intercepts included; red bars indicate air content difference when intercepts larger than 1mm are excluded.

The exclusion of entrapped air yielded no net change in the results of the analysis.

The measured difference in air content of the cylinders (Figure 104) suggests that air content declines as concrete passes through the paver. This is not the case upon reviewing the measured air content difference between the cylinder and core (Figure 105) in which an equal number of sample sites are above and below the zero-difference line. This latter result suggests that there is no net change in air content as concrete passes through the paver.

These conflicting results are likely the product of sample collection methods. Vibrator trails are present evident in many of the cylinder specimens, including cylindrical specimens created from concrete collected after the slipform paver had passed. Concrete in these specimens has therefore been worked and compacted multiple times. It is reasonable to expect that air content would decline with such treatment. Collection of fresh concrete samples after the slipform paver is likely to be the single greatest challenge faced by researchers conducting this sort of investigation.

Figure 1: Images of specimens received. Clockwise from top, left: SW-1; SE-1; SW-3; SW-2.

Figure 2: Images of specimens received. Clockwise from top, left: NC-1; SE-2; NE-2; NC-2.

Figure 3: Images of specimens received. Clockwise from top, left: NE-4; NE-3; NE-1; NW-1.

Figure 4: Images of specimens received. NE-1A (left) NC-2A (right).

Table 1: Results of manual point counts of individual slabs.

ID	Position	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
SW-1A	Top	2429	1878	0.773	10.32	0.073
SW-1A	Bot	2429	696	0.286	5.05	0.160
SW-1B	Top	2429	1624	0.668	6.02	0.110
SW-1B	Bot	2429	1286	0.529	7.42	0.118
SW-1C	Top	2429	1337	0.550	8.49	0.112
SW-1C	Mid	2429	1430	0.589	9.57	0.102
SW-1C	Bot	2429	1316	0.542	8.82	0.108
SE-1A	Top	2429	1026	0.422	4.62	0.098
SE-1A	Bot	2429	1187	0.489	6.99	0.111
SE-1B	Top	2429	1204	0.496	6.13	0.112
SE-1B	Bot	2429	1157	0.476	6.13	0.116
SE-1C	Top	2429	1265	0.521	7.20	0.055
SE-1C	Mid	2429	1640	0.675	7.85	0.084
SE-1C	Bot	2429	1187	0.489	5.70	0.081
SW-3A	Top	2429	1953	0.804	13.44	0.072
SW-3A	Bot	2429	2108	0.868	8.06	0.079
SW-3B	Top	2155	1643	0.762	11.64	0.068
SW-3B	Bot	2429	1532	0.631	7.20	0.083
SW-3C	Top	2429	1855	0.764	10.65	0.061
SW-3C	Bot	2429	1326	0.546	8.60	0.101
SW-2A	Top	2429	1463	0.602	7.20	0.081
SW-2A	Bot	2429	1431	0.589	9.89	0.073
SW-2B	Top	2429	1540	0.634	6.88	0.083
SW-2B	Bot	2429	1660	0.683	6.99	0.088
SW-2C	Top	2429	1456	0.599	6.34	0.061
SW-2C	Mid	2429	1304	0.537	6.99	0.097
SW-2C	Bot	2429	1541	0.634	6.56	0.072
NC-1A	Top	2429	964	0.397	3.33	0.101
NC-1A	Bot	2429	1359	0.559	8.39	0.135
NC-1B	Top	2429	498	0.205	3.76	0.218
NC-1B	Bot	2429	1833	0.755	6.34	0.091
NC-1C	Top	2429	1451	0.597	8.71	0.098
NC-1C	Mid	2429	1539	0.633	8.92	0.099
NC-1C	Bot	2429	1370	0.564	8.92	0.108
SE-2A	Top	2429	966	0.398	8.28	0.109
SE-2A	Bot	2429	979	0.403	4.52	0.137
SE-2B	Top	2429	1186	0.488	6.56	0.127
SE-2B	Bot	2429	1037	0.427	5.48	0.095
SE-2C	Top	2429	868	0.357	6.45	0.126
SE-2C	Mid	2429	854	0.352	3.33	0.127
SE-2C	Bot	2155	743	0.345	7.76	0.163
NE-2A	Top	2429	1636	0.673	10.43	0.073
NE-2A	Bot	2429	1665	0.685	9.89	0.080
NE-2B	Top	2429	1451	0.597	6.77	0.099

ID	Position	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
NE-2B	Bot	2429	1457	0.600	7.63	0.114
NE-2C	Top	2429	1405	0.578	8.17	0.105
NE-2C	Mid	2429	691	0.284	4.73	0.143
NE-2C	Bot	2429	1307	0.538	8.06	0.113
NC-2A	Top	2429	1026	0.422	9.89	0.097
NC-2A	Bot	2429	1194	0.491	10.97	0.103
NC-2B	Top	2429	1358	0.559	10.11	0.103
NC-2B	Bot	2429	1317	0.542	7.74	0.127
NC-2C	Top	2341	1550	0.662	13.17	0.075
NC-2C	Mid	2429	1259	0.518	9.14	0.118
NC-2C	Bot	2429	1369	0.564	9.68	0.110
NE-4A	Top	2429	1511	0.622	4.95	0.082
NE-4A	Bot	2429	1491	0.614	4.09	0.086
NE-4B	Top	2429	1239	0.510	7.74	0.102
NE-4B	Bot	2429	1412	0.581	9.78	0.102
NE-4C	Top	2429	1233	0.508	6.99	0.084
NE-4C	Mid	2429	1313	0.540	7.74	0.082
NE-4C	Bot	2429	1690	0.696	7.20	0.095
NE-3A	Top	2429	1417	0.583	6.99	0.111
NE-3A	Bot	2429	1321	0.544	5.38	0.108
NE-3B	Top	2429	1015	0.418	3.23	0.116
NE-3B	Bot	2429	1106	0.455	5.05	0.139
NE-3C	Top	2429	1362	0.561	5.59	0.080
NE-3C	Mid	2429	1155	0.475	9.25	0.122
NE-3C	Bot	2429	928	0.382	7.20	0.144
NE-1A	Top	2429	848	0.349	5.27	0.066
NE-1A	Bot	2429	1261	0.519	6.67	0.079
NE-1B	Top	2429	891	0.367	2.58	0.097
NE-1B	Bot	2429	1053	0.433	6.45	0.140
NE-1C	Top	2429	873	0.359	4.84	0.148
NE-1C	Mid	2429	1646	0.678	9.25	0.054
NE-1C	Bot	2429	1583	0.652	12.26	0.098
NW-1A	Top	2429	1102	0.454	6.88	0.149
NW-1A	Bot	2429	1128	0.464	7.20	0.120
NW-1B	Top	2429	970	0.399	4.41	0.122
NW-1B	Bot	2429	1096	0.451	5.91	0.136
NW-1C	Top	2429	1390	0.572	7.20	0.121
NW-1C	Mid	2429	862	0.355	5.38	0.106
NW-1C	Bot	2429	1184	0.487	7.31	0.125
NE-1AA	Top	2429	1558	0.641	6.02	0.092
NE-1AA	Bot	2429	1289	0.531	7.63	0.117
NE-1AB	Top	2429	1494	0.615	6.34	0.081
NE-1AB	Bot	2429	1527	0.629	7.63	0.113
NE-1AC	Top	2429	1356	0.558	6.77	0.095
NE-1AC	Mid	2429	2041	0.840	11.51	0.084
NE-1AC	Bot	2429	1514	0.623	9.25	0.091
NC-2AA	Top	2429	1343	0.553	8.39	0.085
NC-2AA	Bot	2429	1317	0.542	6.24	0.087

ID	Position	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
NC-2AB	Top	2429	999	0.411	5.48	0.143
NC-2AB	Bot	2429	1164	0.479	5.91	0.135
NC-2AC	Top	2429	1036	0.426	6.24	0.120
NC-2AC	Bot	2429	1160	0.477	7.96	0.113

Table 2: Results of manual point counts of each specimen (cylinder or core).

ID	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
SW-1A	4859	2574	0.530	7.69	0.070
SW-1B	4859	2910	0.599	6.72	0.078
SW-1C	7288	4083	0.560	8.96	0.073
SE-1A	4859	2213	0.455	5.81	0.088
SE-1B	4859	2361	0.486	6.13	0.090
SE-1C	7288	4104	0.563	6.92	0.050
SW-3A	4859	4061	0.836	10.75	0.035
SW-3B	4584	3175	0.693	9.29	0.042
SW-3C	4859	3181	0.655	9.62	0.046
SW-2A	4859	2894	0.596	8.55	0.049
SW-2B	4859	3200	0.659	6.94	0.050
SW-2C	7288	4301	0.590	6.63	0.049
NC-1A	4859	2323	0.478	5.86	0.101
NC-1B	4859	2331	0.480	5.05	0.094
NC-1C	7288	4360	0.598	8.85	0.065
SE-2A	4859	1947	0.401	6.40	0.128
SE-2B	4859	2223	0.458	6.02	0.094
SE-2C	7014	2465	0.351	5.77	0.163
NE-2A	4859	3301	0.679	10.16	0.043
NE-2B	4859	2908	0.599	7.20	0.068
NE-2C	7288	3403	0.467	6.99	0.095
NE-4A	4859	3002	0.618	4.52	0.053
NE-4B	4859	2651	0.546	8.76	0.072
NE-4C	7288	4236	0.581	7.31	0.058
NE-3A	4859	2738	0.564	6.18	0.074
NE-3B	4859	2121	0.437	4.14	0.113
NE-3C	7288	3445	0.473	7.35	0.090
NE-1A	4859	2109	0.434	5.97	0.065
NE-1B	4859	1944	0.400	4.52	0.122
NE-1C	7288	4102	0.563	8.78	0.062
NW-1A	4859	2230	0.459	7.04	0.112
NW-1B	4859	2066	0.425	5.16	0.118
NW-1C	7288	3439	0.472	6.63	0.096
NC-2A	4859	2220	0.457	10.43	0.084
NC-2B	4859	2675	0.551	8.92	0.080
NC-2C	7199	4178	0.580	10.63	0.066
NE-1AA	4859	2847	0.586	6.83	0.067
NE-1AB	4859	3021	0.622	6.99	0.060
NE-1AC	7288	4911	0.674	9.18	0.051
NC-2AA	4859	2660	0.547	7.31	0.060
NC-2AB	4859	2163	0.445	5.70	0.119
NC-2AC	4859	2196	0.452	7.10	0.099

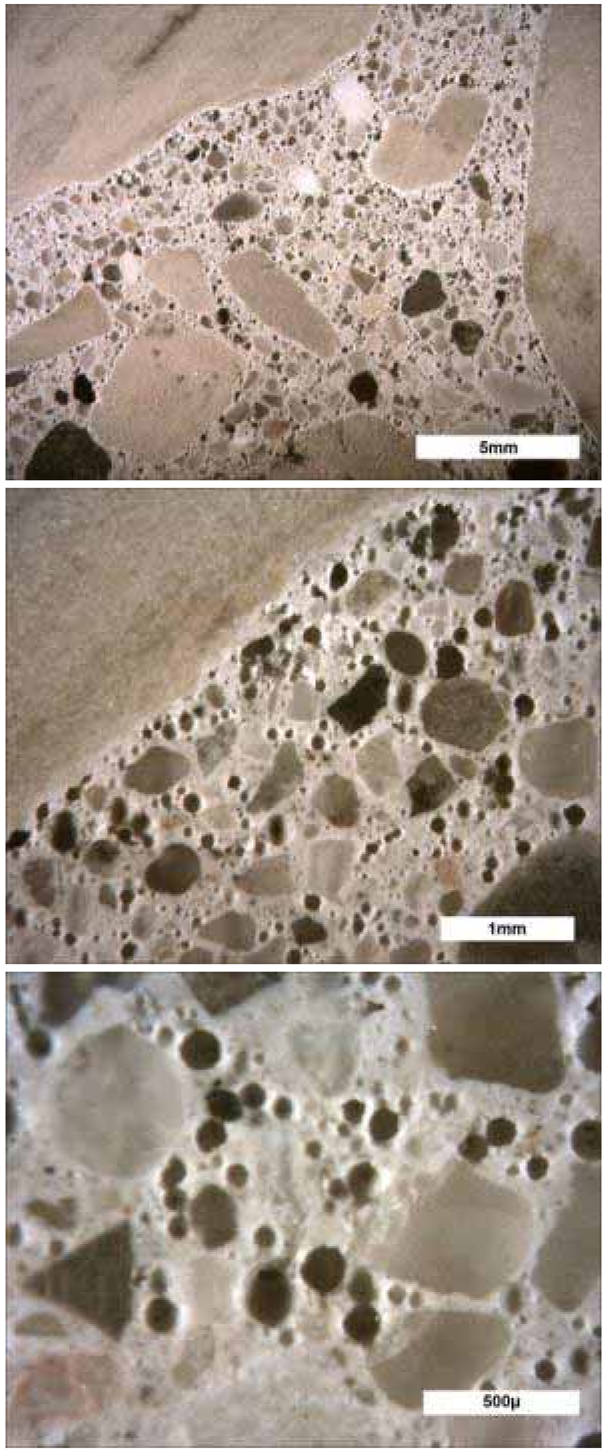


Figure 5: Micrographs of SW-1A.

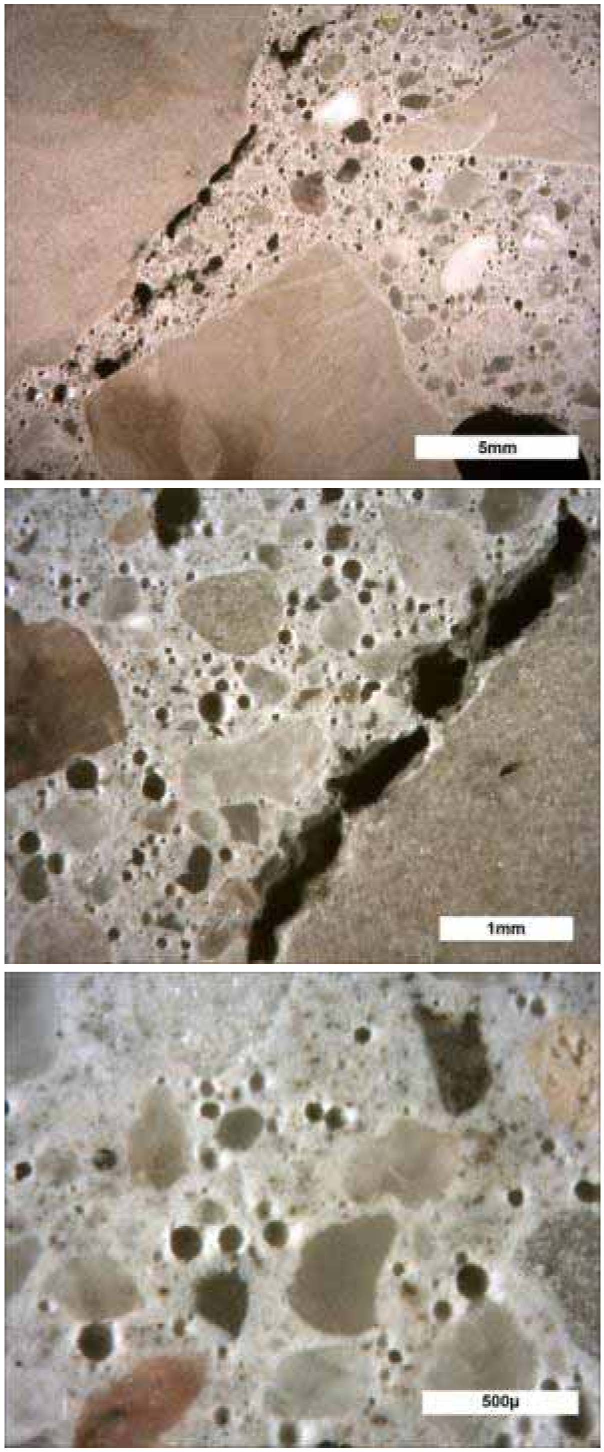


Figure 6: Micrographs of SW-1B.

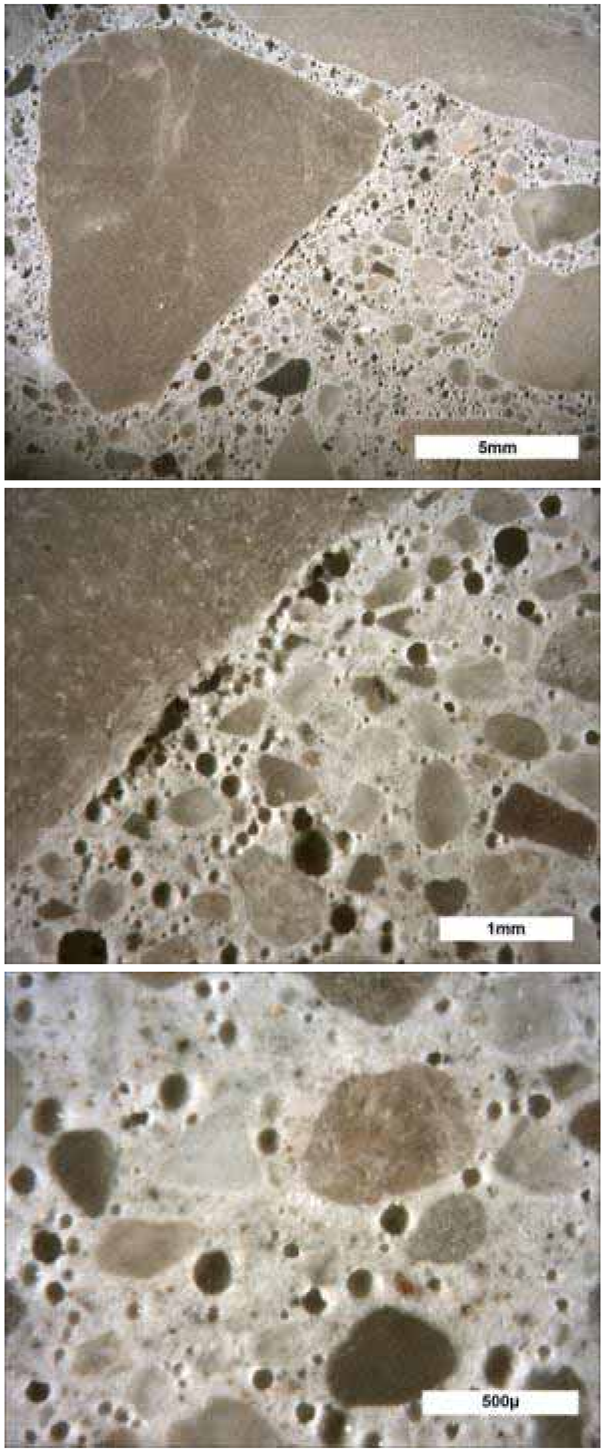


Figure 7: Micrographs of SW-1C.

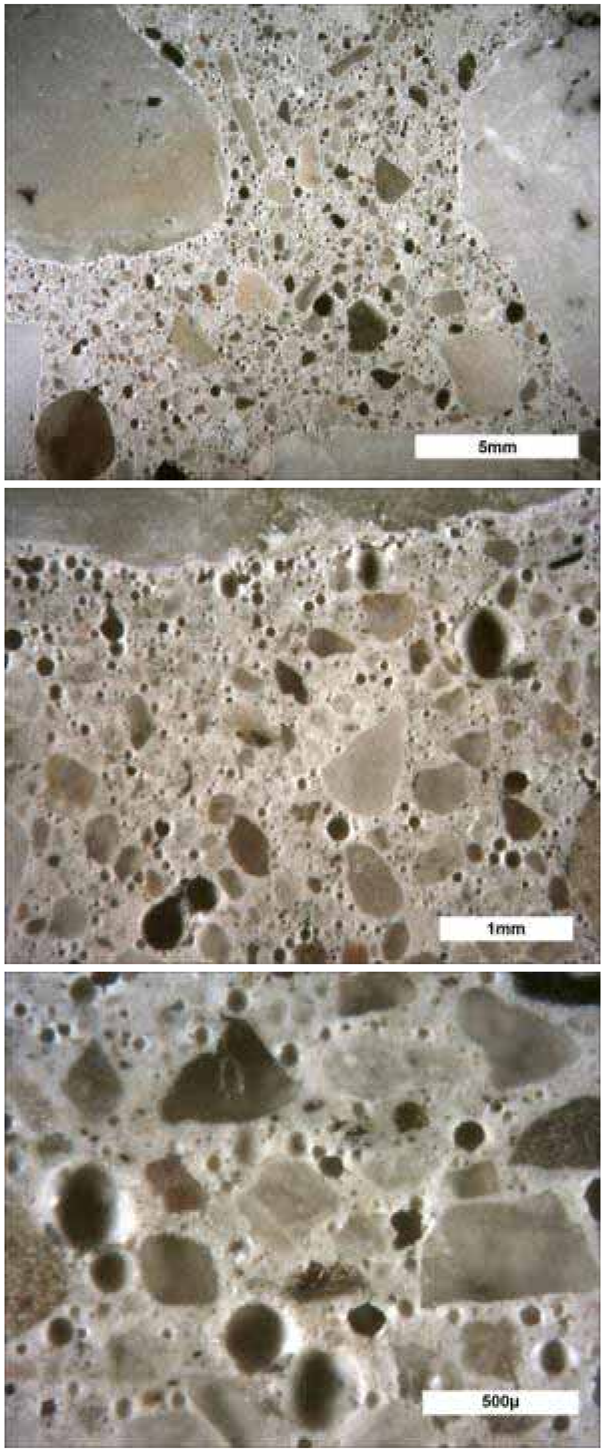


Figure 8: Micrographs of SE-1A.

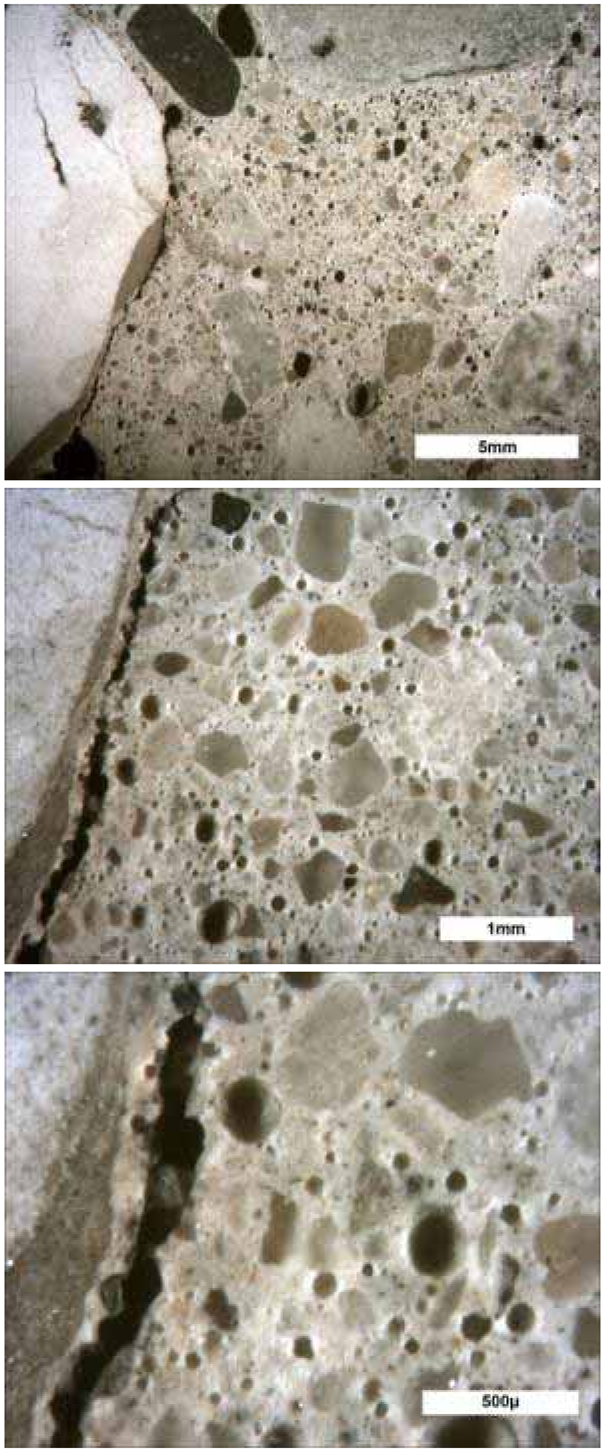


Figure 9: Micrographs of SE-1B.

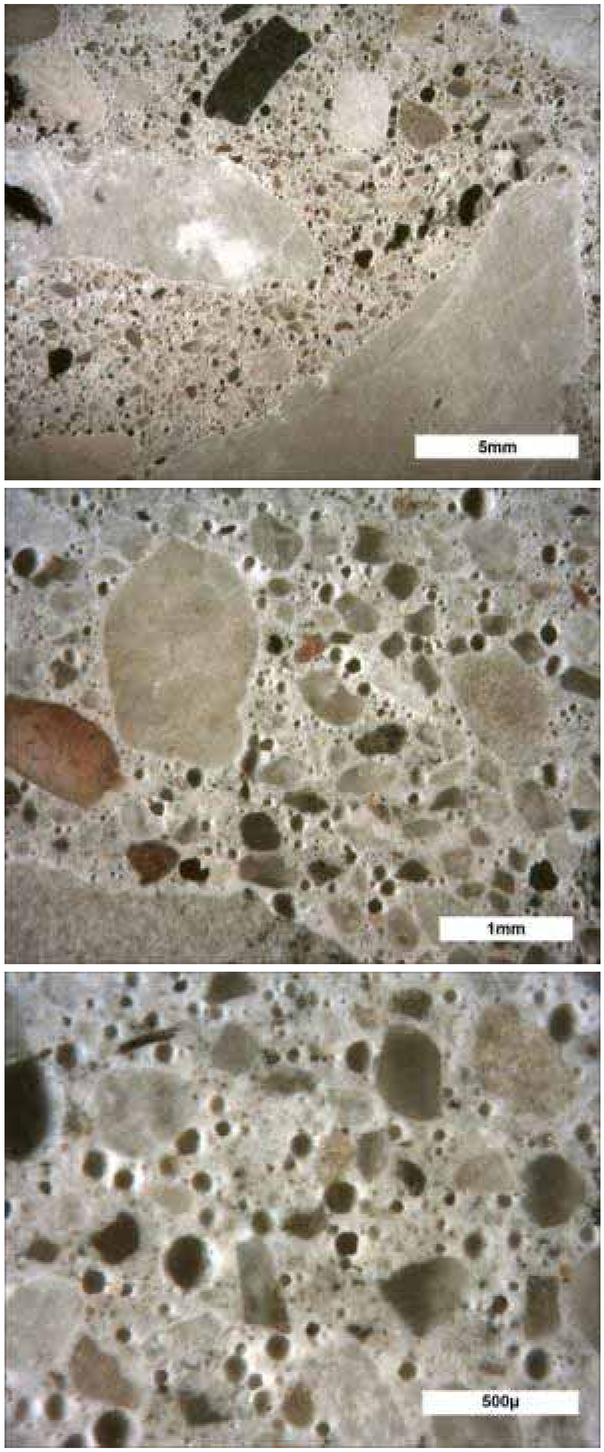


Figure 10: Micrographs of SE-1C.

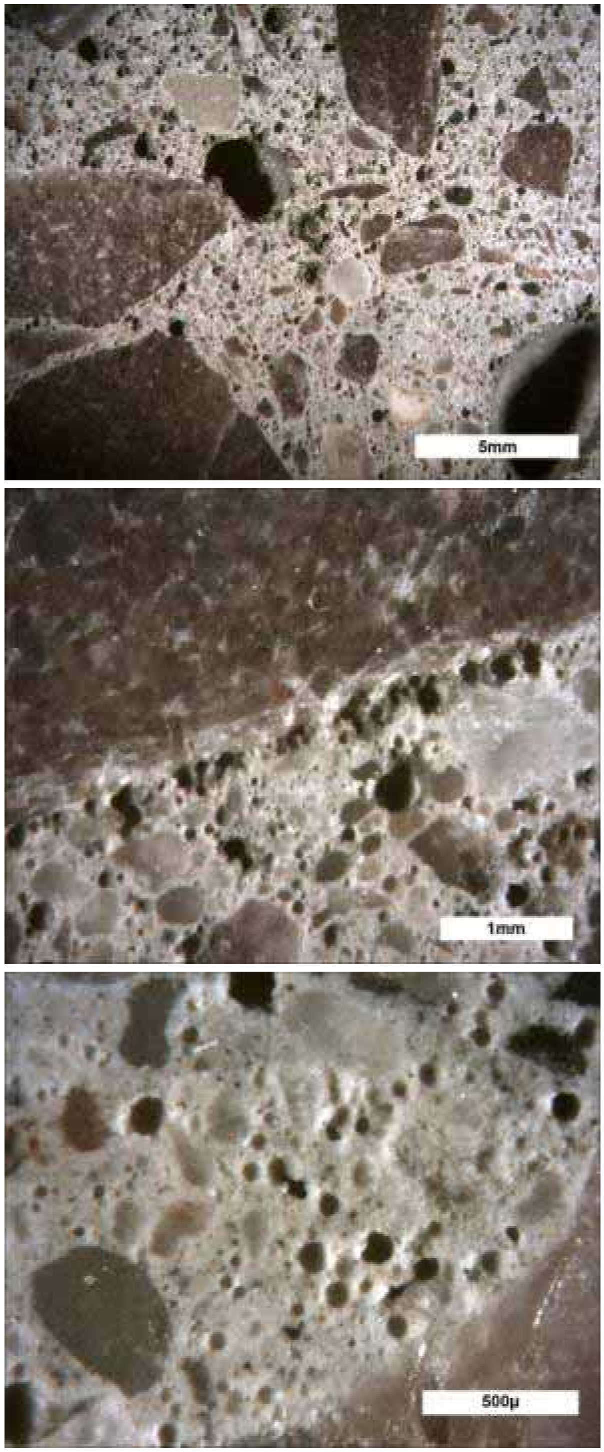


Figure 11: Micrographs of SW-3A.

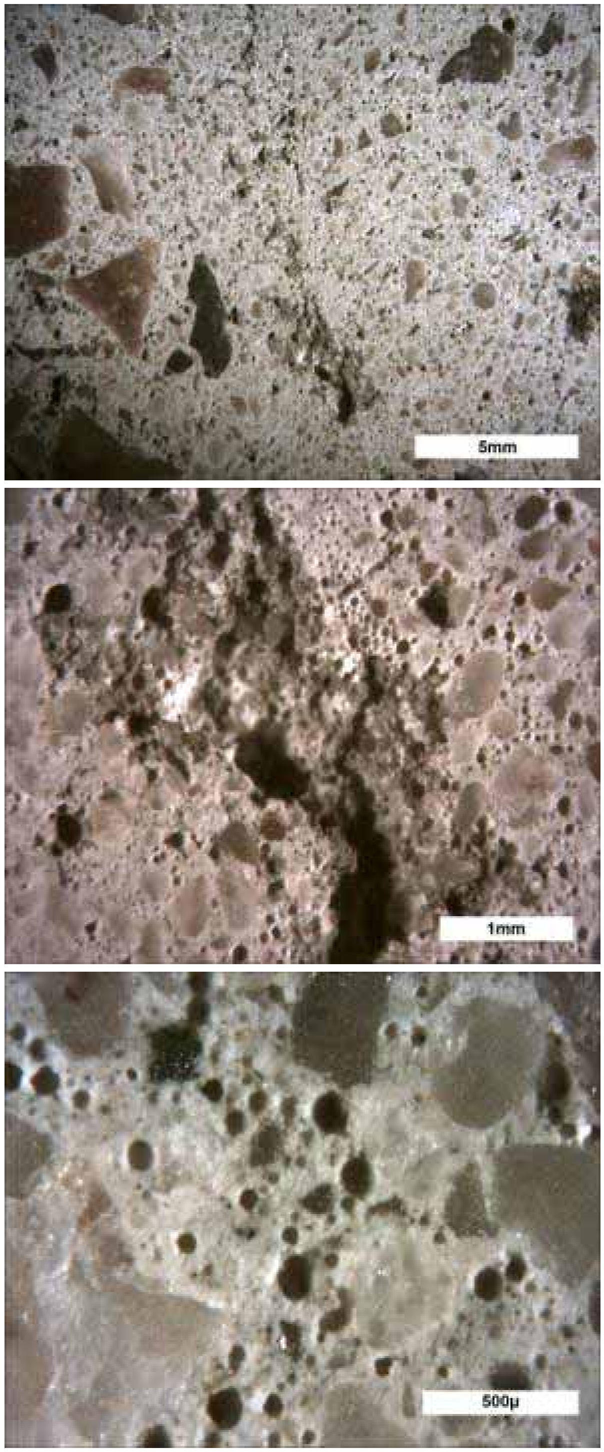


Figure 12: Micrographs of SW-3B.

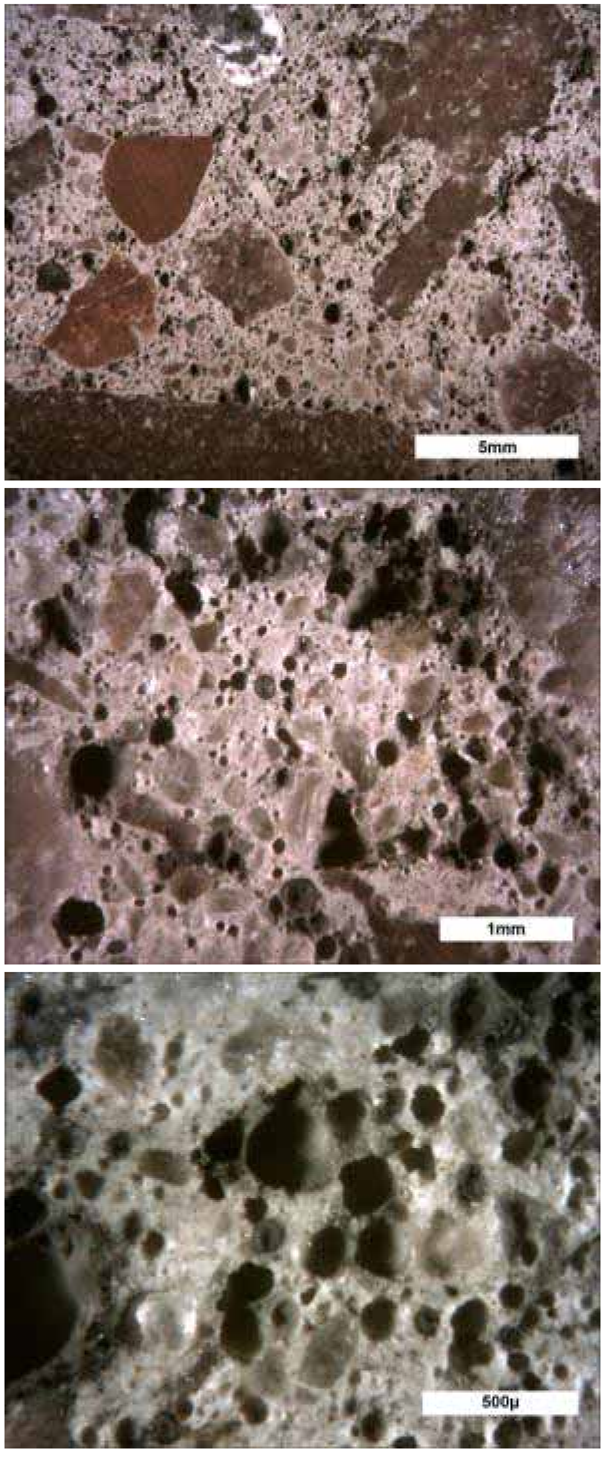


Figure 13: Micrographs of SW-3C.

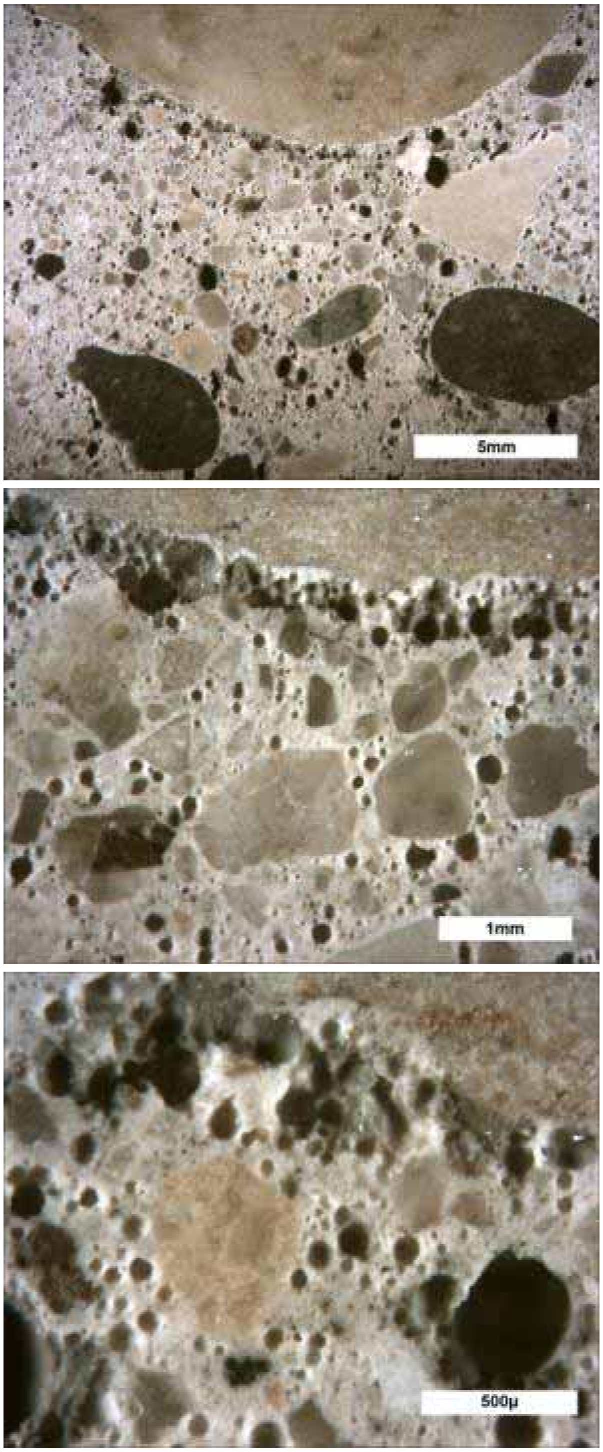


Figure 14: Micrographs of SW-2A.

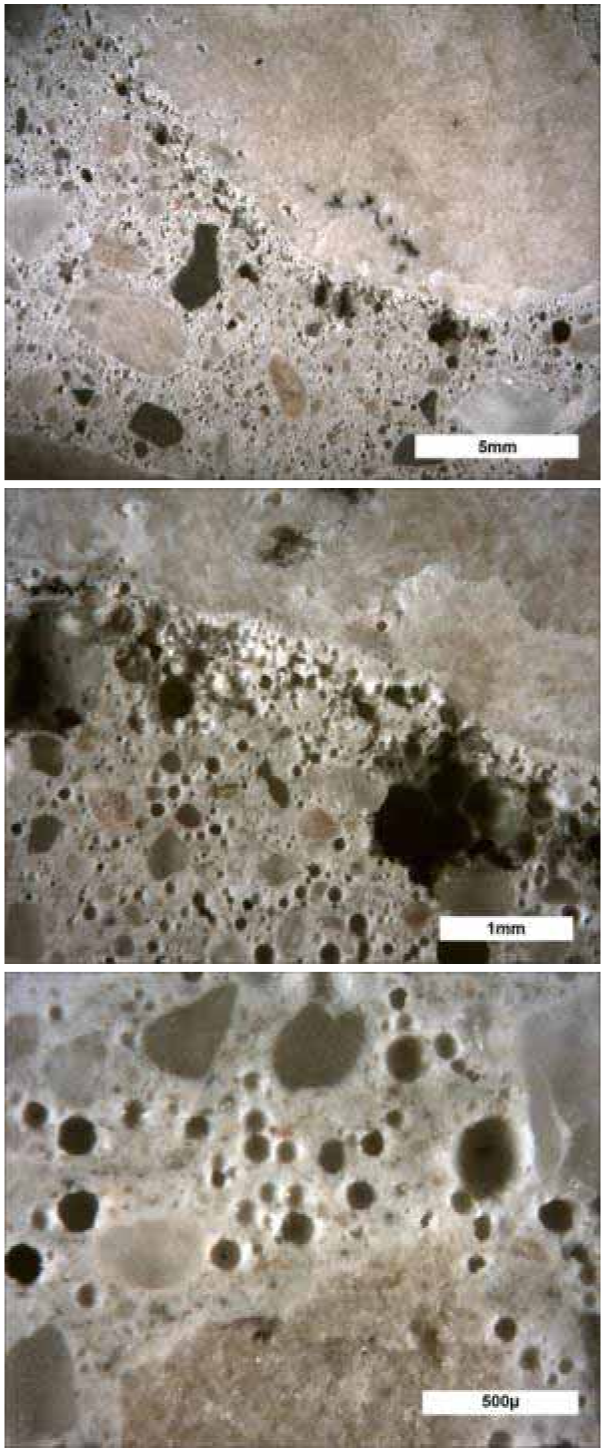


Figure 15: Micrographs of SW-2B.

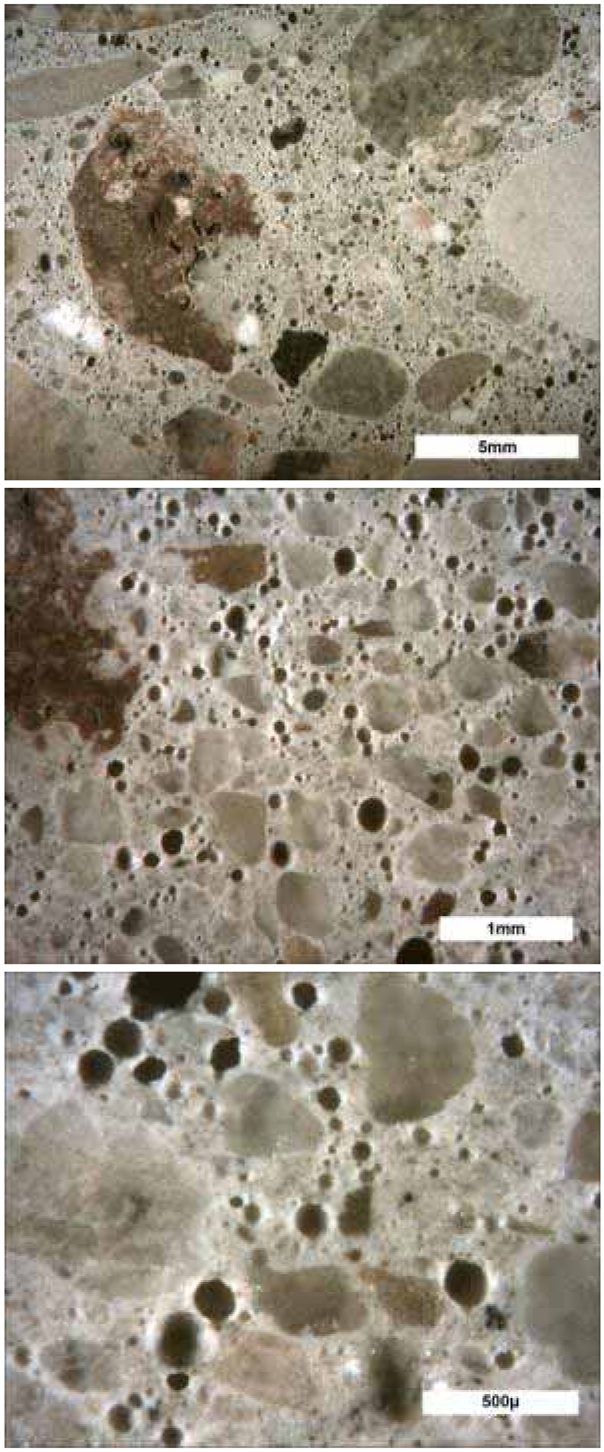


Figure 16: Micrographs of SW-2C.

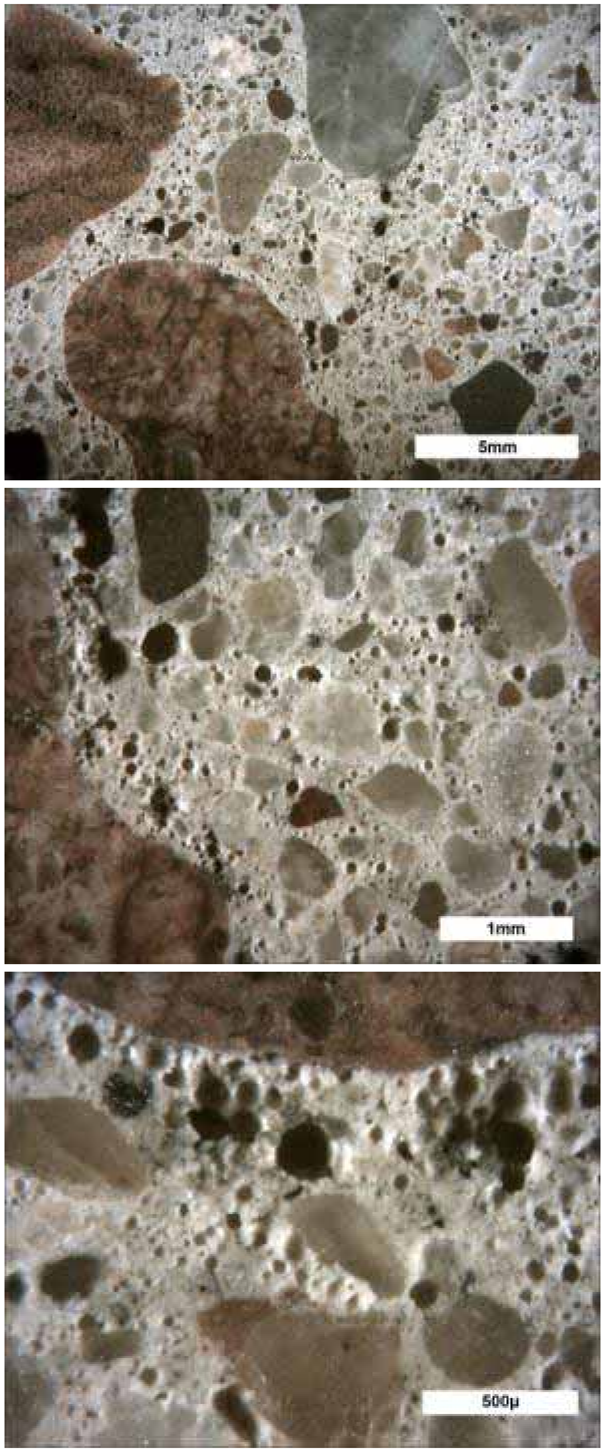


Figure 17: Micrographs of NC-1A.

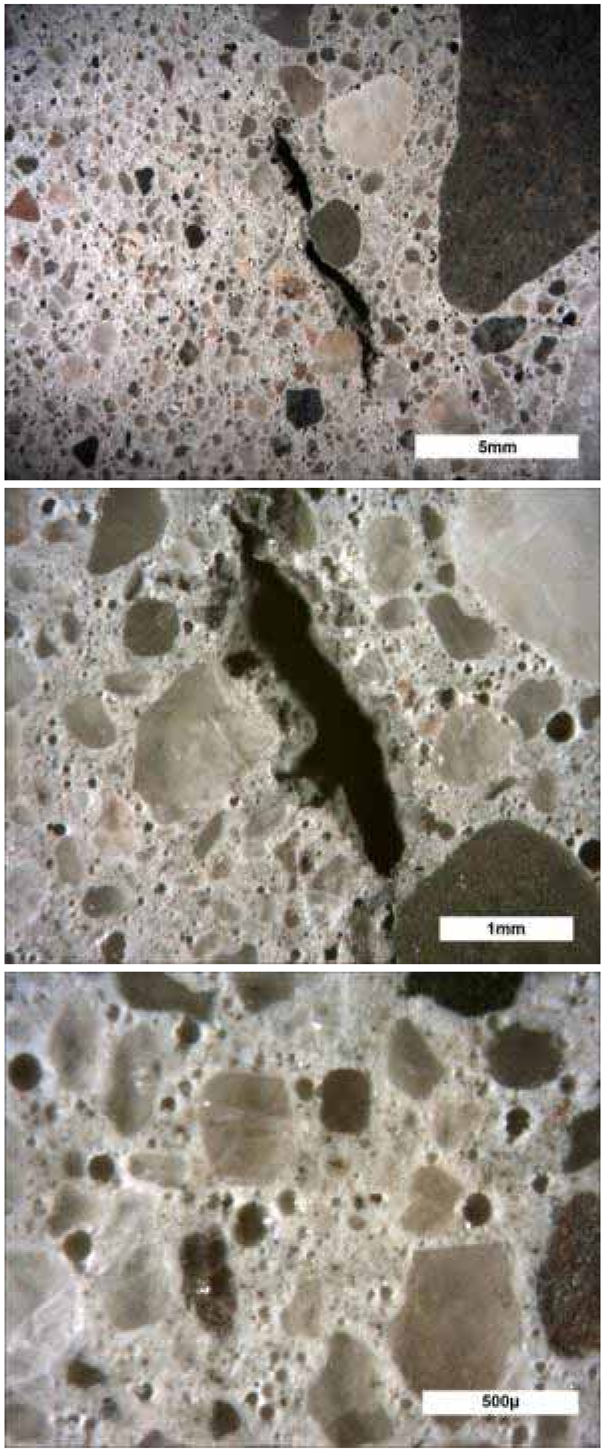


Figure 18: Micrographs of NC-1B.

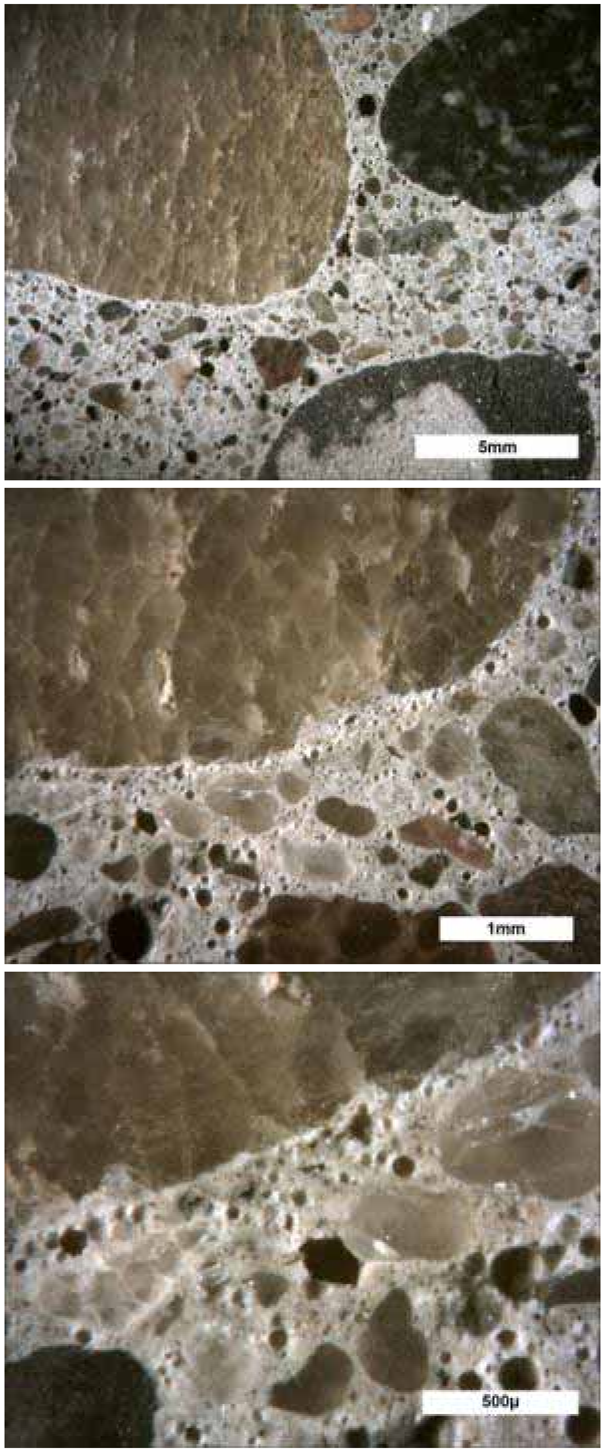


Figure 19: Micrographs of NC-1C.

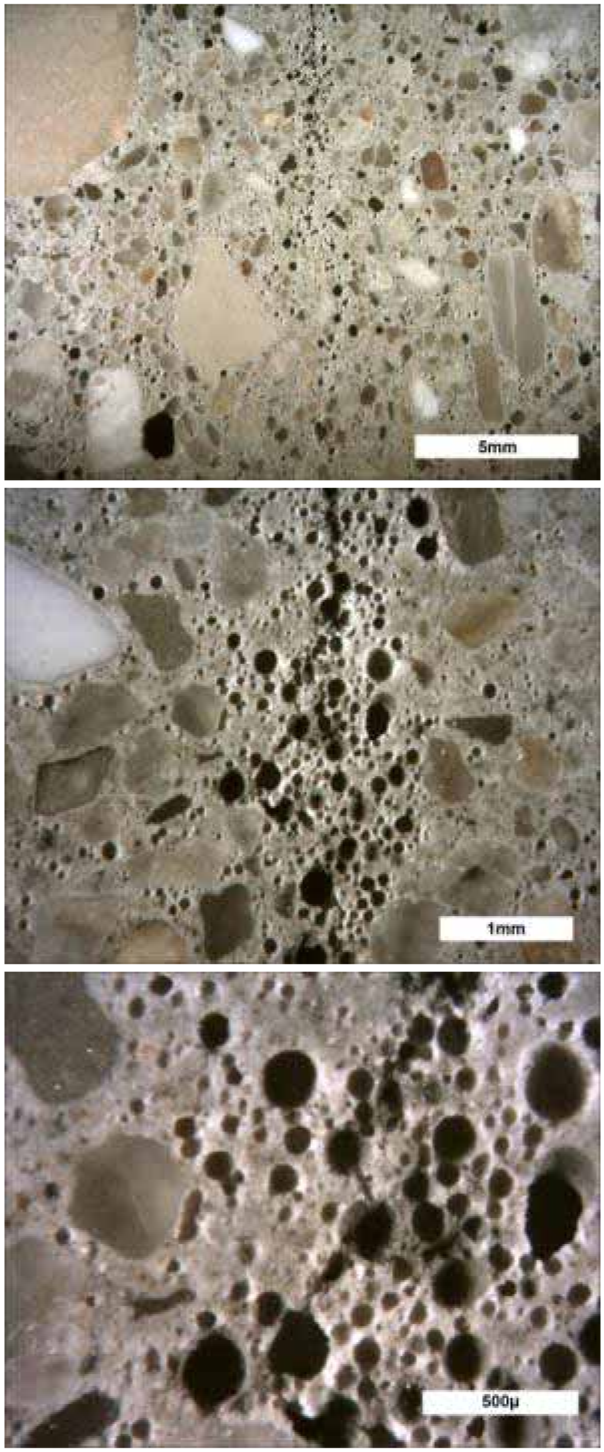


Figure 20: Micrographs of SE-2A.

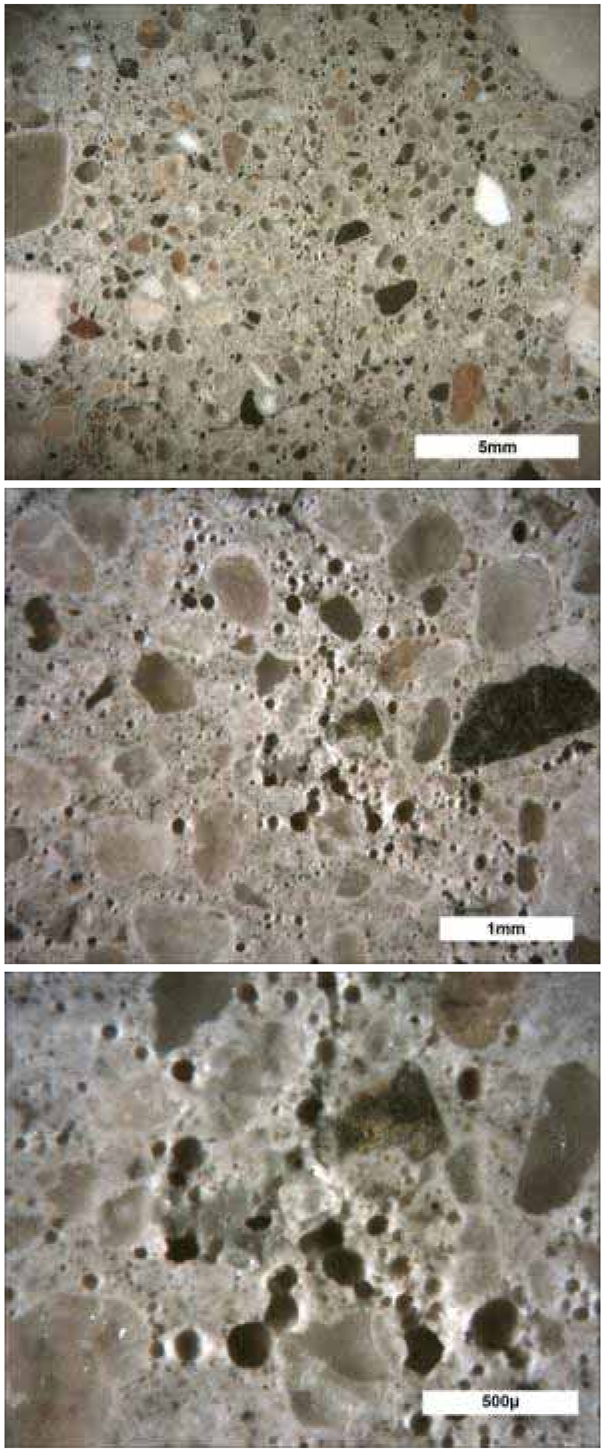


Figure 21: Micrographs of SE-2B.

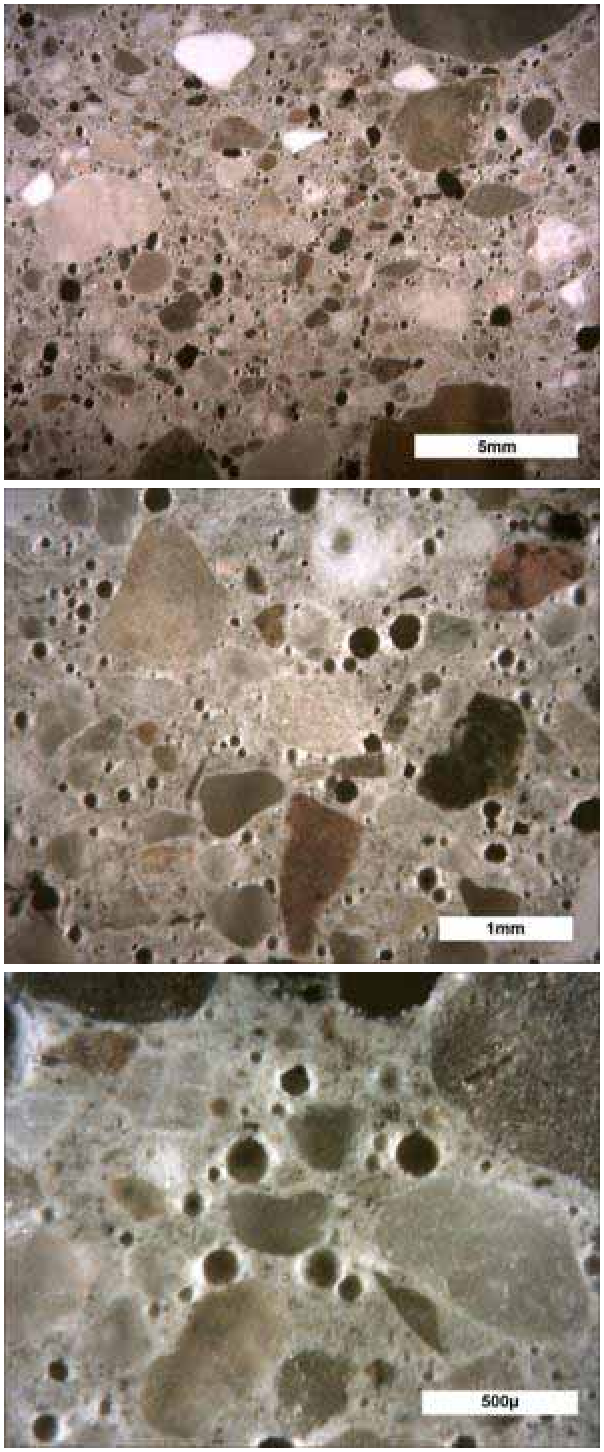


Figure 22: Micrographs of SE-2C.

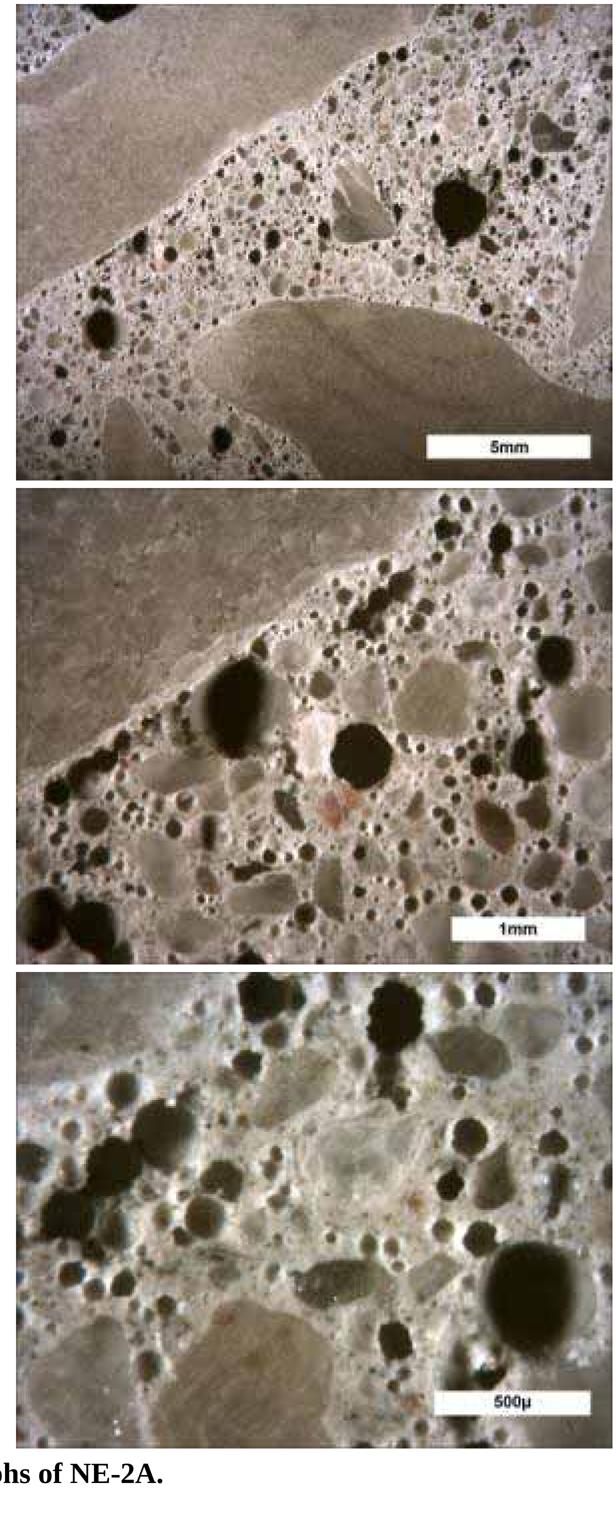


Figure 23: Micrographs of NE-2A.

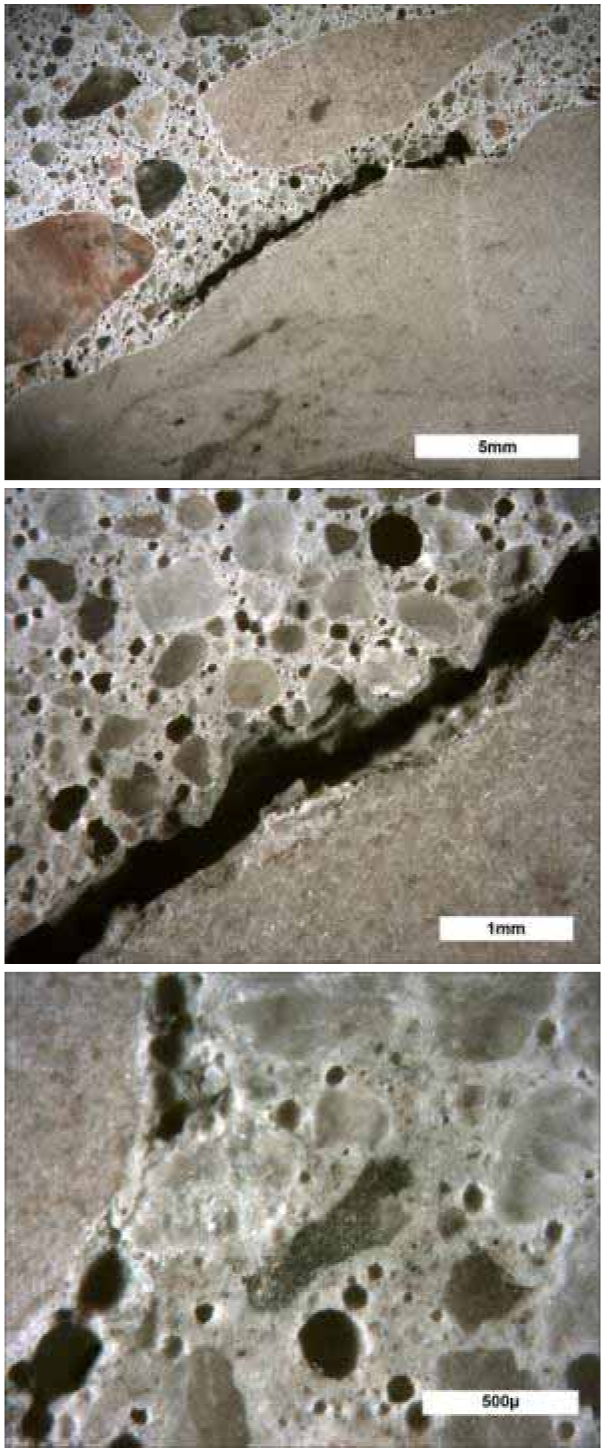


Figure 24: Micrographs of NE-2B.

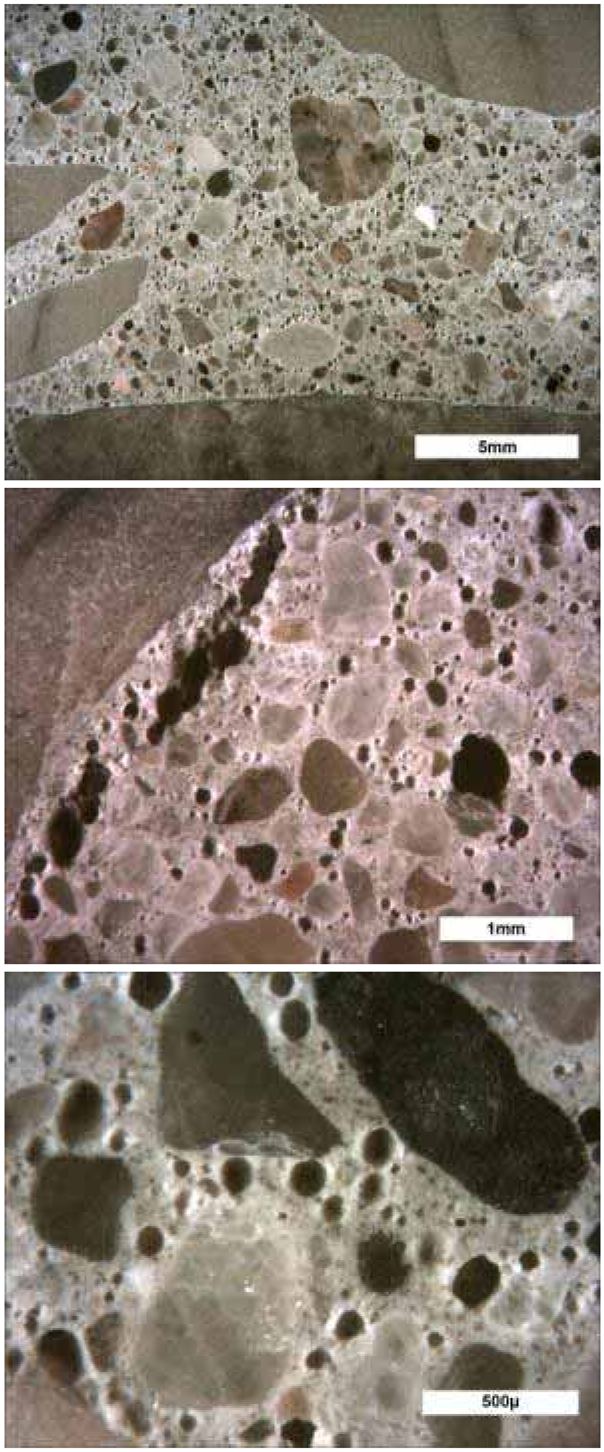


Figure 25: Micrographs of NE-2C.

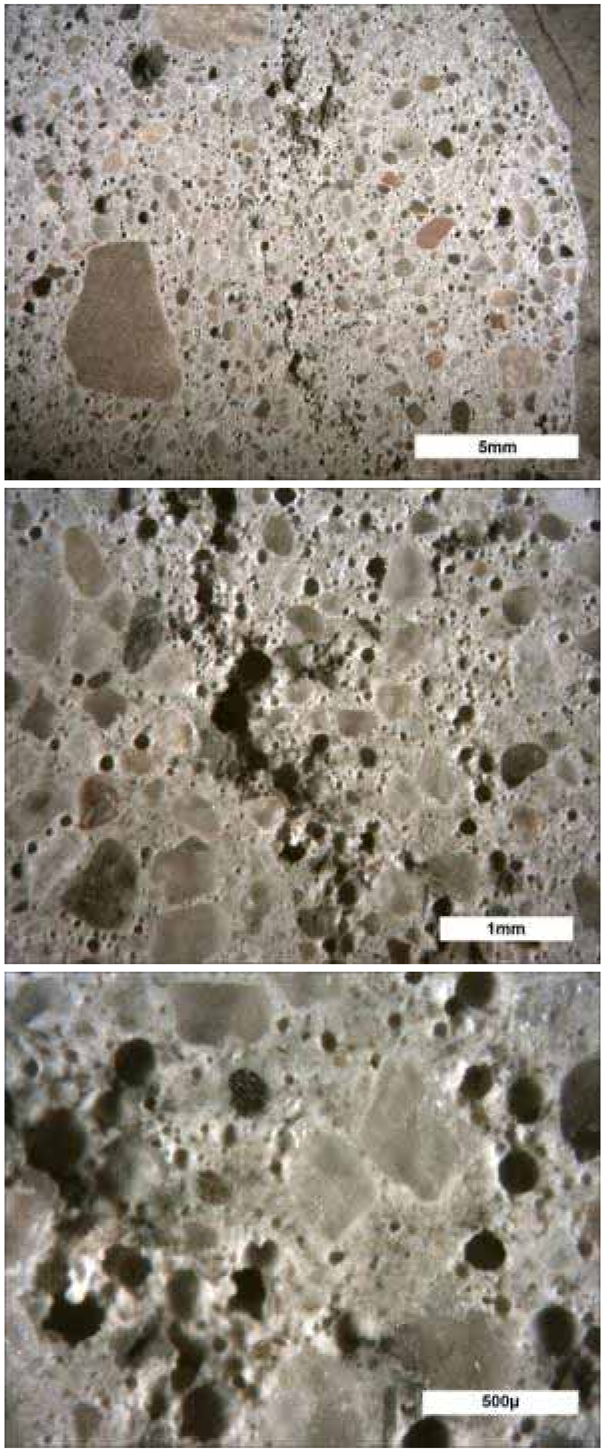


Figure 26: Micrographs of NE-4A.

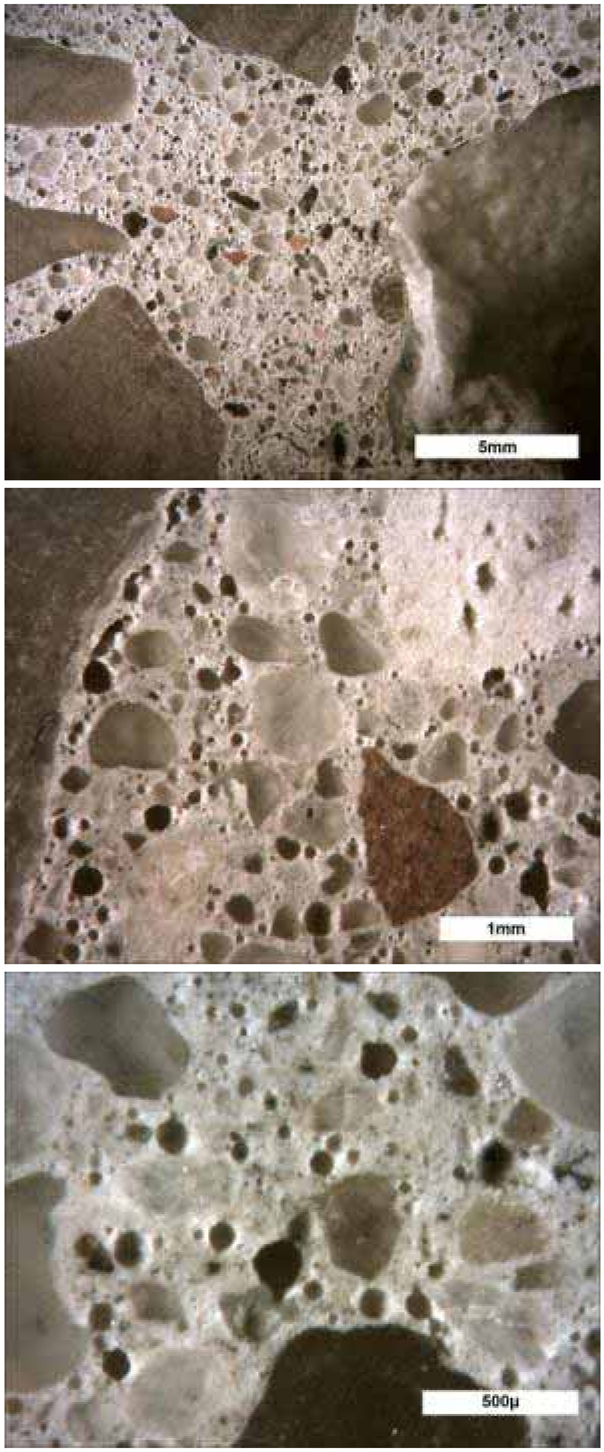


Figure 27: Micrographs of NE-4B.

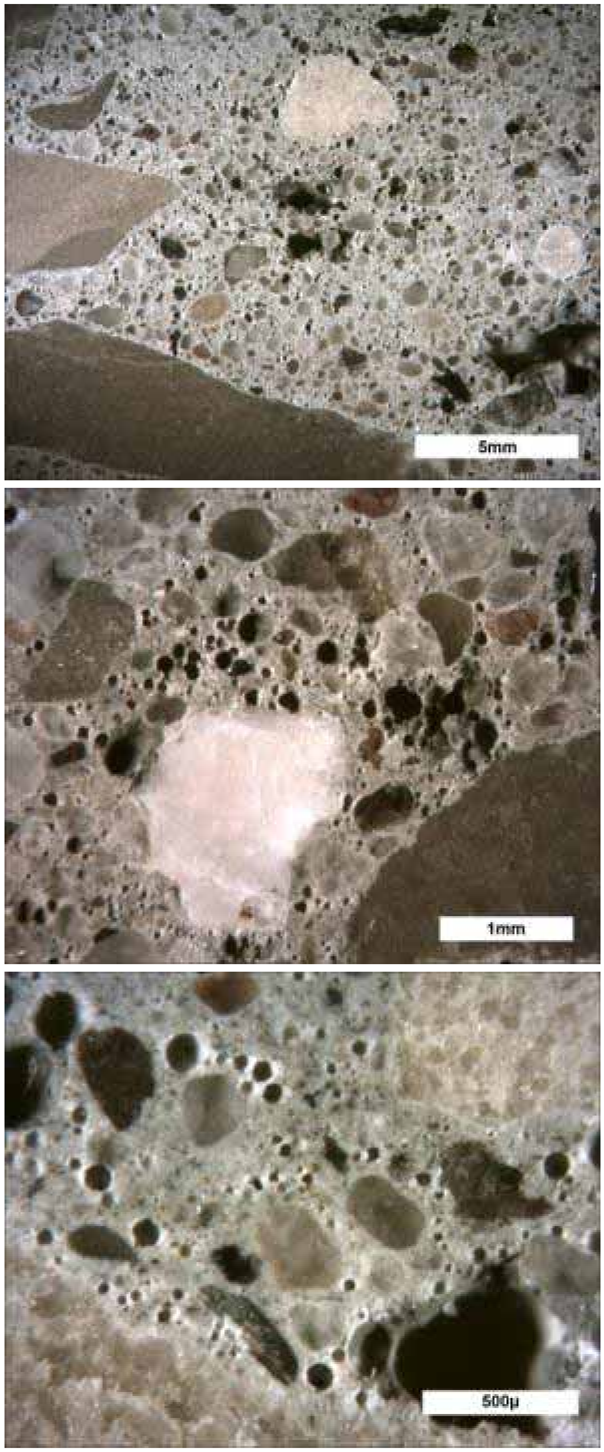


Figure 28: Micrographs of NE-4C.

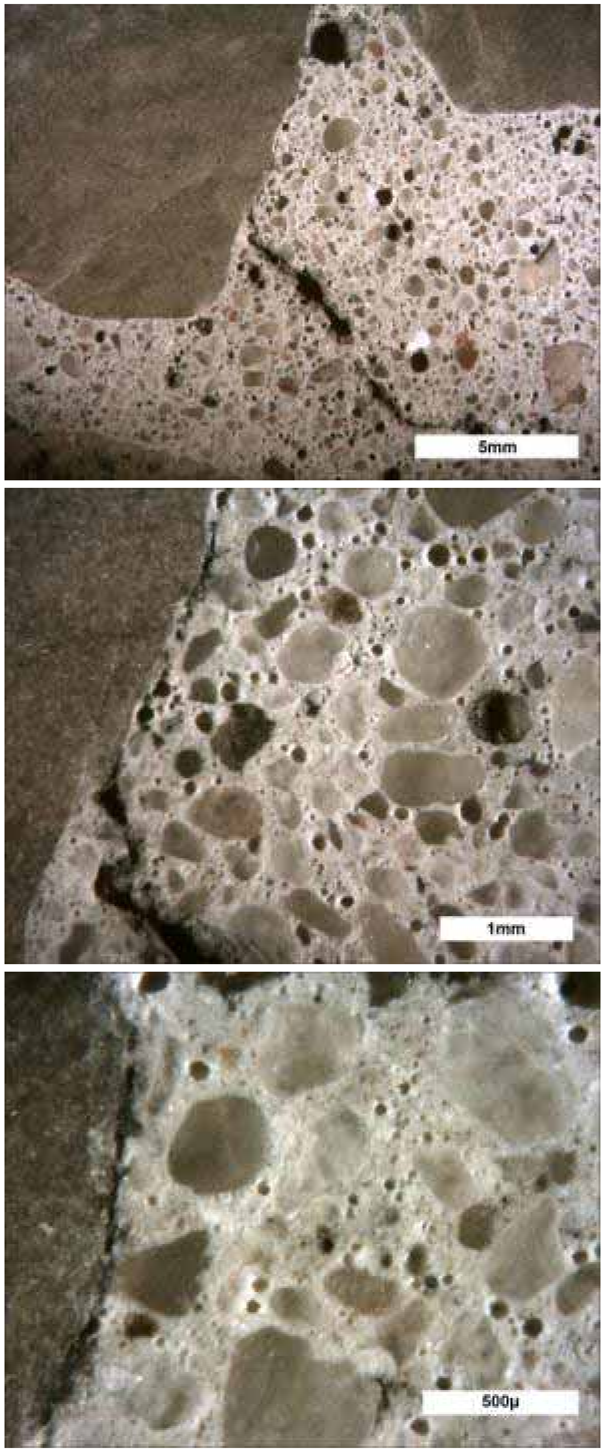


Figure 29: Micrographs of NE-3A.

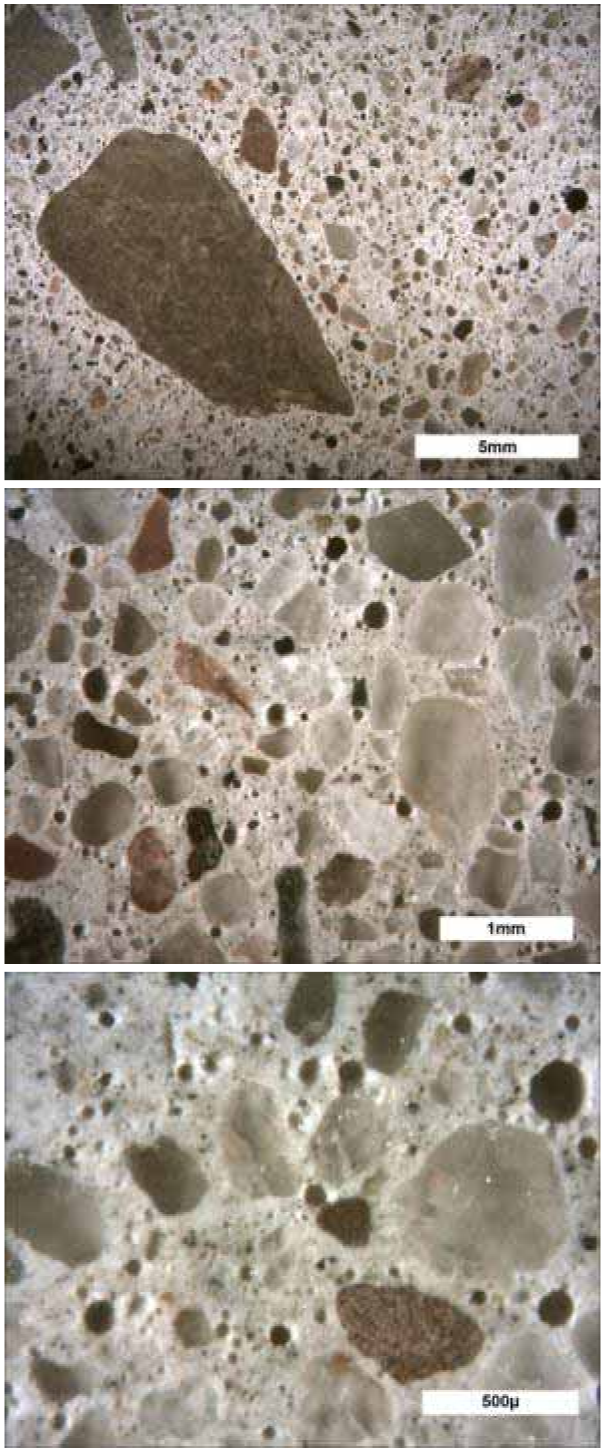


Figure 30: Micrographs of NE-3B.

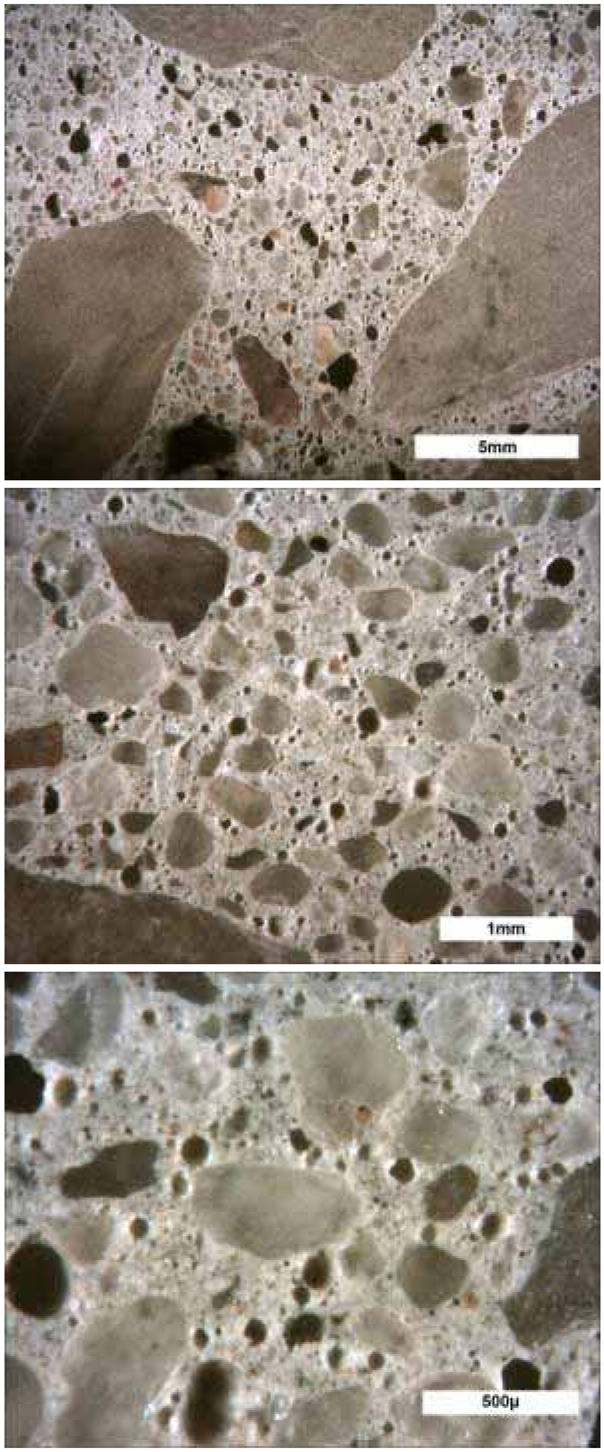


Figure 31: Micrographs of NE-3C.

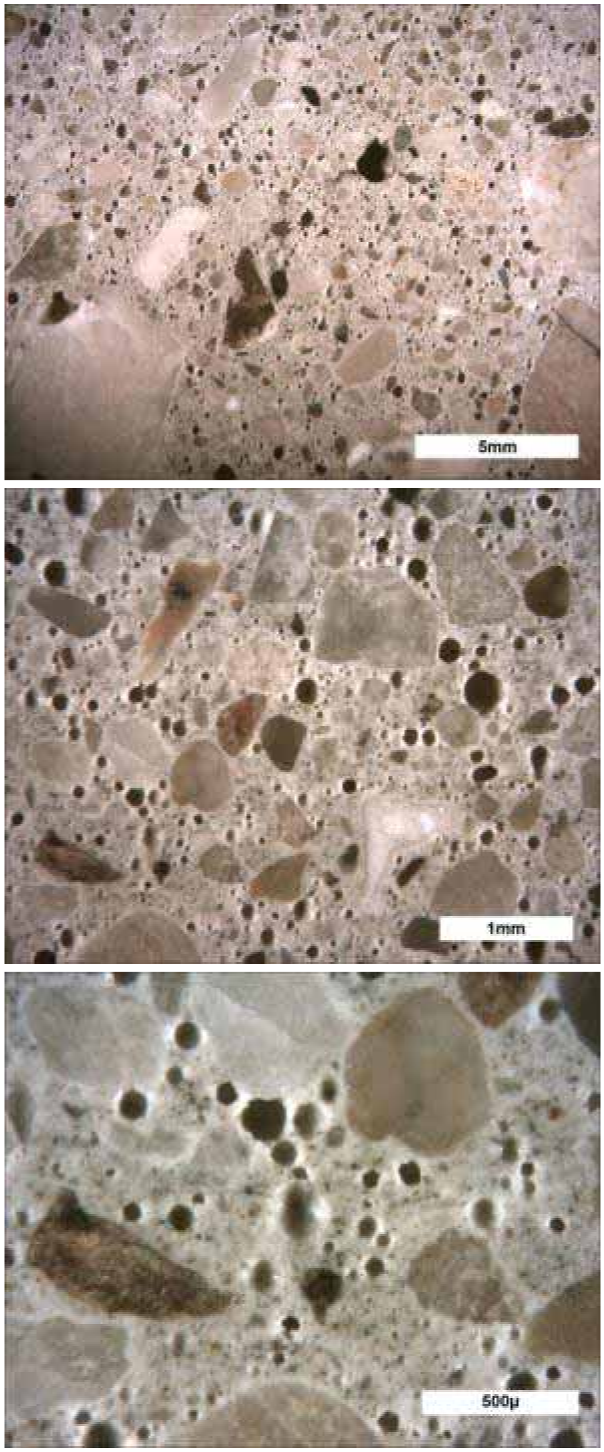


Figure 32: Micrographs of NE-1A.

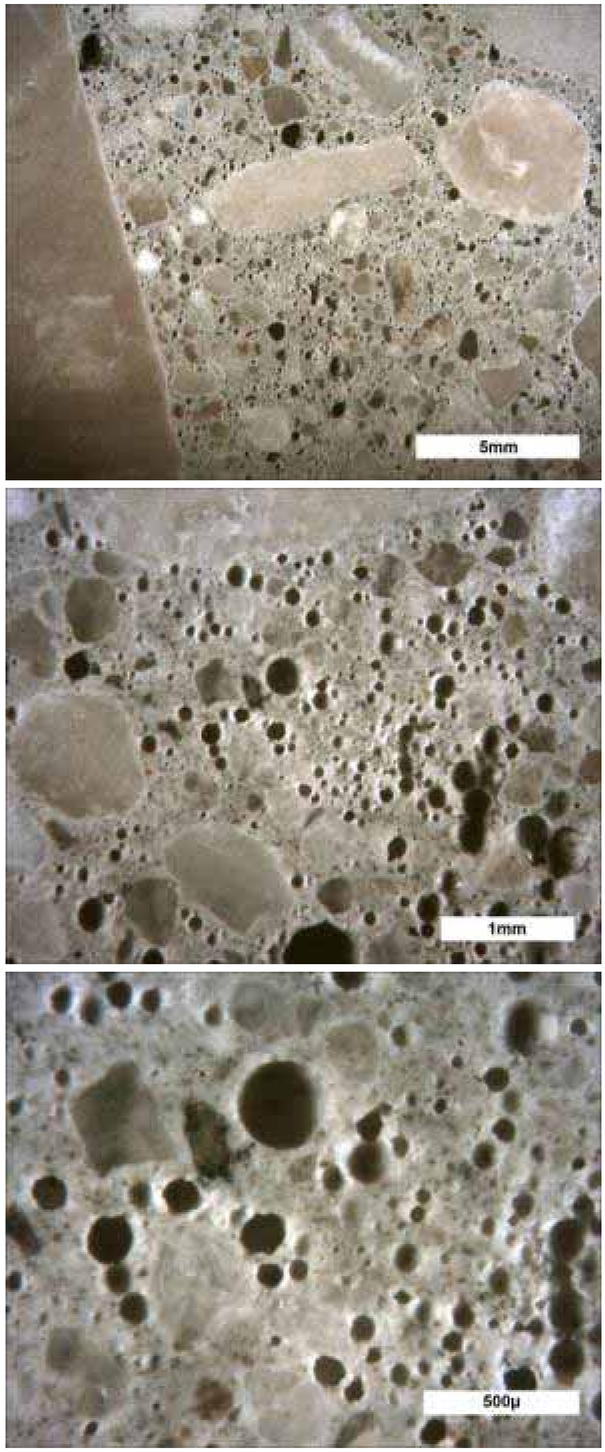


Figure 33: Micrographs of NE-1B.

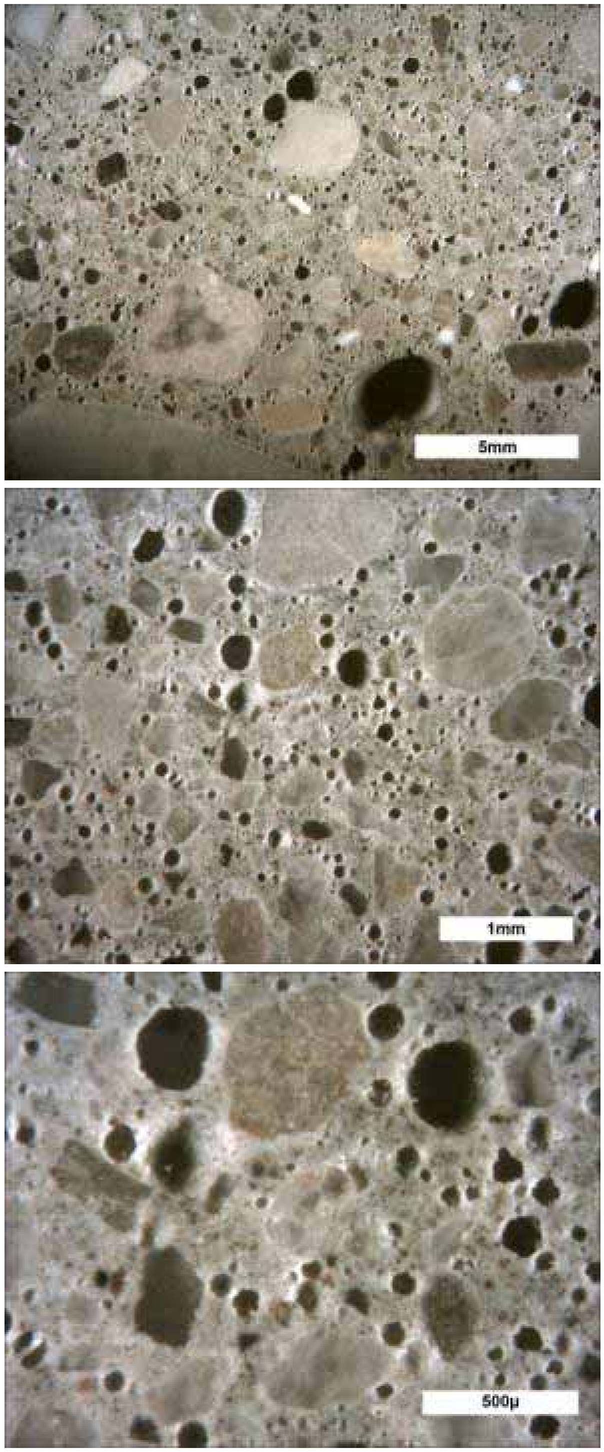


Figure 34: Micrographs of NE-1C.

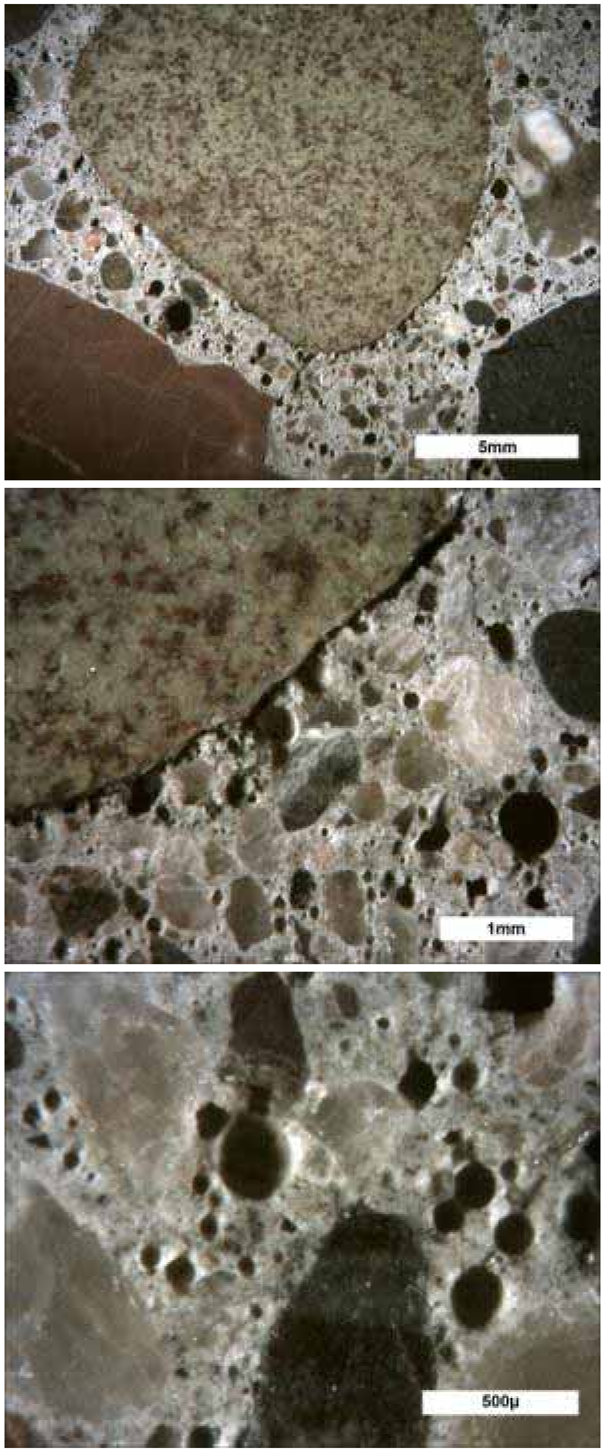


Figure 35: Micrographs of NW-1A.

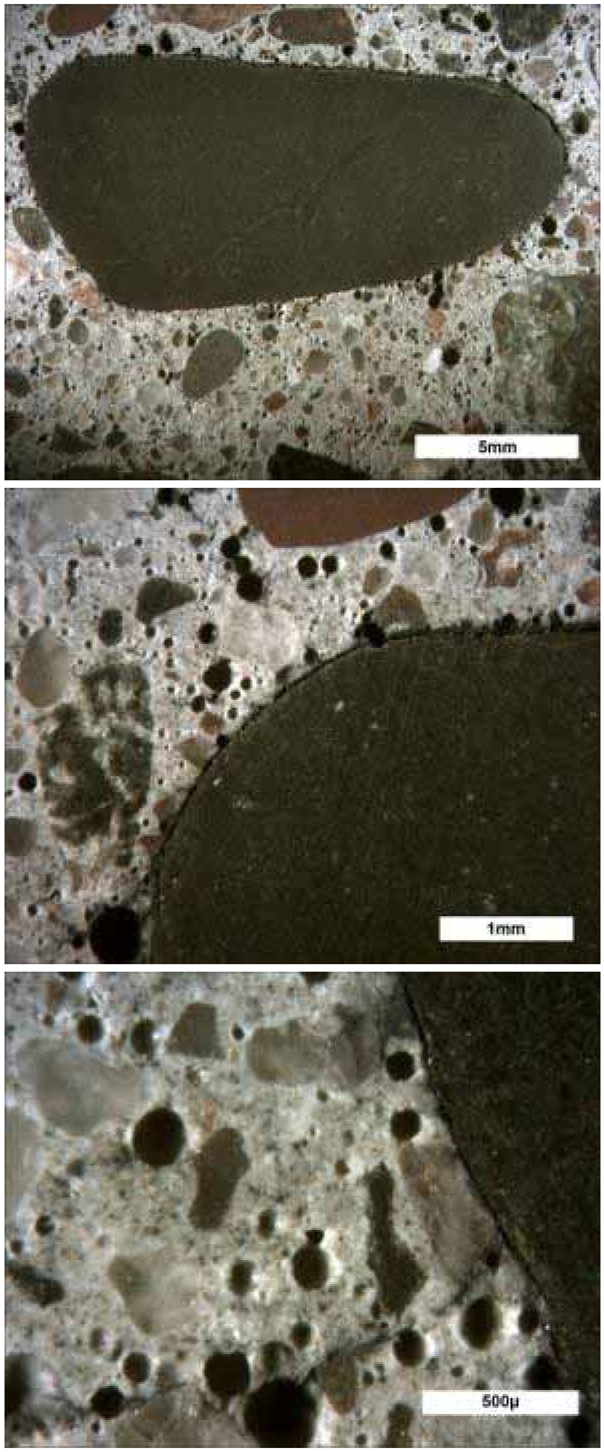


Figure 36: Micrographs of NW-1B.

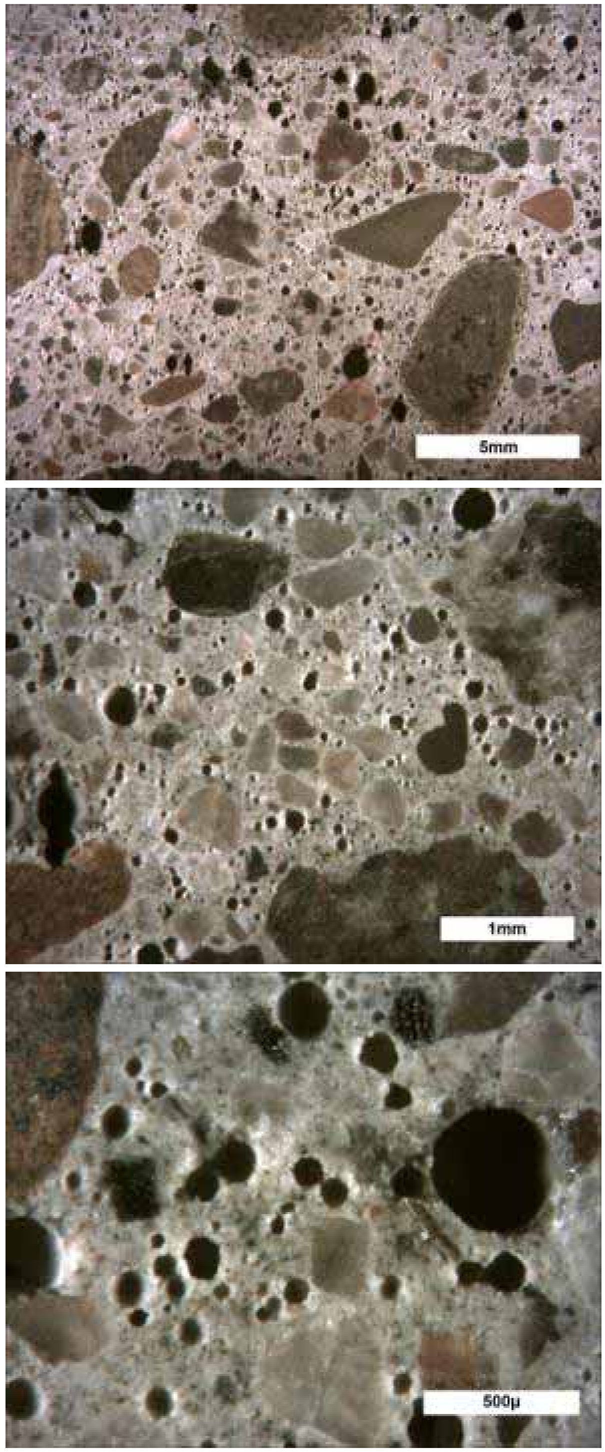


Figure 37: Micrographs of NW-1C.

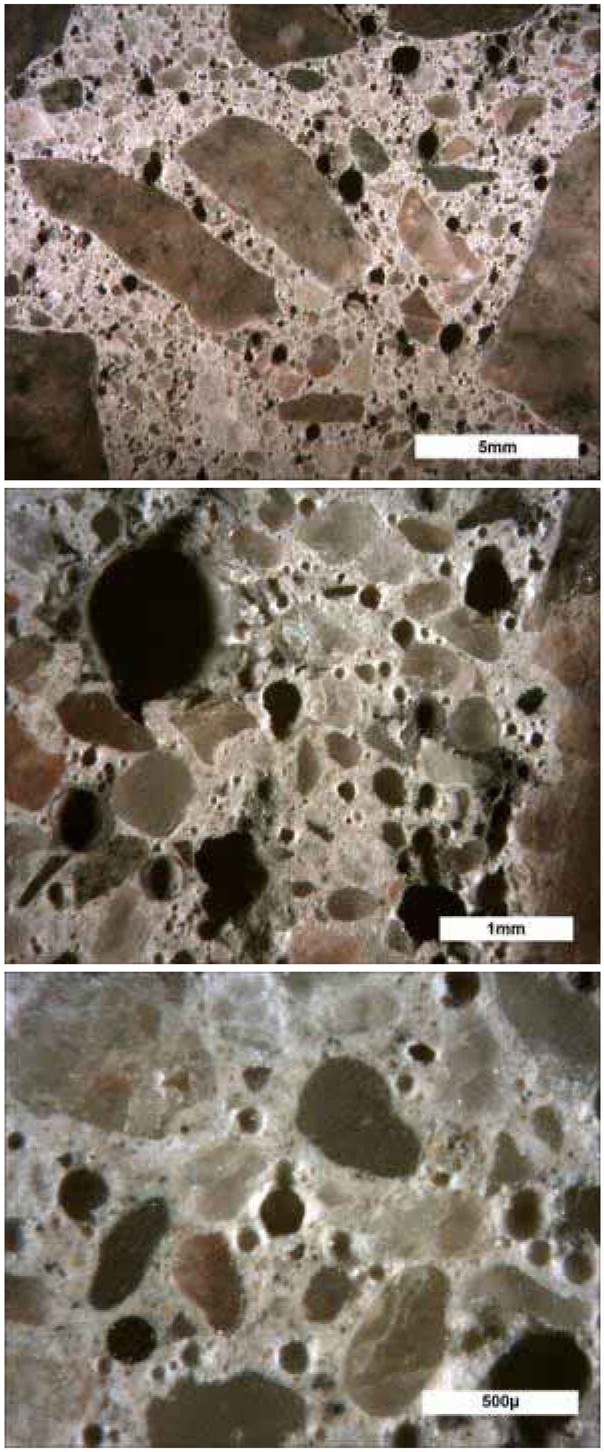


Figure 38: Micrographs of NC-2A.

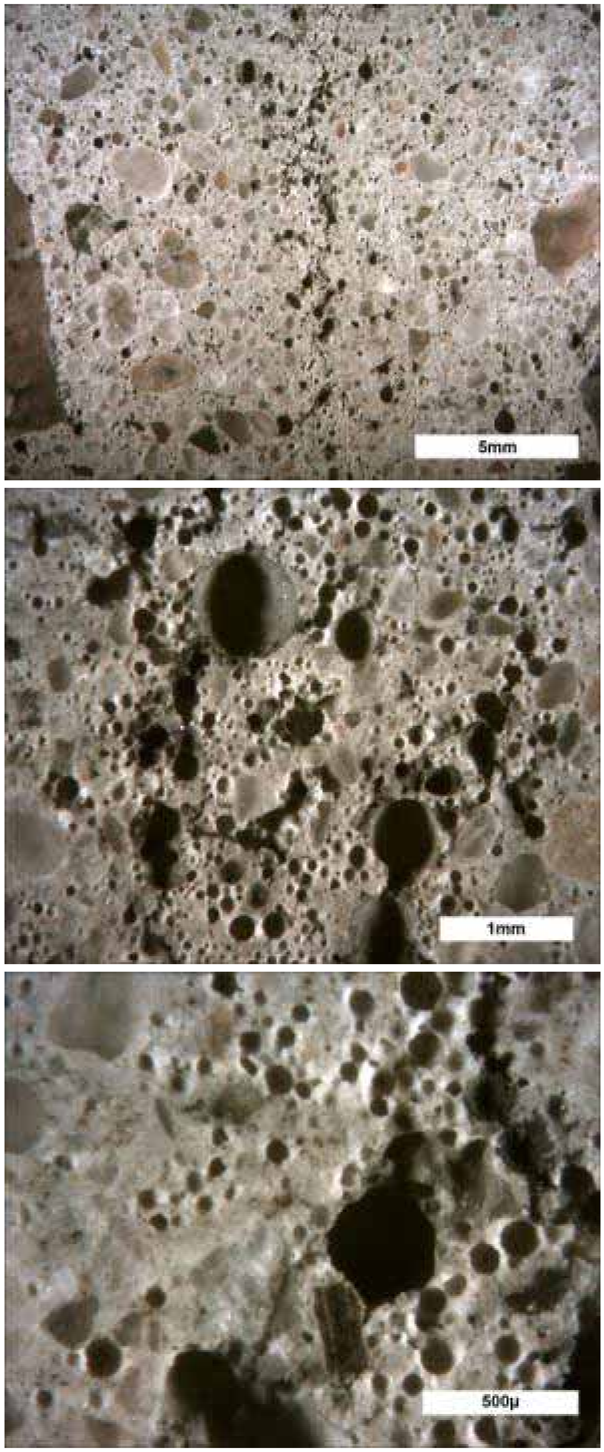


Figure 39: Micrographs of NC-2B.

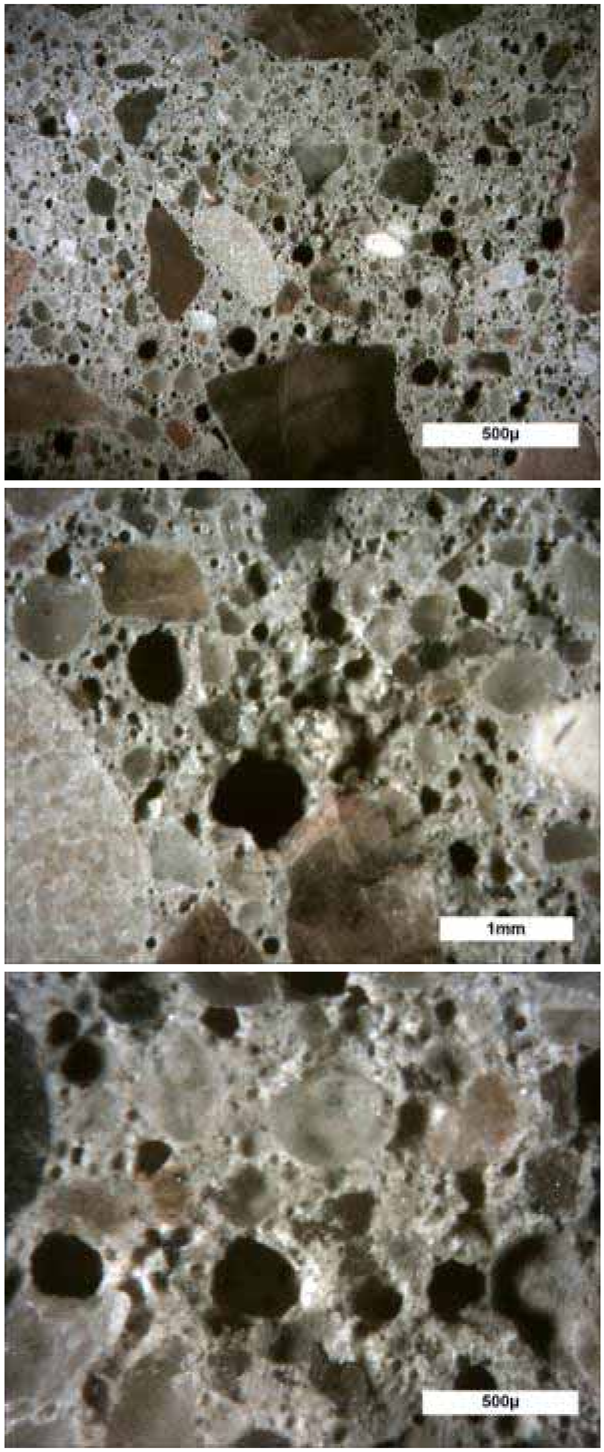


Figure 40: Micrographs of NC-2C.

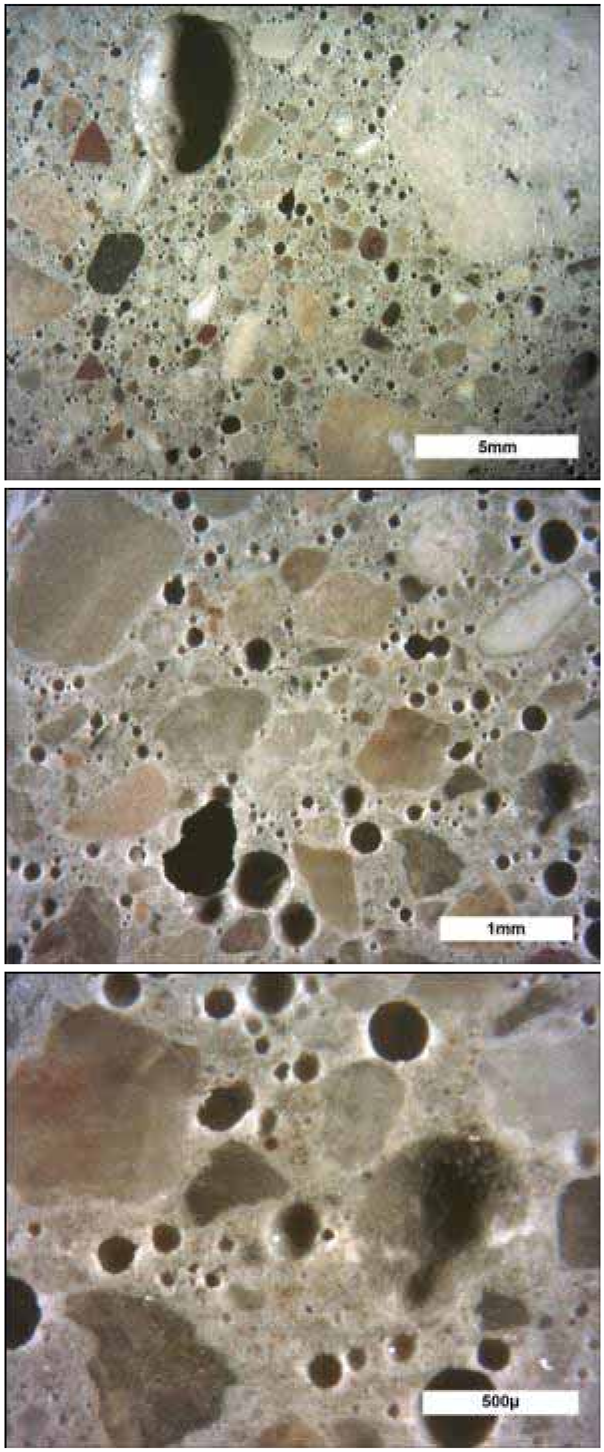


Figure 41: Micrographs of NE-1AA.

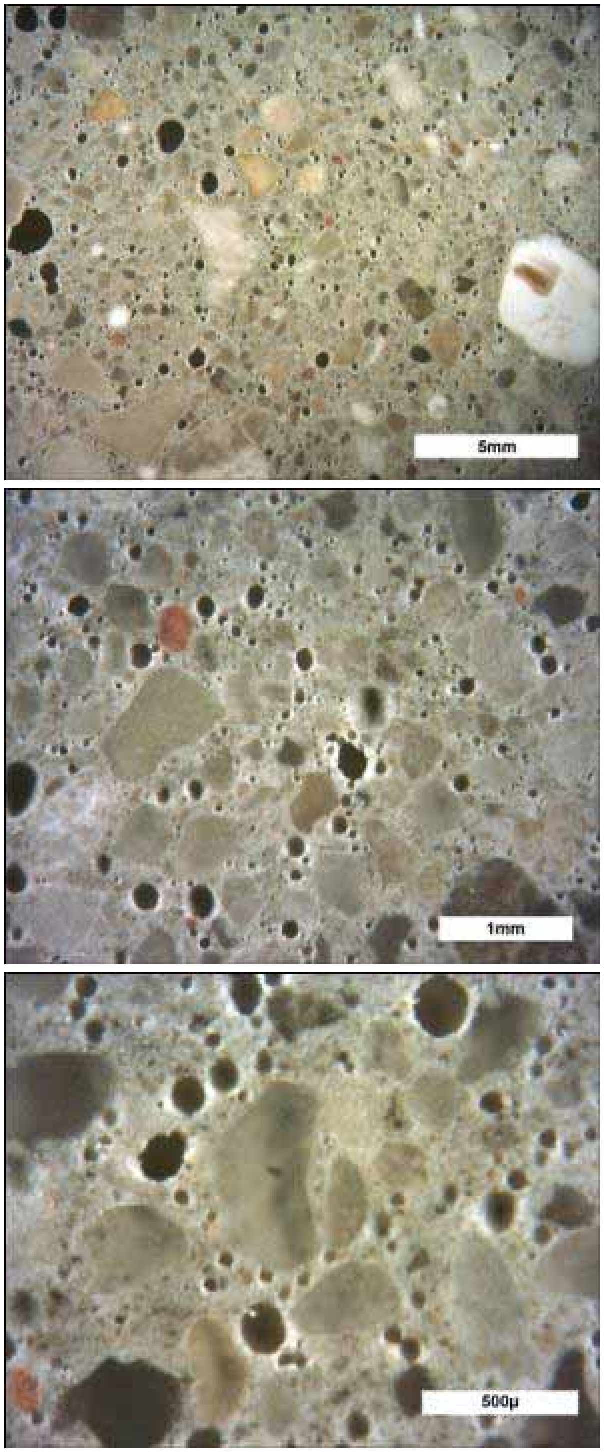


Figure 42: Micrographs of NE-1AB.

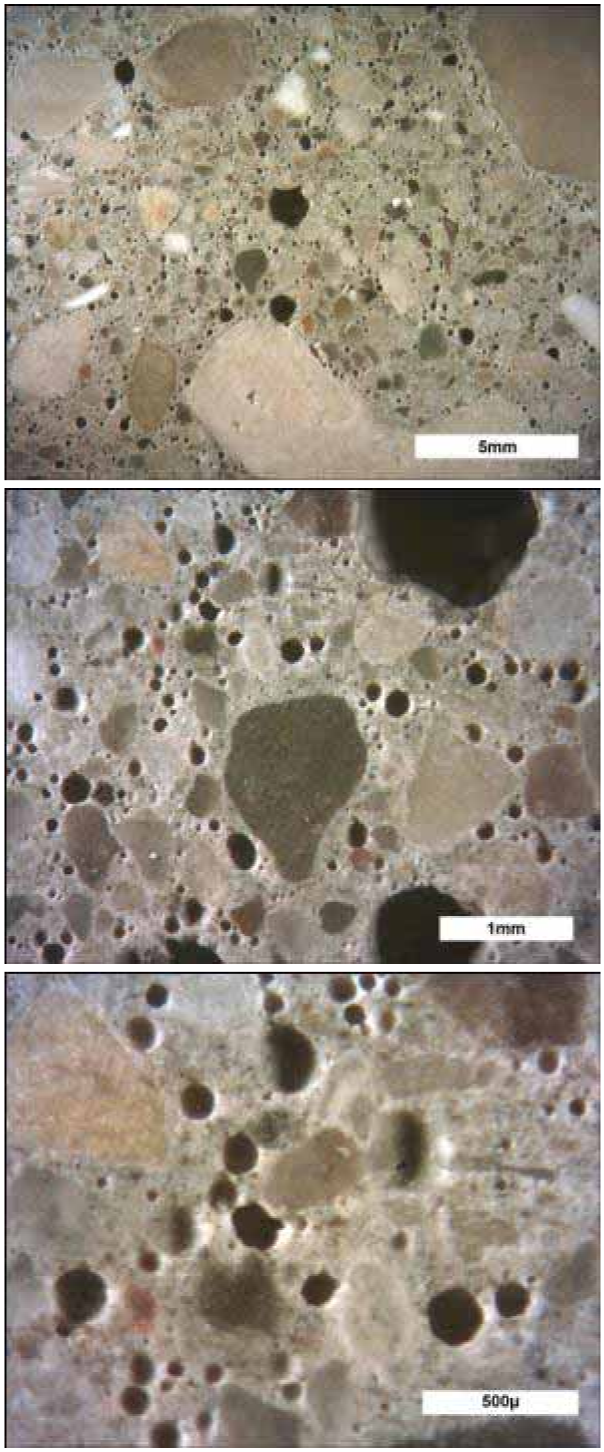


Figure 43: Micrographs of NE-1AC.

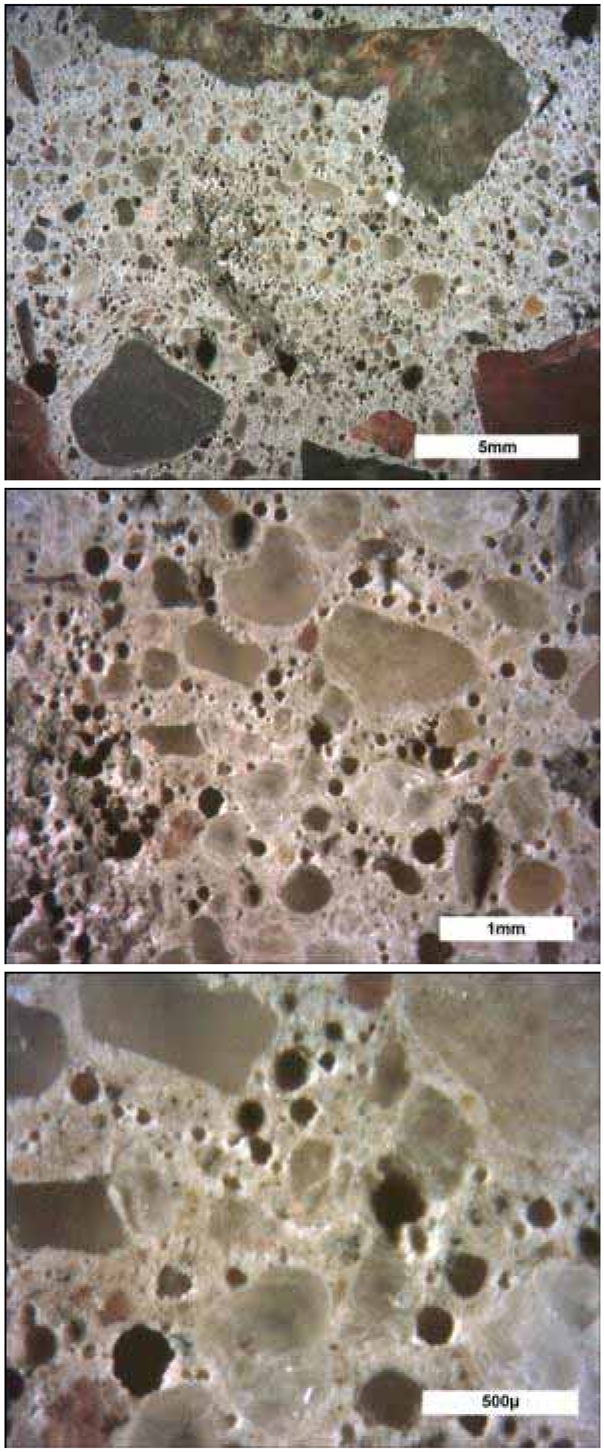


Figure 44: Micrographs of NC-2AA.

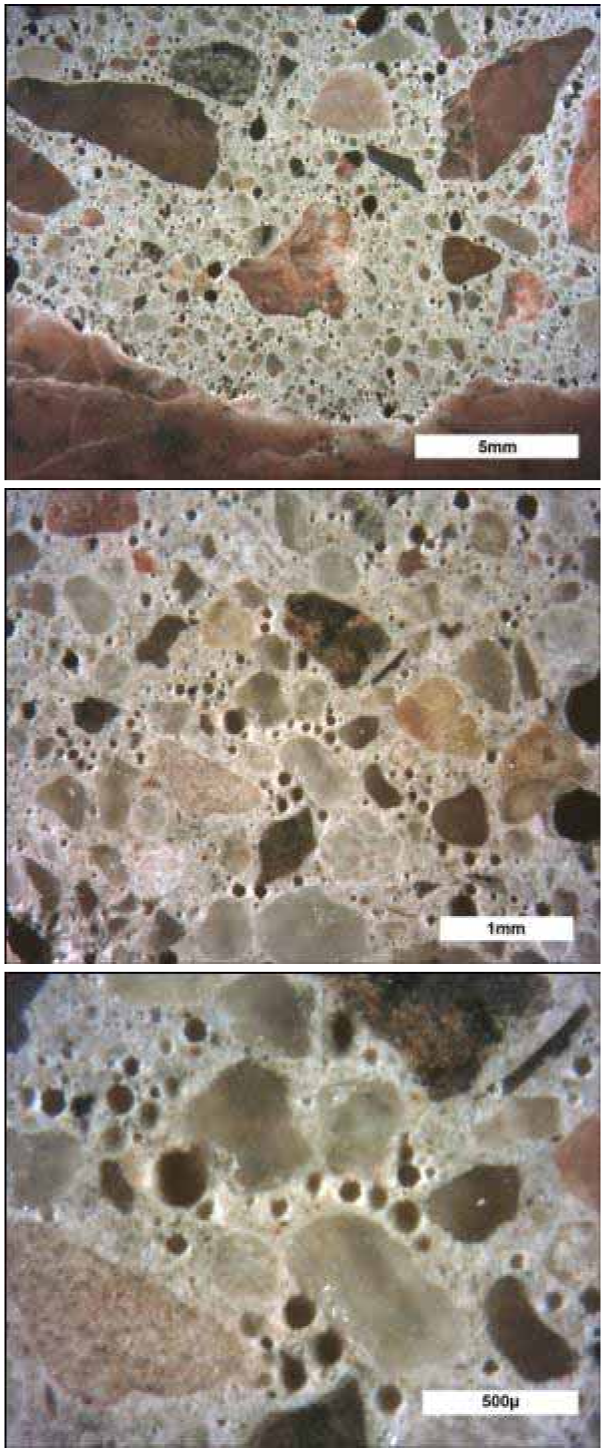


Figure 45: Micrographs of NC-2AB.

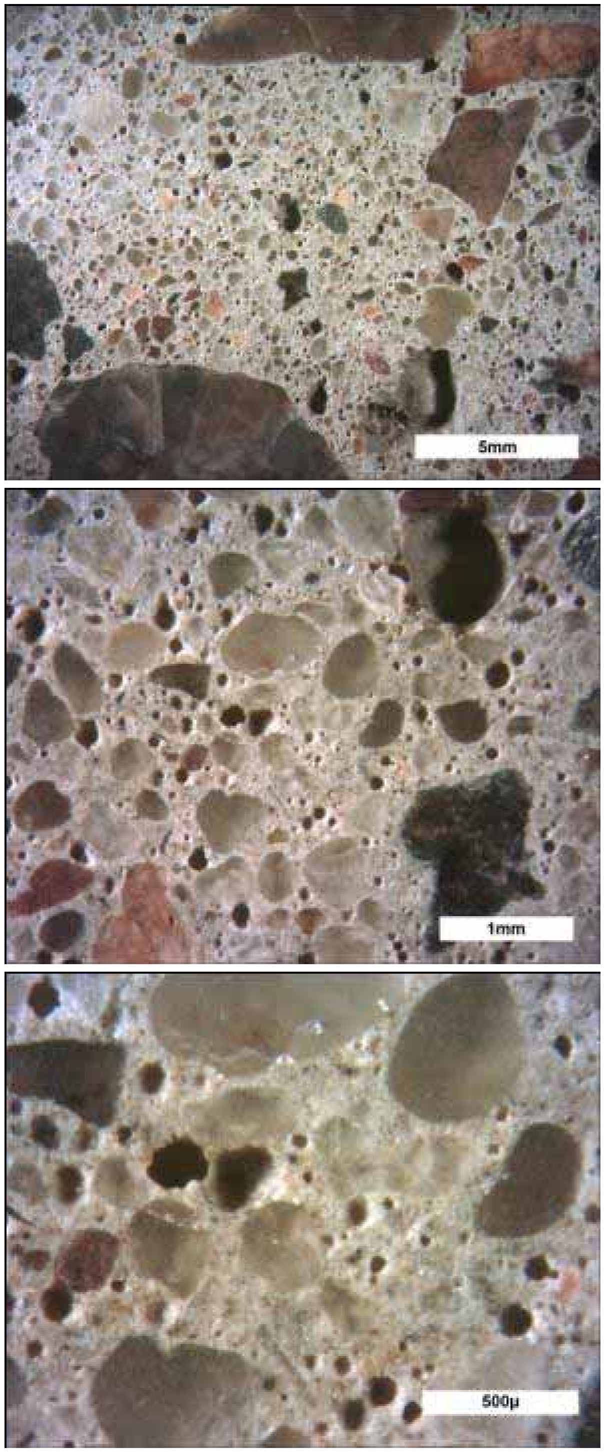


Figure 46: Micrographs of NC-2AC.

Manual

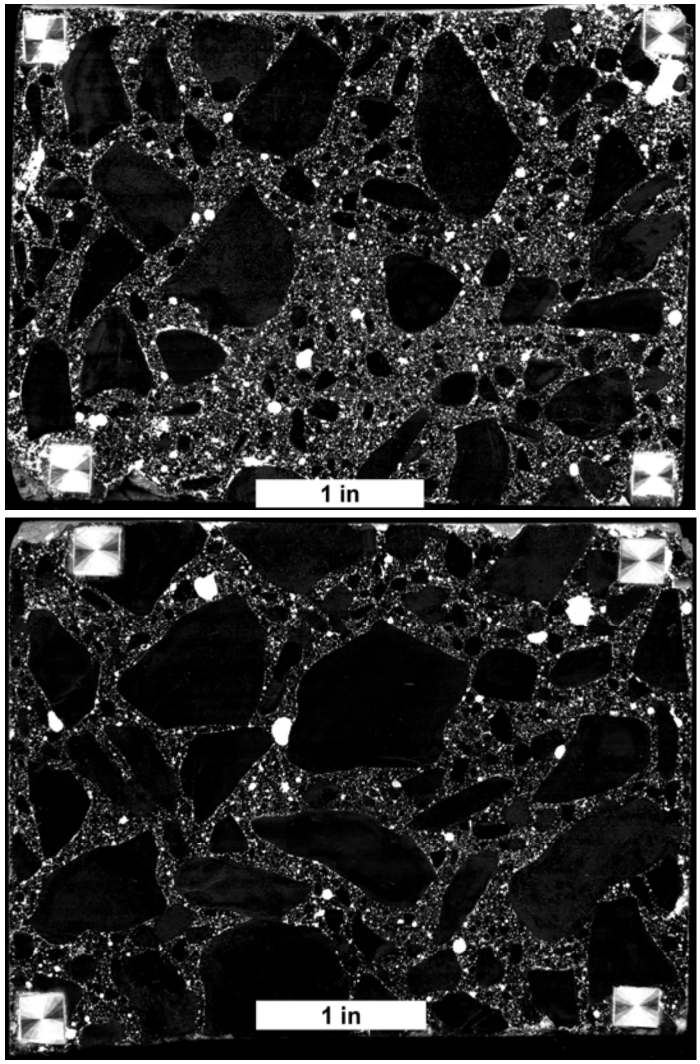
10.32% air

0.073mm SF

Automatic

11.66% air

0.070mm SF



5.05% air

0.160mm SF

7.10% air

0.097mm SF

Figure 47: Scanned images of SW-1A slabs post contrast treatment analyzed using the automatic technique

Manual | Automatic
6.02% air | 6.55% air
0.110mm SF | 0.134mm SF
7.42% air | 6.19% air
0.118mm SF | 0.132mm SF

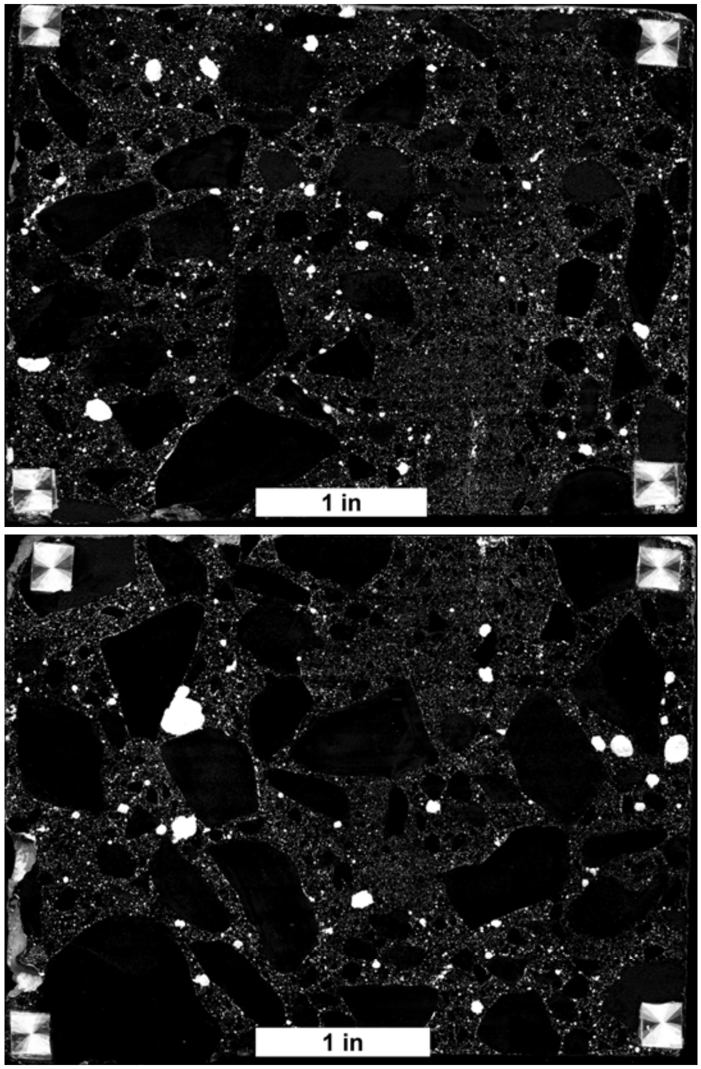
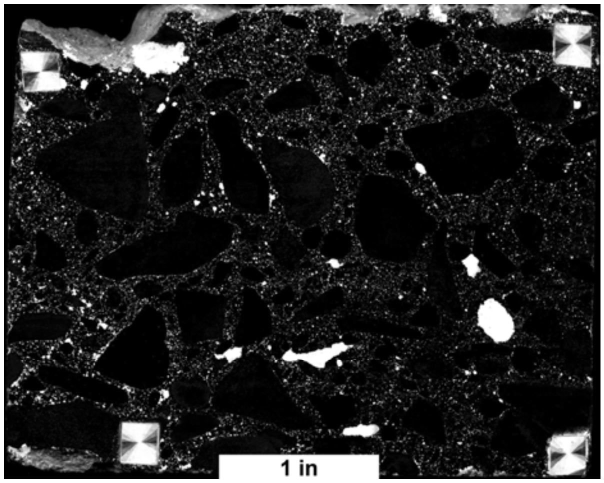


Figure 48: Scanned images of SW-1B slabs post contrast treatment analyzed using the automatic technique

Manual | Automatic

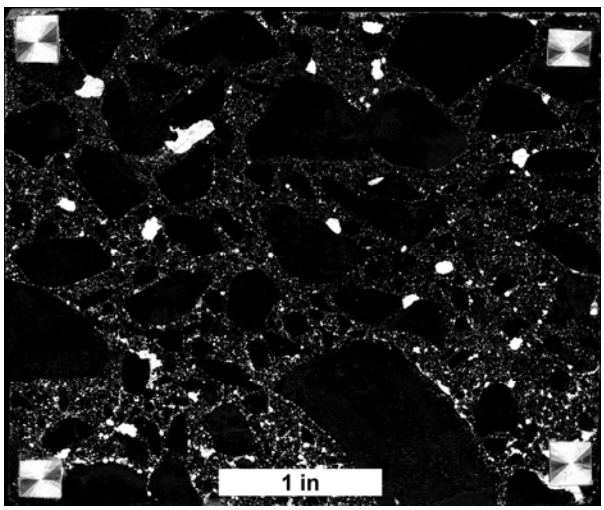
8.49% air | 5.53% air

0.112mm SF | 0.144mm SF



9.57% air | 6.70% air

0.102mm SF | 0.144mm SF



8.82% air | 8.68% air

0.108mm SF | 0.110mm SF

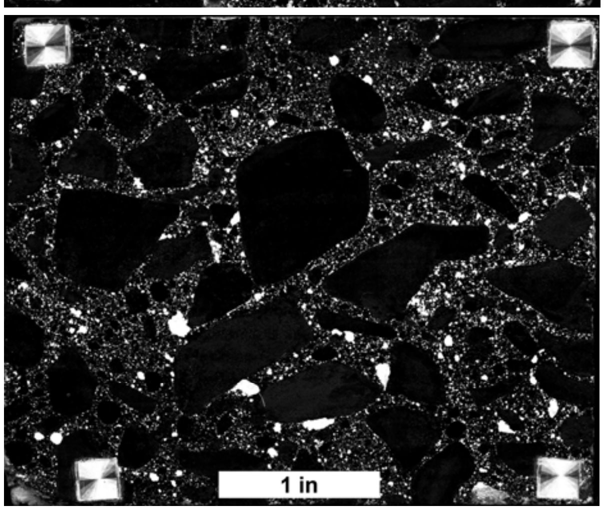


Figure 49: Scanned images of SW-1C slabs post contrast treatment analyzed using the automatic technique

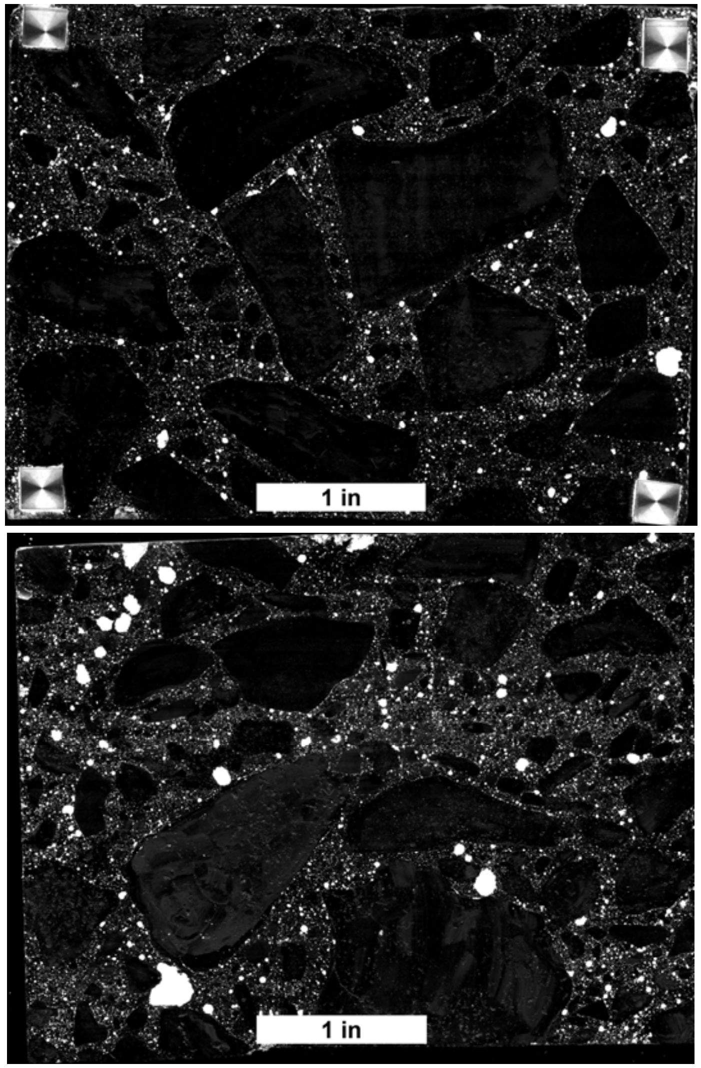
Manual | Automatic

4.62% air

0.098mm SF

4.53% air

0.103mm SF



6.99% air

0.111mm SF

7.66% air

0.089mm SF

Figure 50: Scanned images of SE-1A slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
6.13% air	5.95% air
0.112mm SF	0.119mm SF
6.13% air	4.54% air
0.116mm SF	0.150mm SF

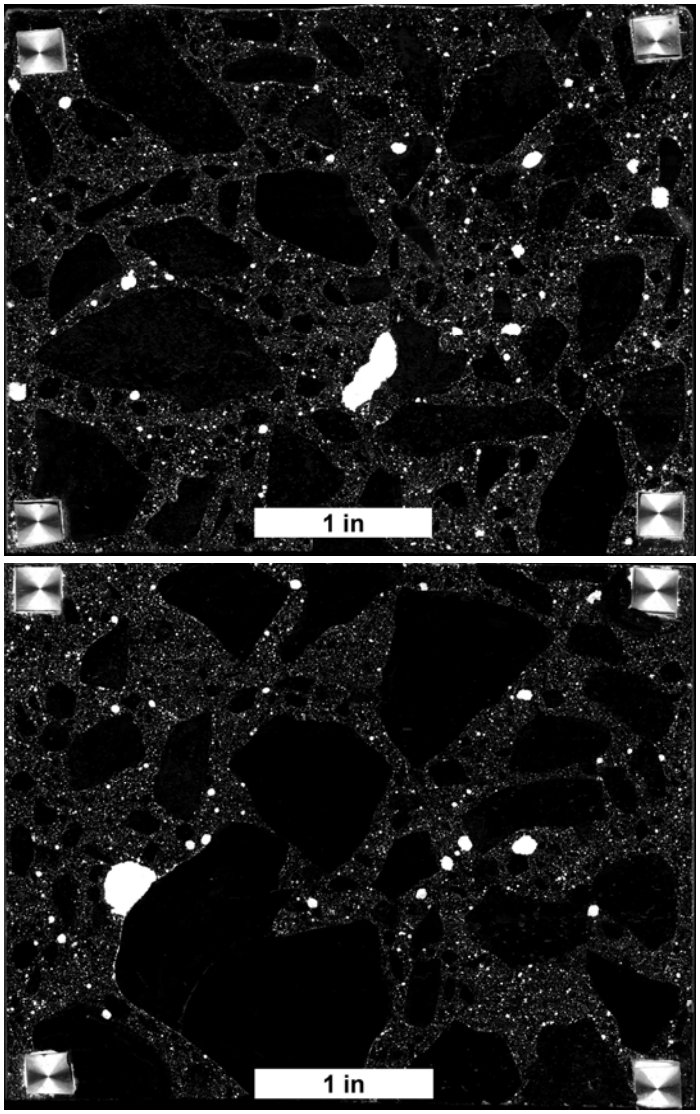
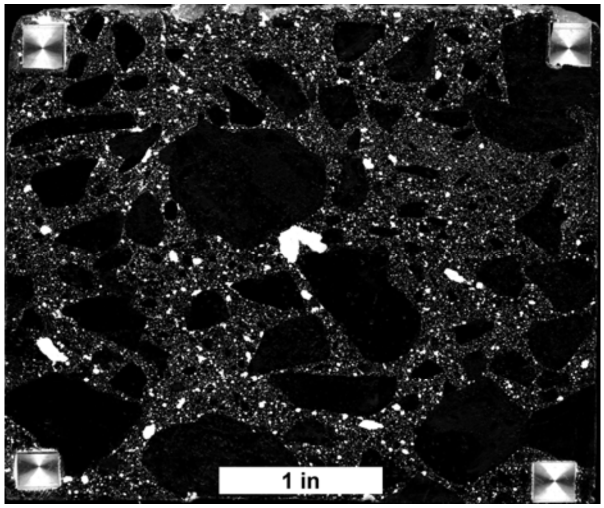


Figure 51: Scanned images of SE-1B slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

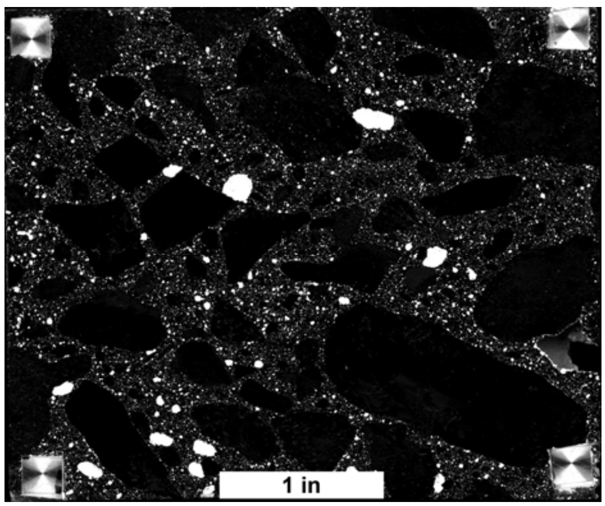
7.20% air | 8.82% air

0.055mm SF | 0.044mm SF



7.85% air | 6.68% air

0.084mm SF | 0.124mm SF



5.70% air | 5.22% air

0.081mm SF | 0.098mm SF

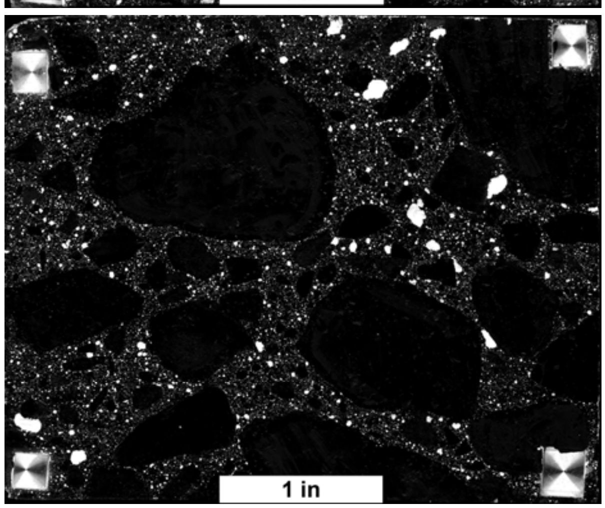


Figure 52: Scanned images of SE-1C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

13.44% air | 15.41% air

0.072mm SF | 0.065mm SF

8.06% air | 8.96% air

0.079mm SF | 0.095mm SF

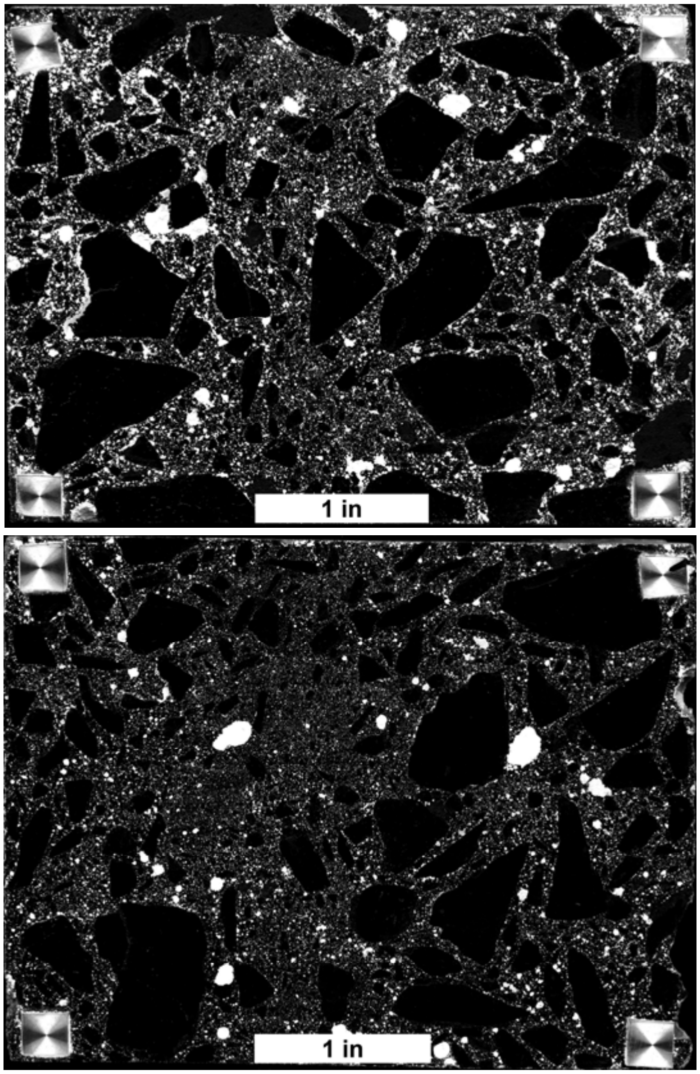


Figure 53: Scanned images of SW-3A slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
11.64% air	13.46% air
0.068mm SF	0.066mm SF
7.20% air	7.88% air
0.083mm SF	0.075mm SF

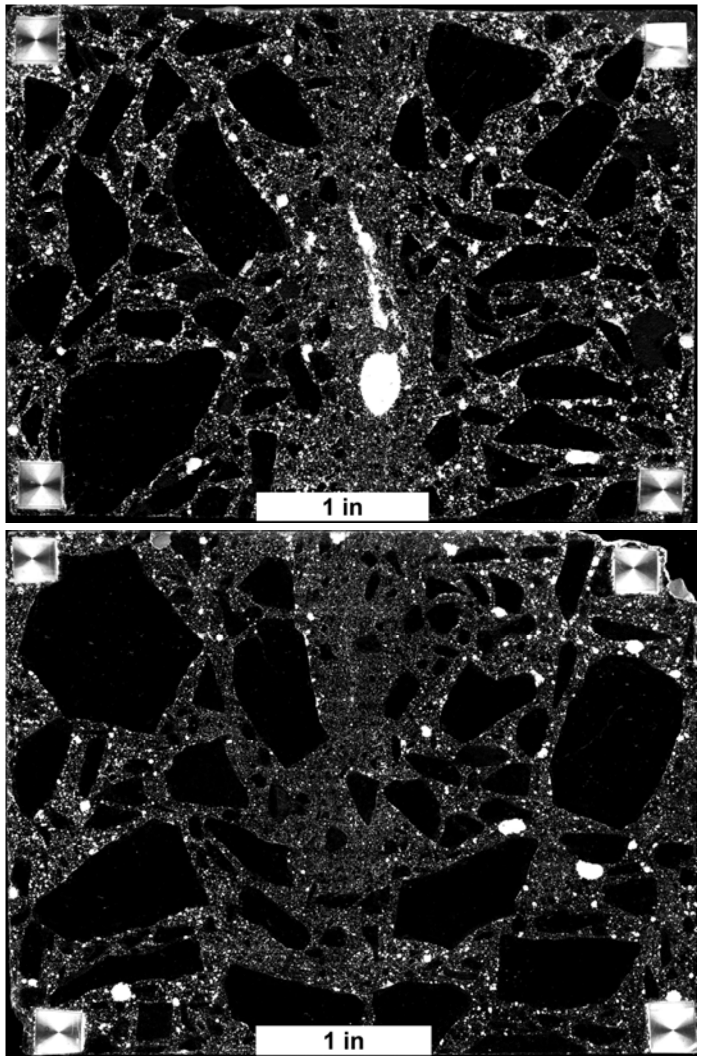


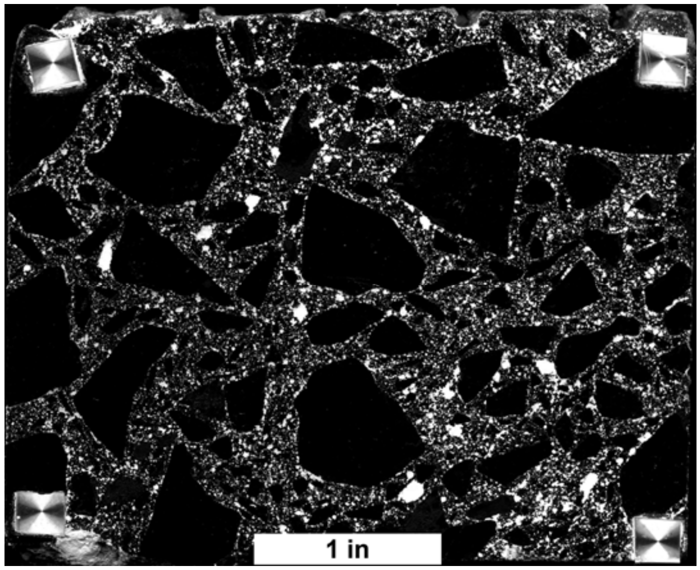
Figure 54: Scanned images of SW-3B slabs post contrast treatment analyzed using the automatic technique.

Manual

Automatic

10.65% air

0.061mm SF

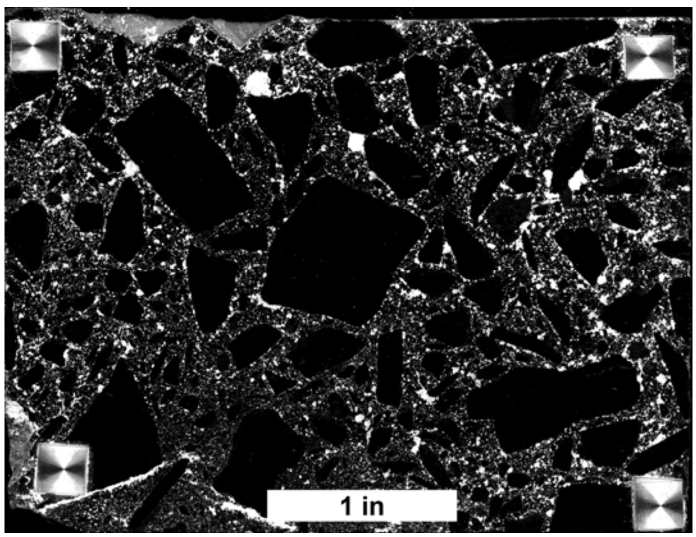


12.60% air

0.065mm SF

8.60% air

0.101mm SF



10.87% air

0.082mm SF

Figure 55: Scanned images of SW-3C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

7.20% air | 7.72% air

0.081mm SF | 0.090mm SF

9.89% air | 9.24% air

0.073mm SF | 0.063mm SF

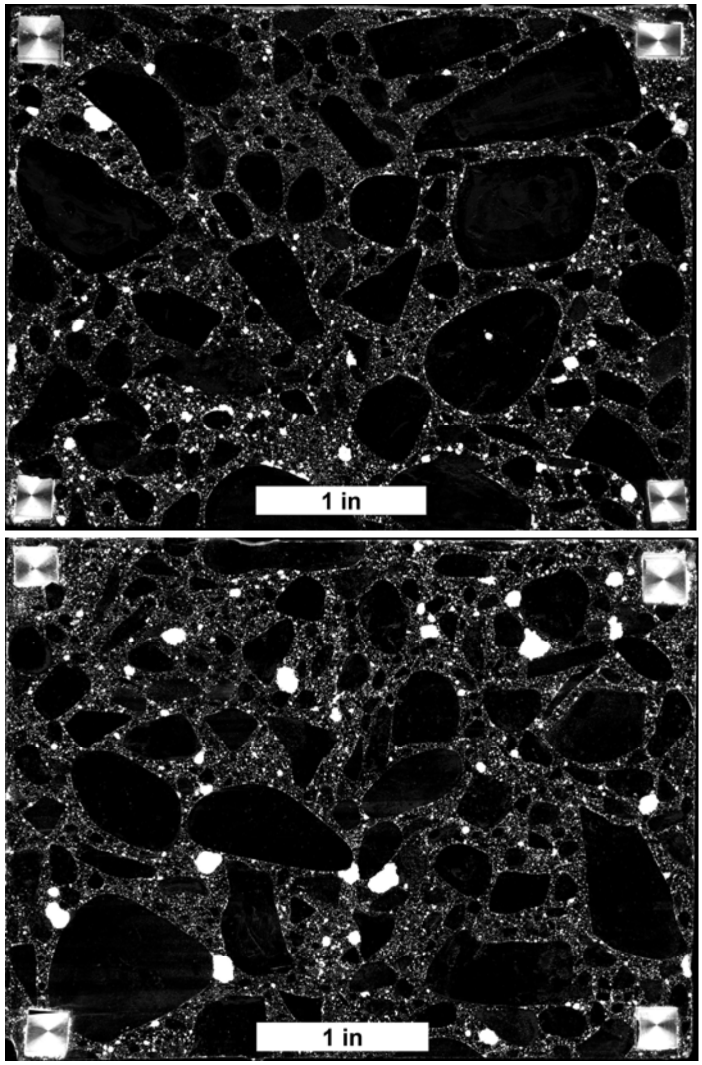


Figure 56: Scanned images of SW-2A slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

6.88% air | 6.13% air

0.083mm SF | 0.109mm SF

6.99% air | 6.52% air

0.088mm SF | 0.104mm SF

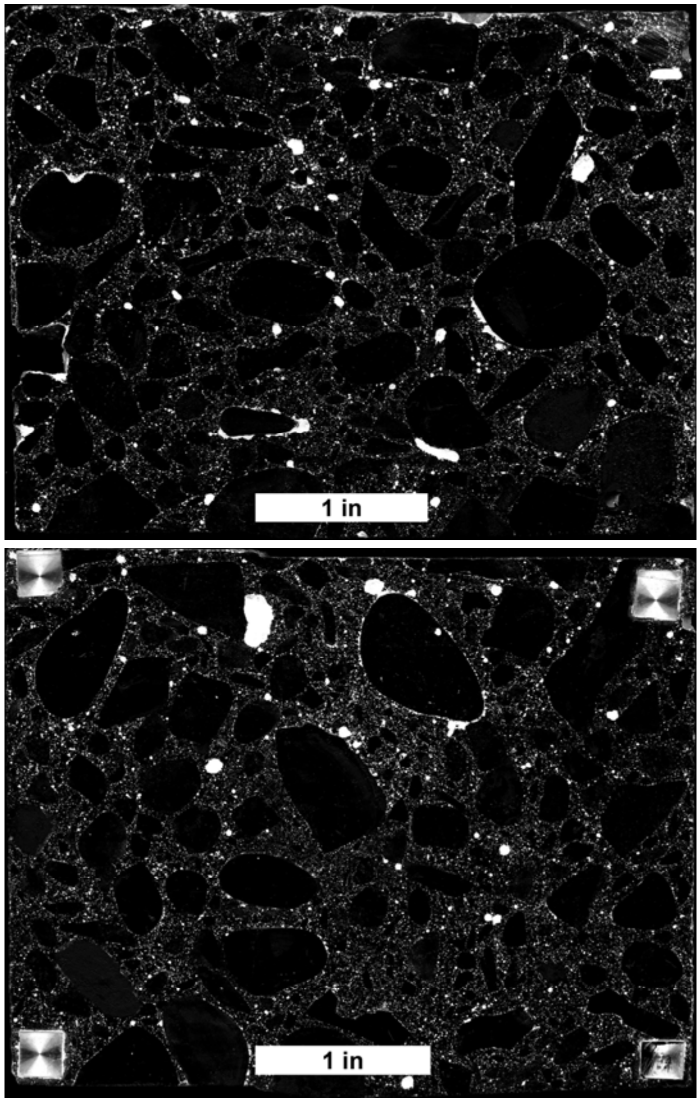


Figure 57: Scanned images of SW-2B slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
6.34% air	5.27% air
0.061mm SF	0.076mm SF
6.99% air	6.70% air
0.097mm SF	0.094mm SF
6.56% air	8.30% air
0.072mm SF	0.078mm SF

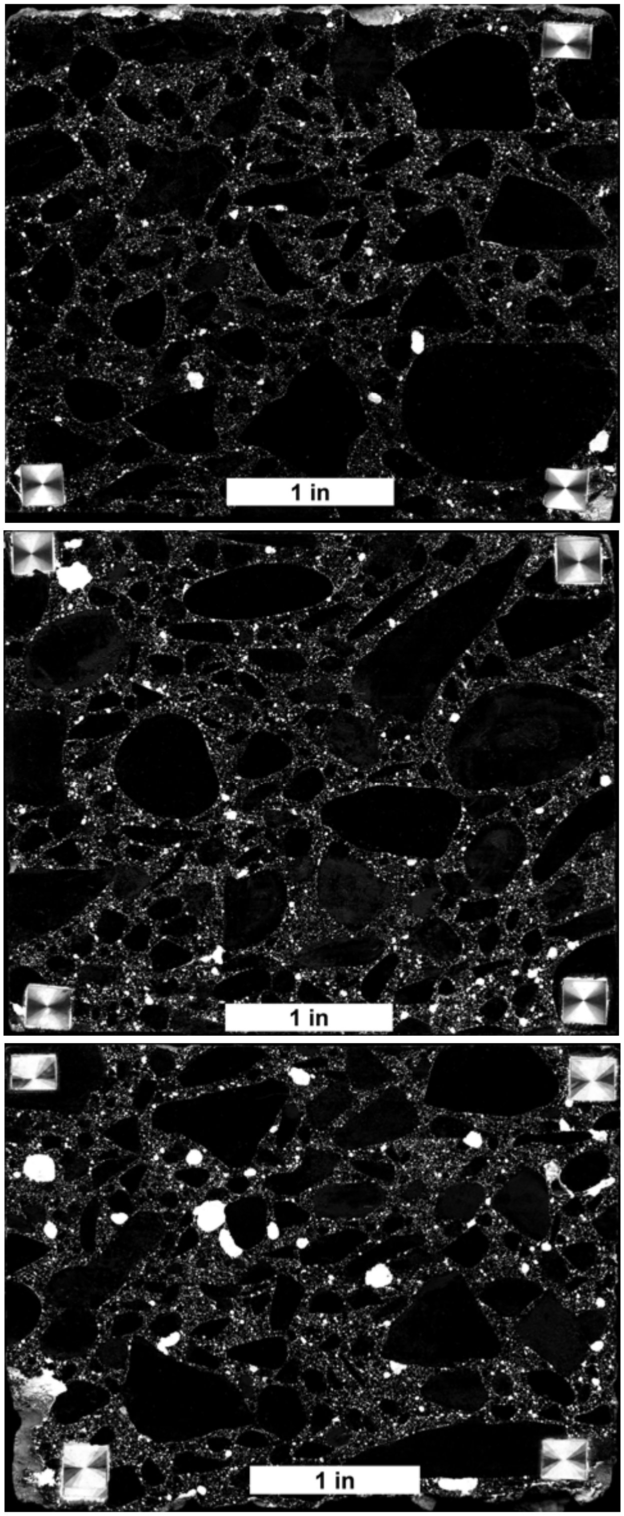


Figure 58: Scanned images of SW-2C slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
3.33% air	4.73% air
0.101mm SF	0.135mm SF
8.39% air	8.87% air
0.135mm SF	0.129mm SF

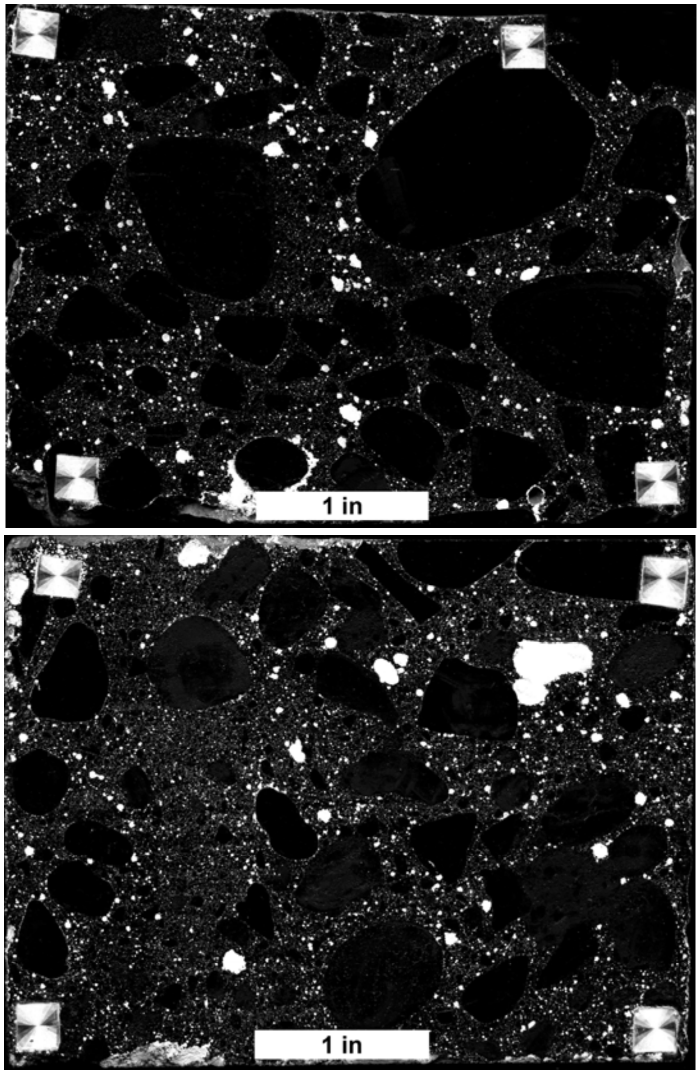
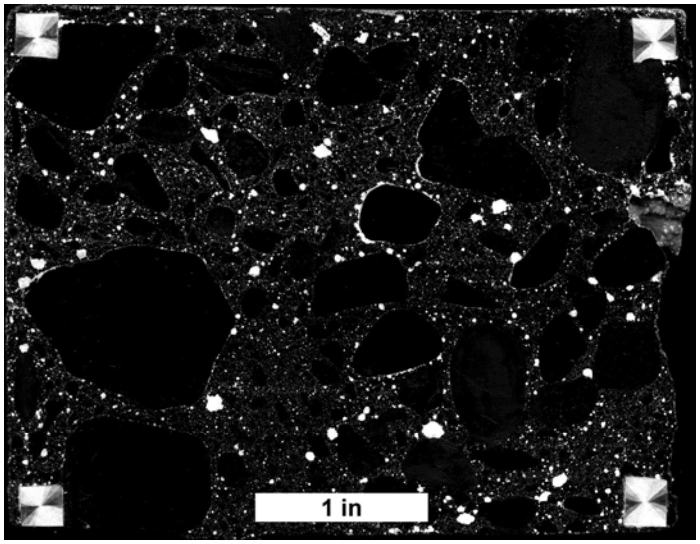


Figure 59: Scanned images of NC-1A slabs post contrast treatment analyzed using the automatic technique.

Manual		Automatic

Manual	Automatic
3.76% air	5.08% air
0.218mm SF	0.130mm SF



6.34% air	8.32% air
0.091mm SF	0.092mm SF

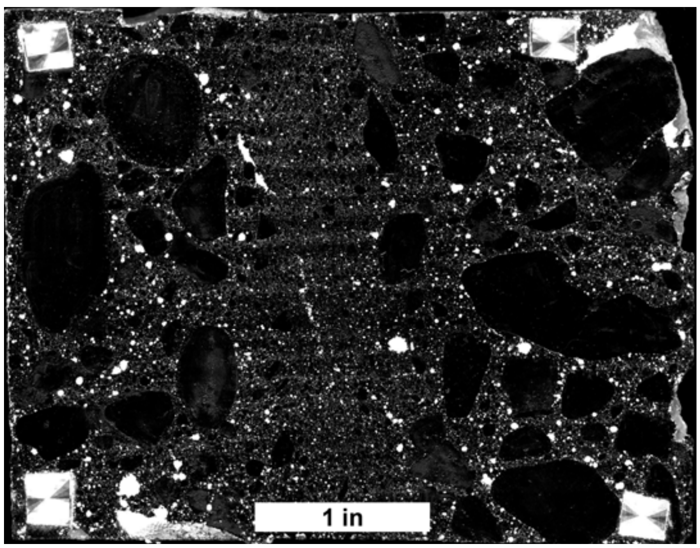


Figure 60: Scanned images of NC-1B slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
8.71% air	7.87% air
0.098mm SF	0.121mm SF
8.92% air	8.45% air
0.099mm SF	0.124mm SF
8.92% air	11.62% air
0.108mm SF	0.088mm SF

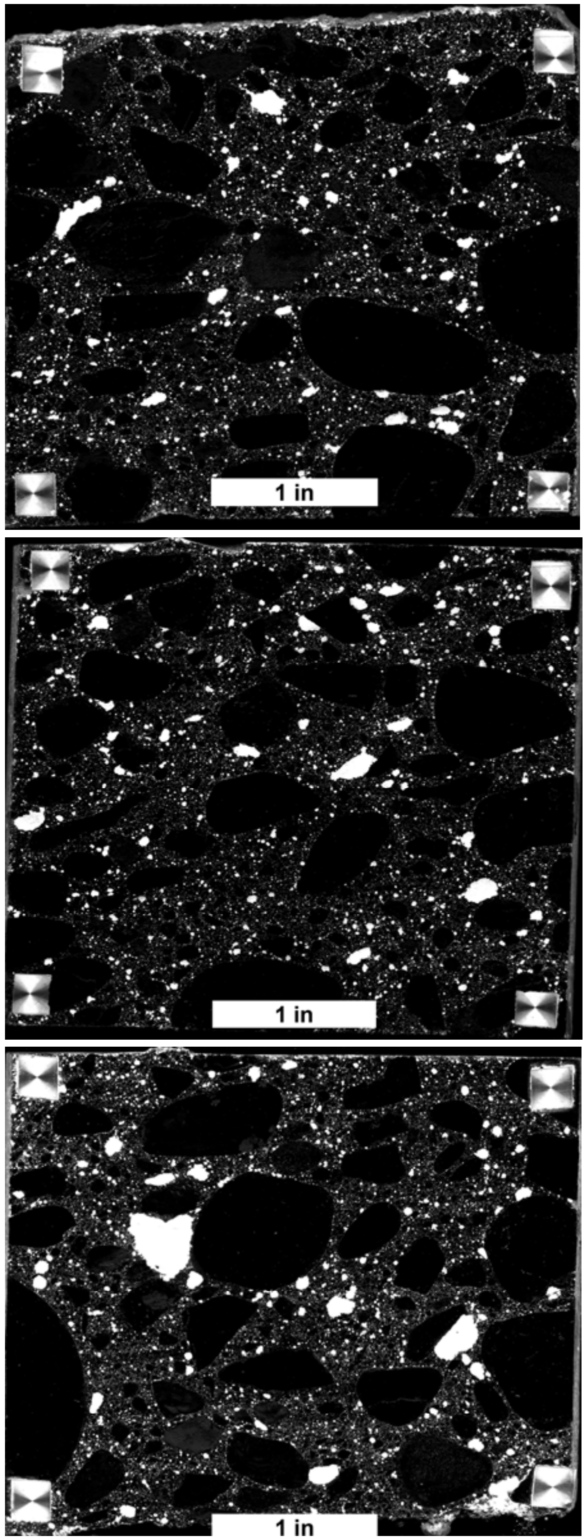


Figure 61: Scanned images of NC-1C slabs post contrast treatment analyzed using the automatic technique.

Manual

8.28% air

0.109mm SF

Automatic

8.07% air

0.080mm SF

4.52% air

0.137mm SF

5.49% air

0.150mm SF

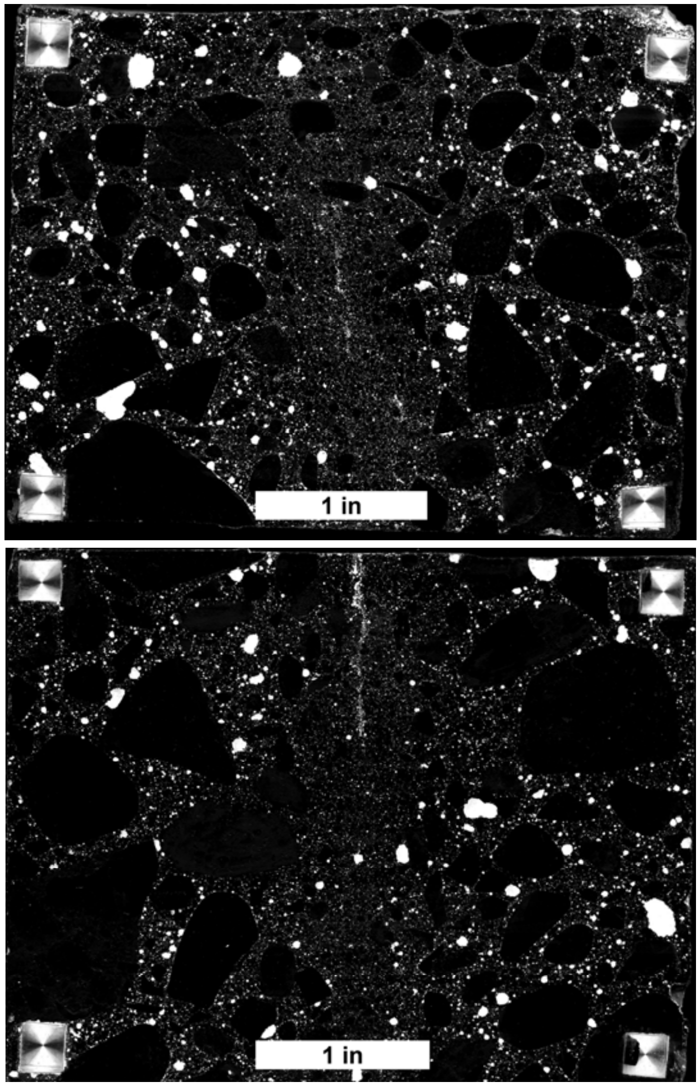


Figure 62: Scanned images of SE-2A slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
6.56% air	5.18% air
0.127mm SF	0.180mm SF
5.48% air	4.65% air
0.095mm SF	0.121mm SF

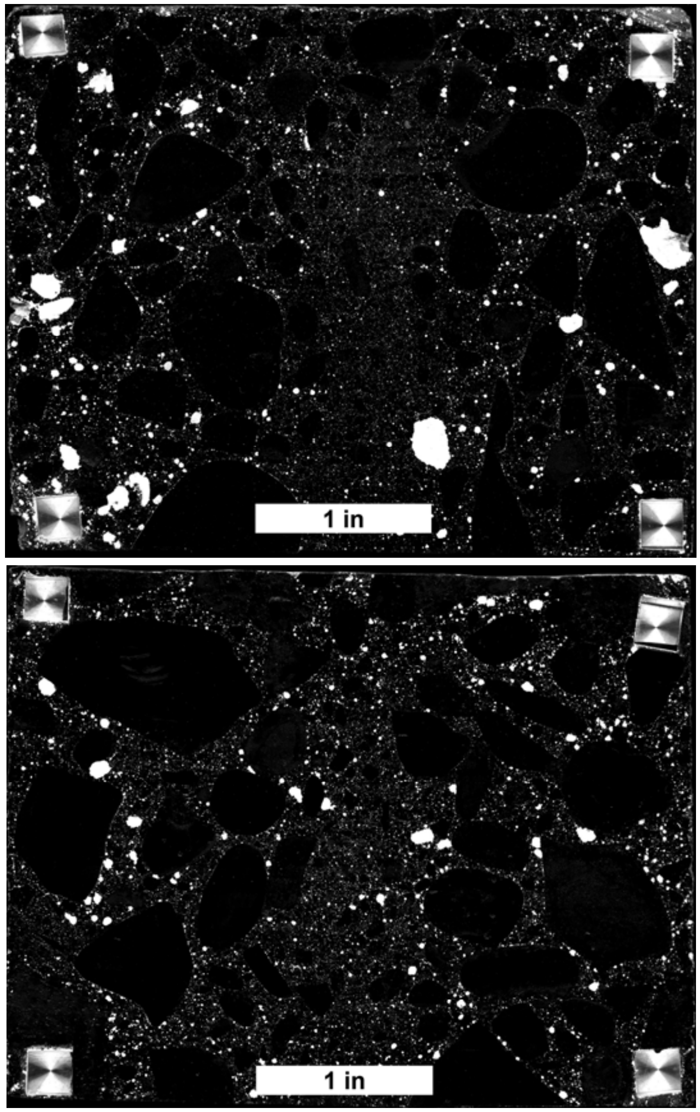
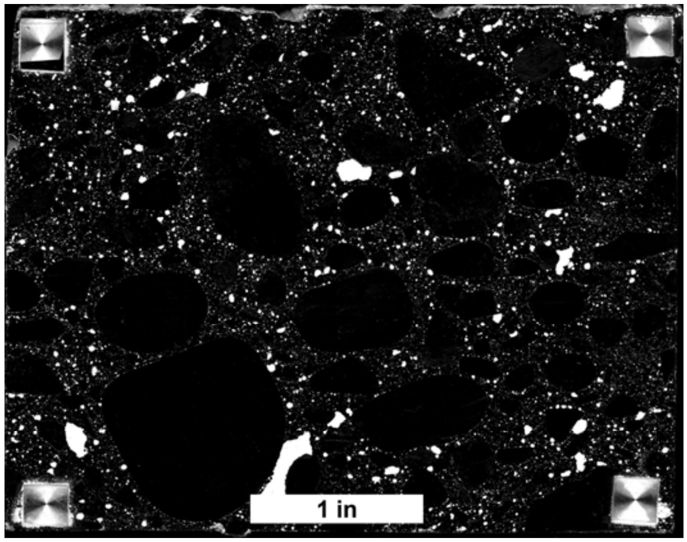


Figure 63: Scanned images of SE-2b slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

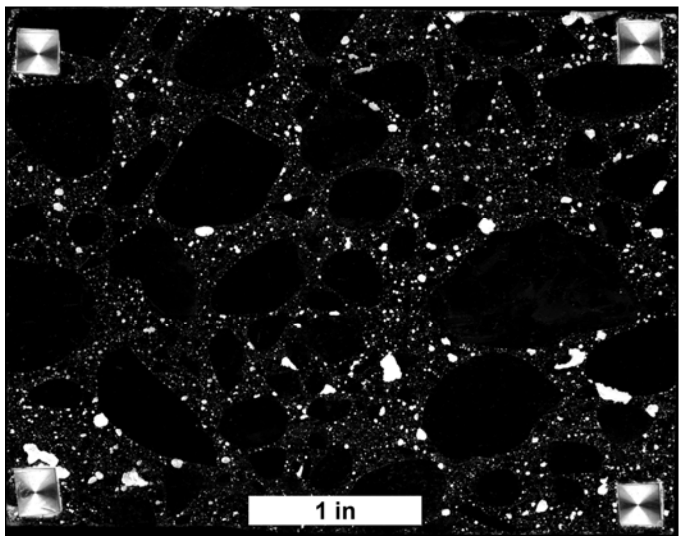
6.45% air | 5.97% air

0.126mm SF | 0.150mm SF



3.33% air | 4.43% air

0.127mm SF | 0.206mm SF



7.76% air | 6.48% air

0.163mm SF | 0.204mm SF

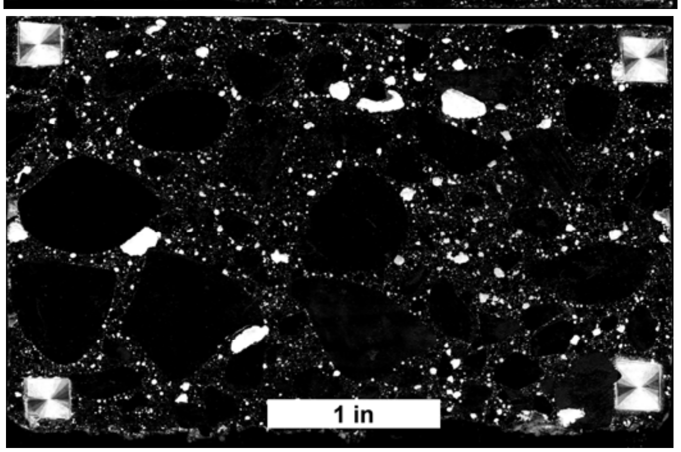


Figure 64: Scanned images of SE-2C slabs post contrast treatment analyzed using the automatic technique.

Manual

Automatic

10.43% air

0.073mm SF

8.43% air

.083mm SF

9.89% air

0.080mm SF

8.47% air

0.101mm SF

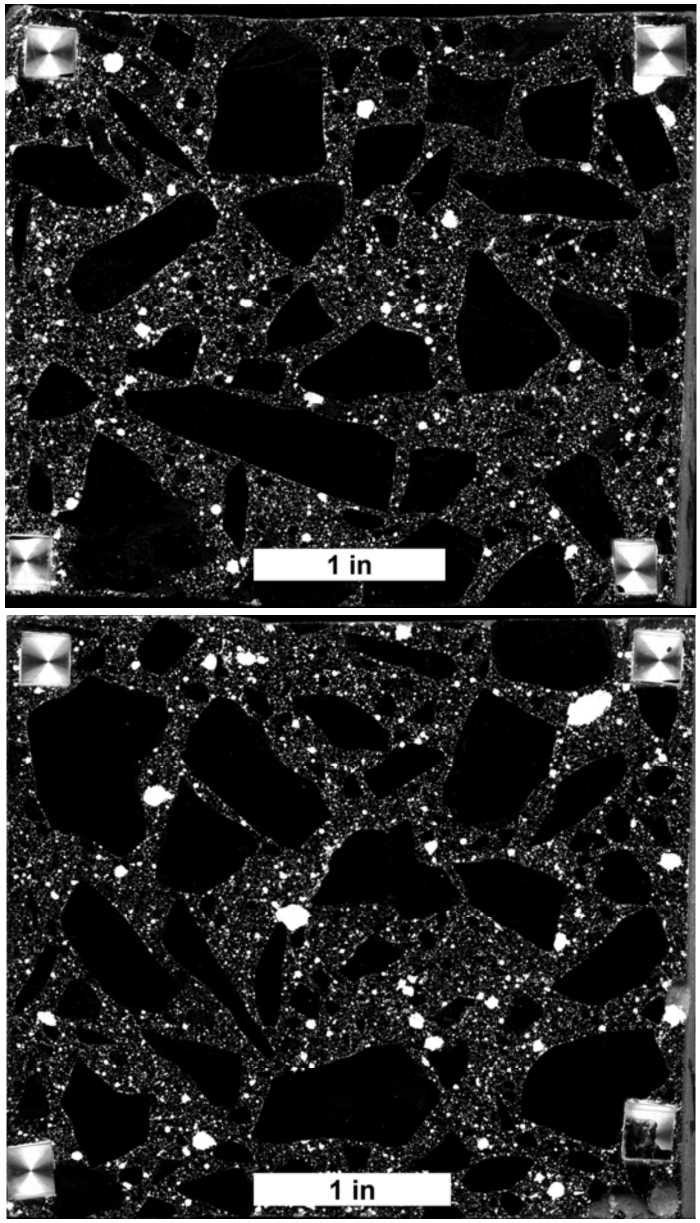


Figure 65: Scanned images of NE-2A slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
6.77% air	6.90% air
0.099mm SF	0.111mm SF
7.63% air	7.86% air
0.114mm SF	0.110mm SF

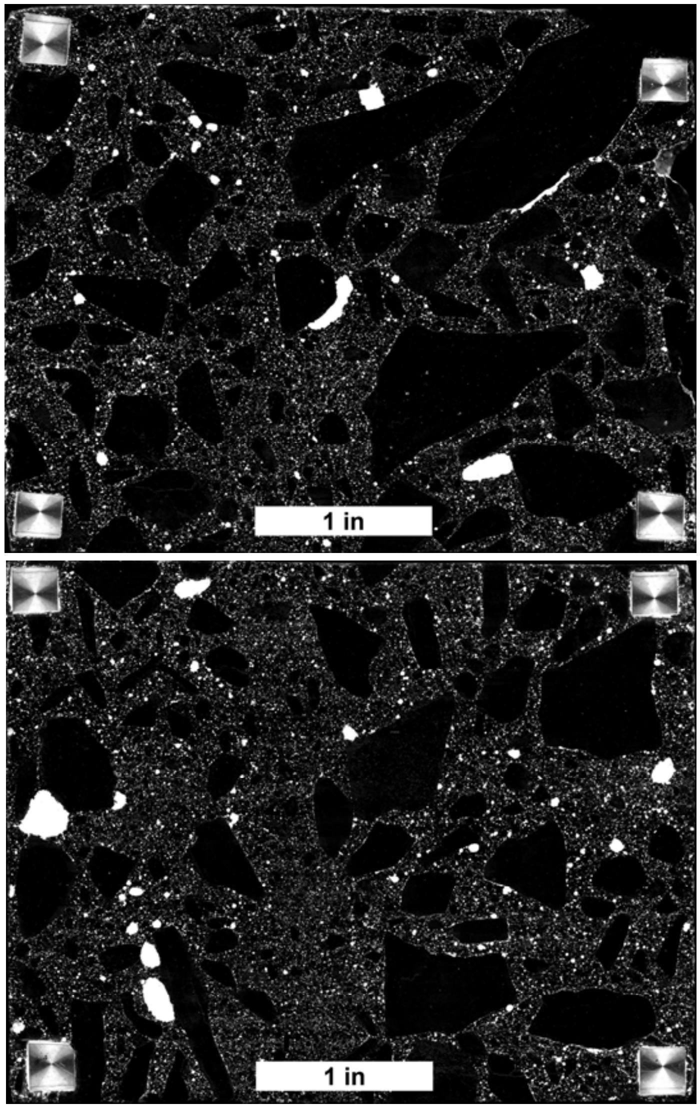


Figure 66: Scanned images of NE-2B slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
8.17% air	7.32% air
0.105mm SF	0.100mm SF
4.73% air	4.59% air
0.143mm SF	0.126mm SF
8.06% air	7.18% air
0.113mm SF	0.130mm SF

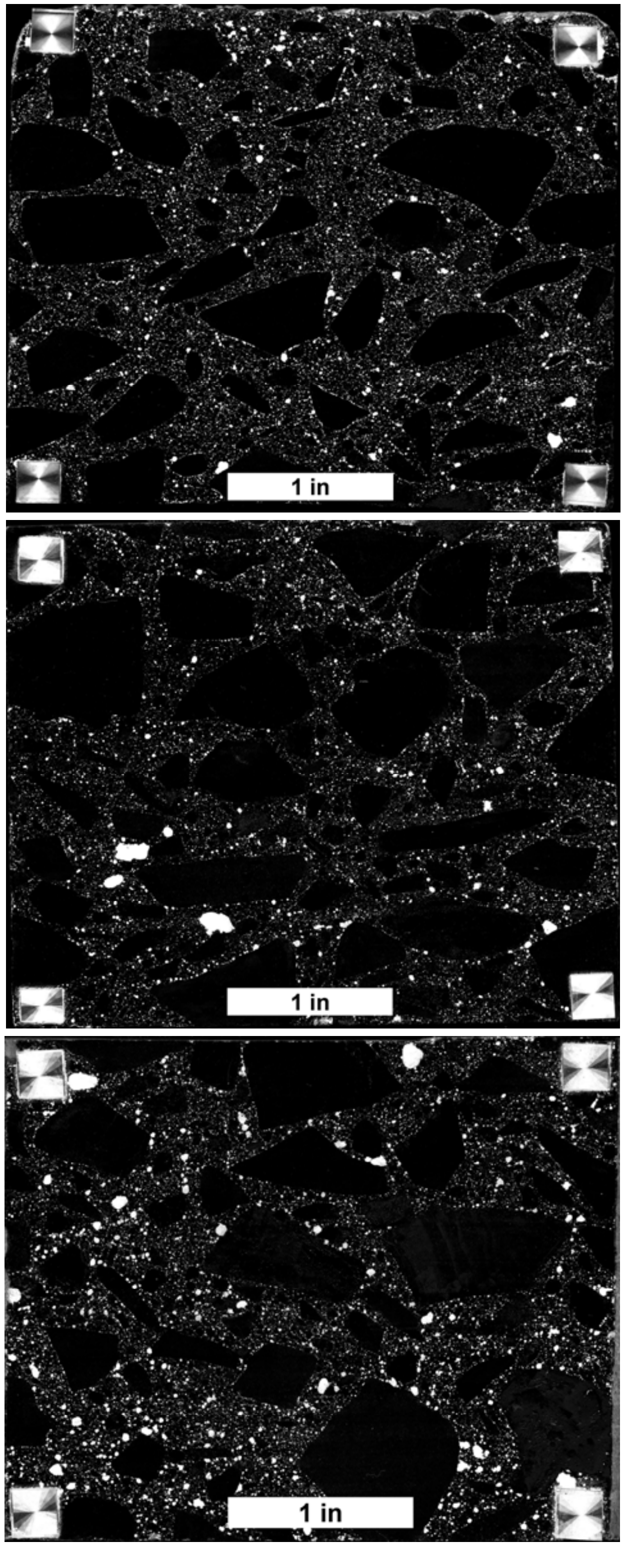
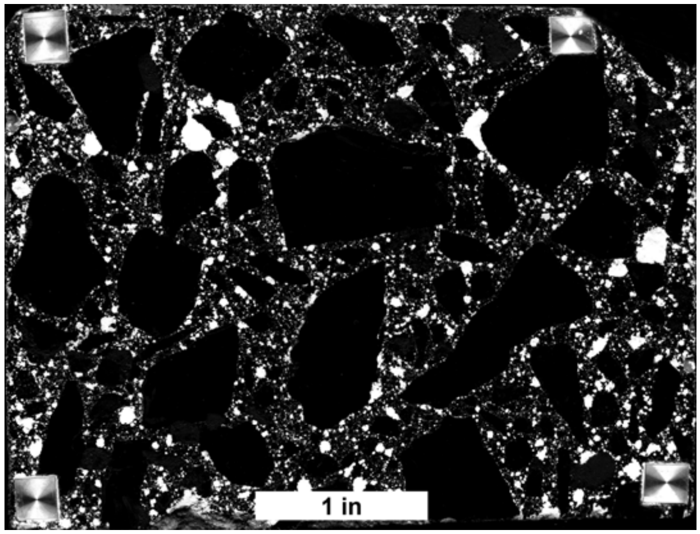


Figure 67: Scanned images of NE-2C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

9.89% air | 10.11% air

0.097mm SF | 0.102mm SF



10.97% air | 11.09% air

0.103mm SF | 0.110mm SF

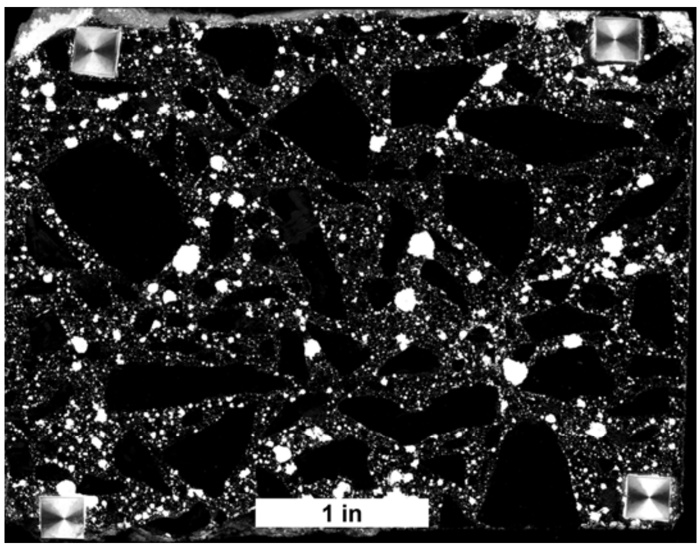


Figure 68: Scanned images of NC-2A slabs post contrast treatment analyzed using the automatic technique.

Manual		Automatic
10.11% air		8.59% air
0.103mm SF		0.124mm SF
7.74% air		9.94% air
0.127mm SF		0.105mm SF

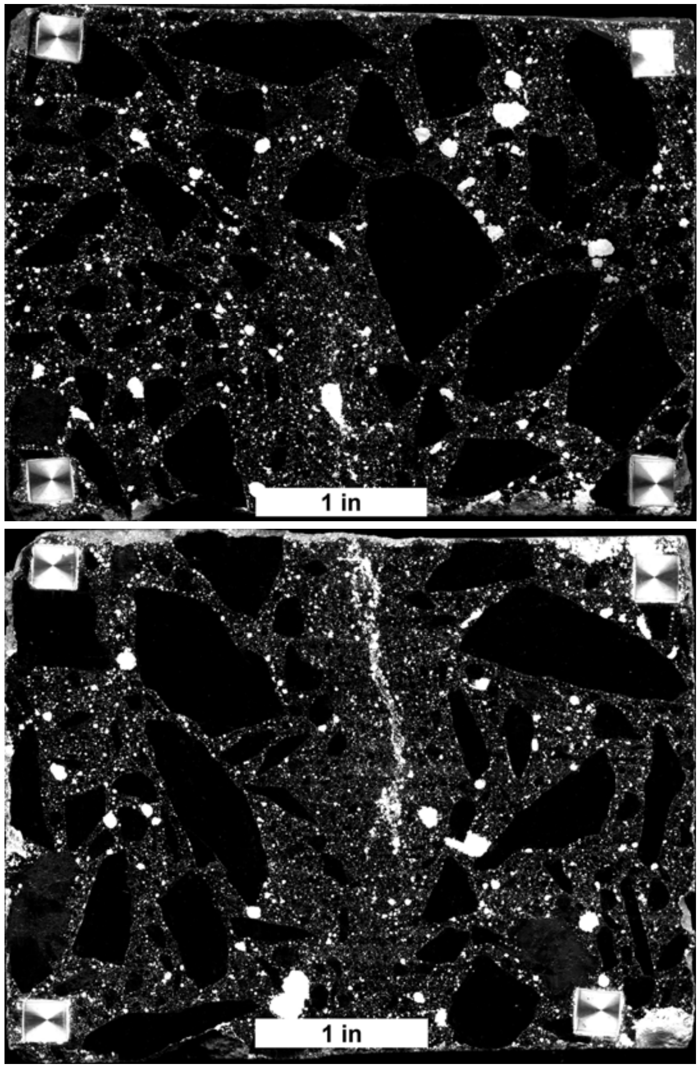


Figure 69: Scanned images of NC-2B slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
13.17% air	17.24% air
0.075mm SF	0.079mm SF
9.14% air	10.85% air
0.118mm SF	0.105mm SF
9.68% air	10.70% air
0.110mm SF	0.105mm SF

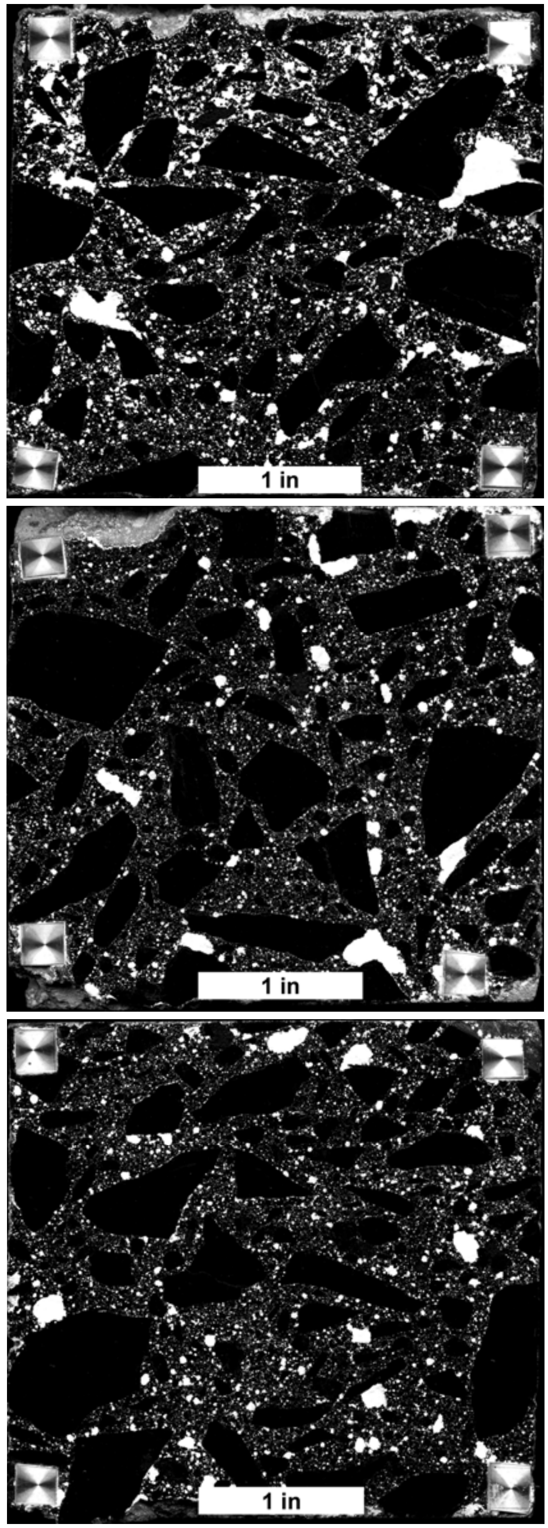
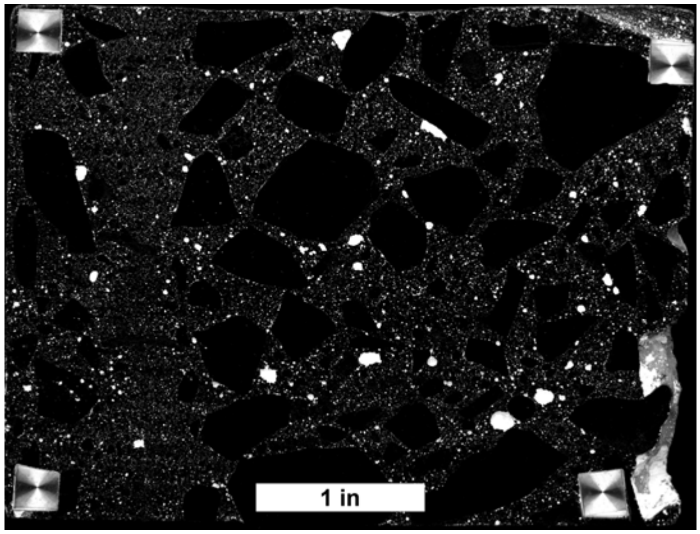


Figure 70: Scanned images of NC-2C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

4.95% air | 5.41% air

0.082mm SF | 0.112mm SF



4.09% air | 7.27% air

0.086mm SF | 0.110mm SF

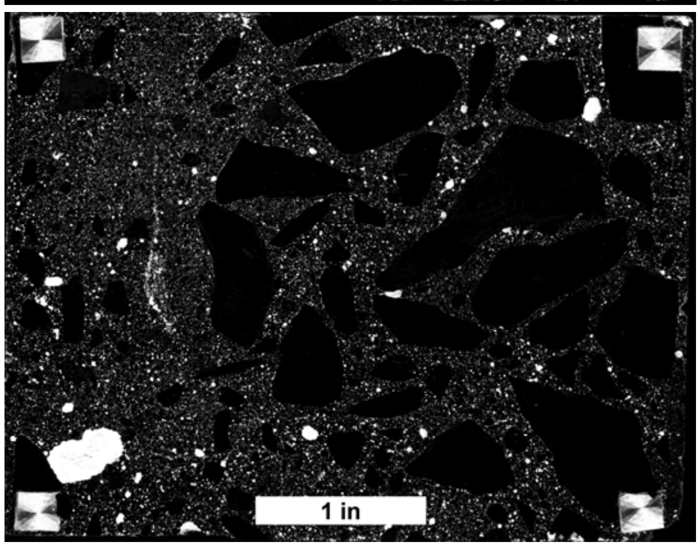


Figure 71: Scanned images of NE-4A slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

7.74% air | 8.37% air

0.102mm SF | 0.082mm SF

9.78% air | 10.86% air

0.102mm SF | 0.101mm SF

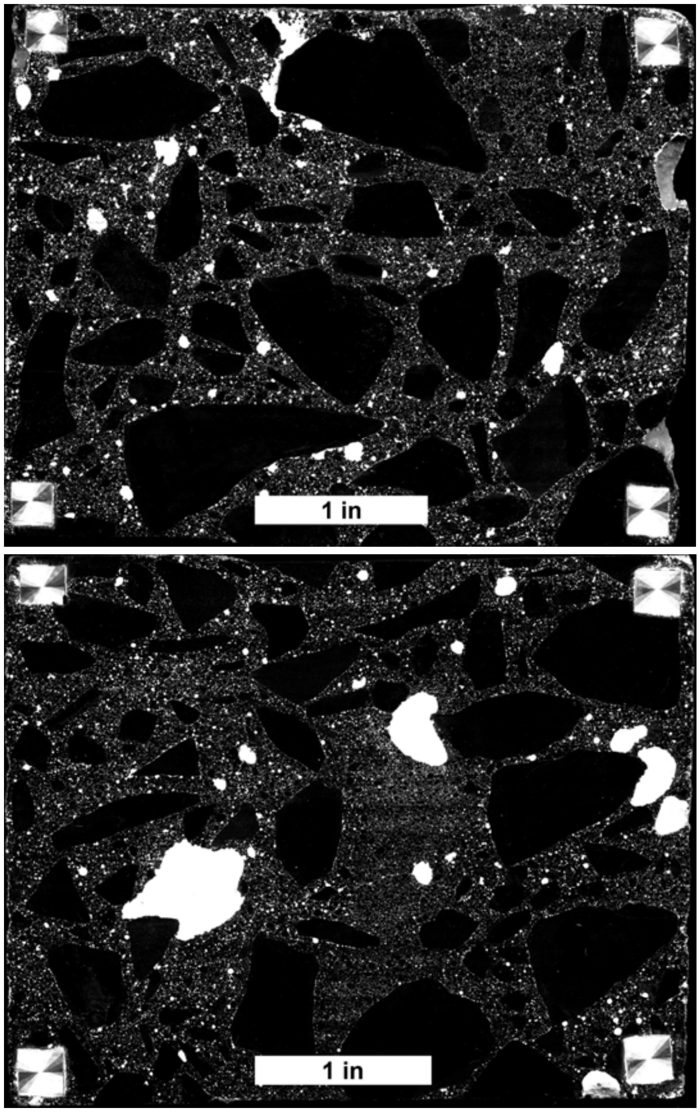
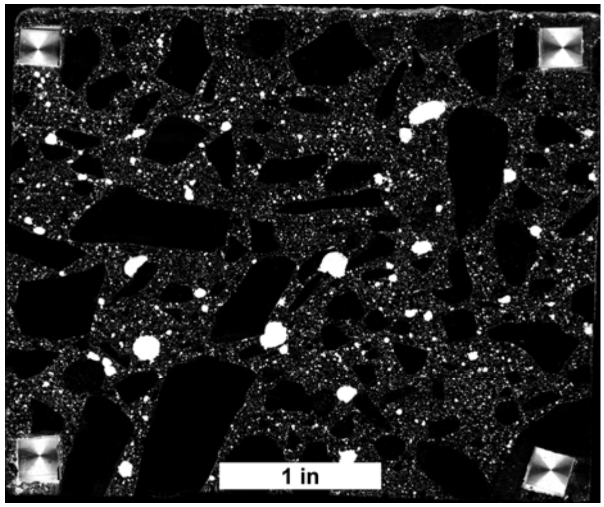


Figure 72: Scanned images of NE-4B slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

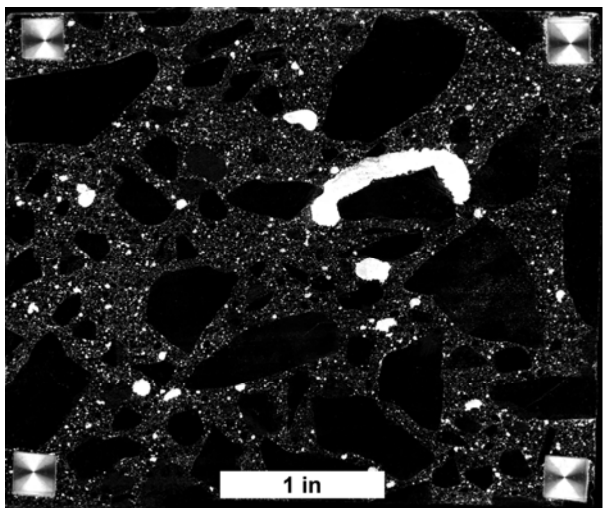
6.99% air | 8.70% air

0.084mm SF | 0.079mm SF



7.74% air | 8.95% air

0.082mm SF | 0.089mm SF



7.20% air | 6.98% air

0.095mm SF | 0.126mm SF

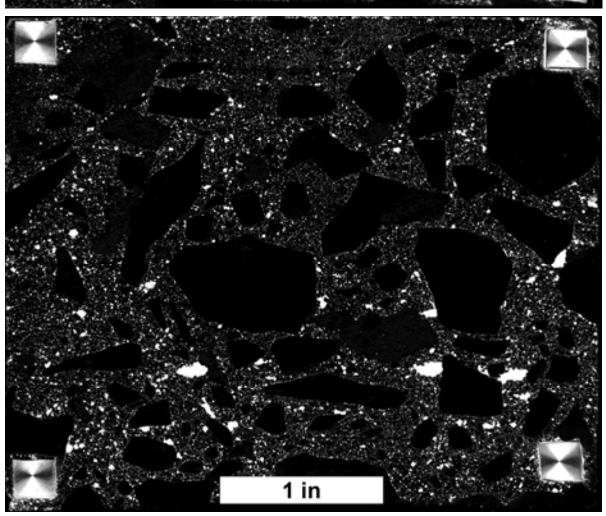
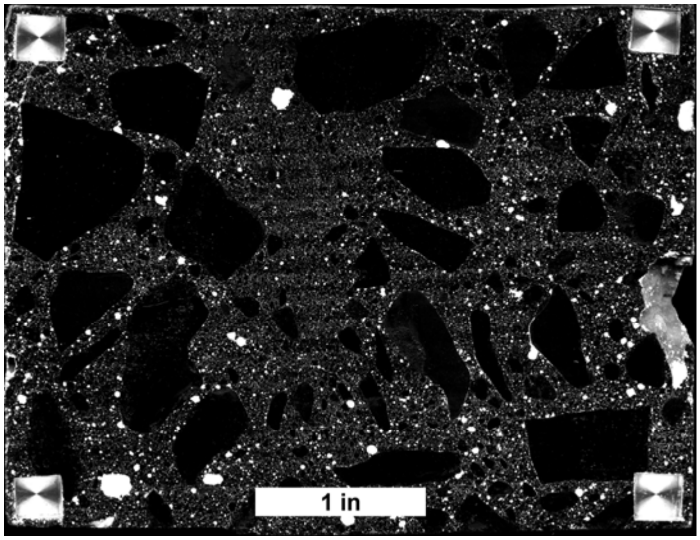


Figure 73: Scanned images of NE-4C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic
6.99% air | 7.45% air
0.111mm SF | 0.093mm SF



5.38% air | 3.58% air
0.108mm SF | 0.176mm SF

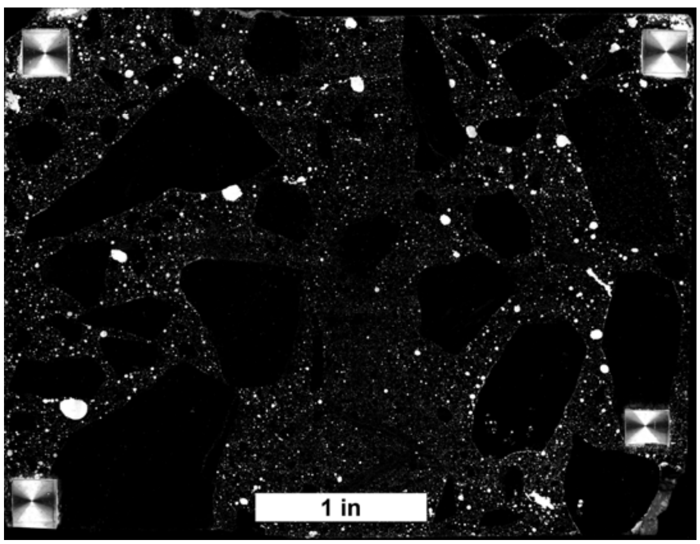


Figure 74: Scanned images of NE-3A slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

3.23% air | 3.87% air

0.116mm SF | 0.144mm SF

5.05% air | 3.36% air

0.139mm SF | 0.160mm SF

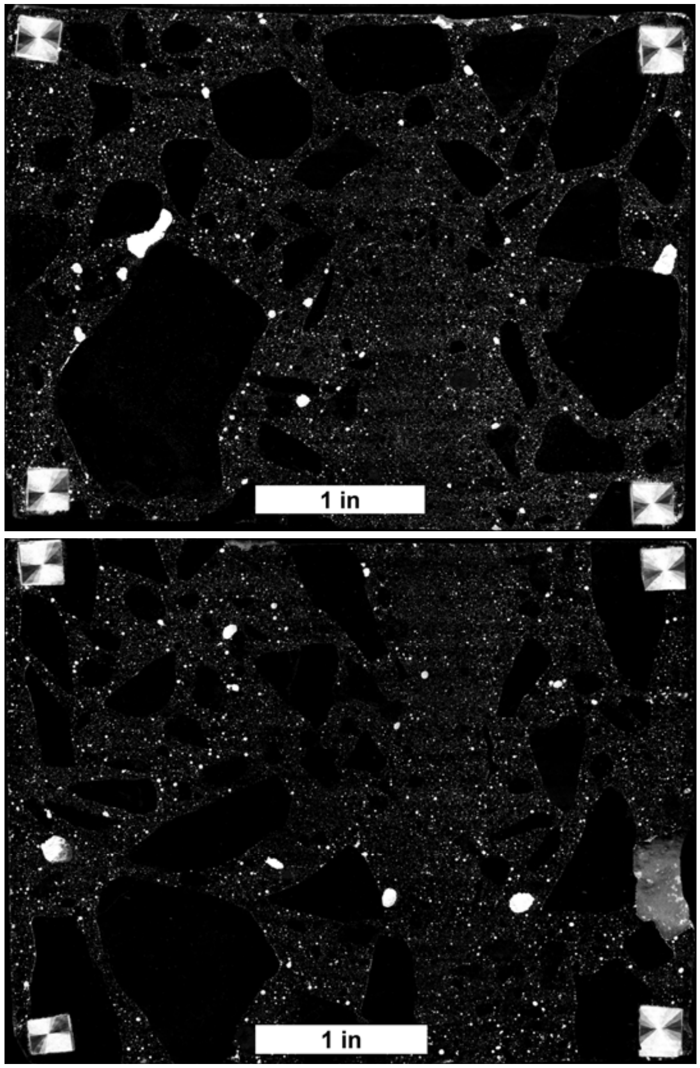
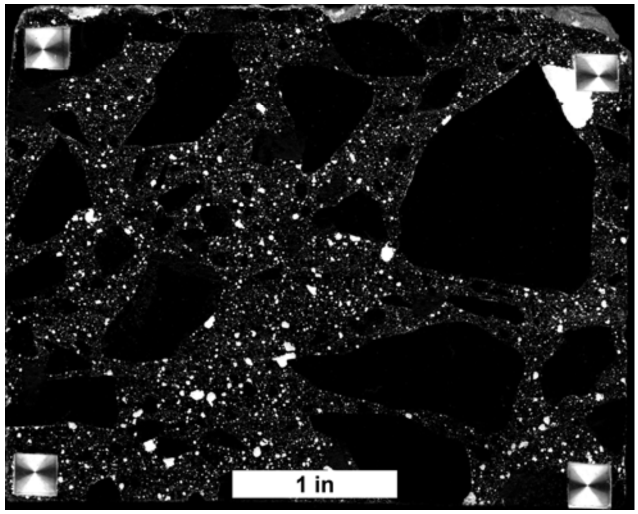


Figure 75: Scanned images of NE-3B slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

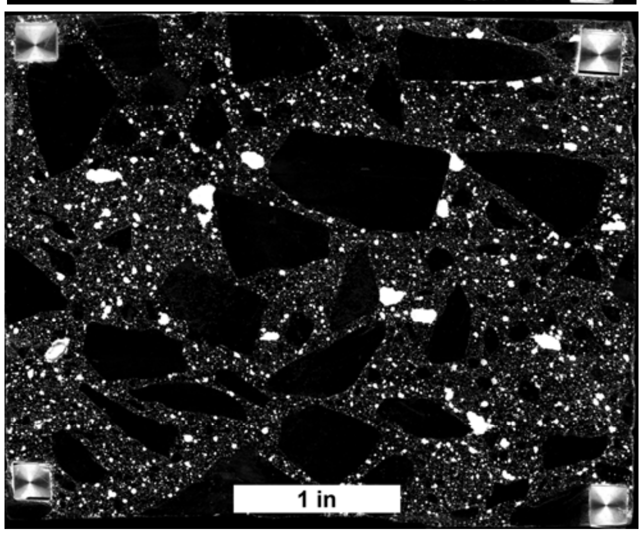
5.59% air | 5.87% air

0.080mm SF | 0.115mm SF



9.25% air | 8.59% air

0.122mm SF | 0.086mm SF



7.20% air | 6.49% air

0.144mm SF | 0.141mm SF

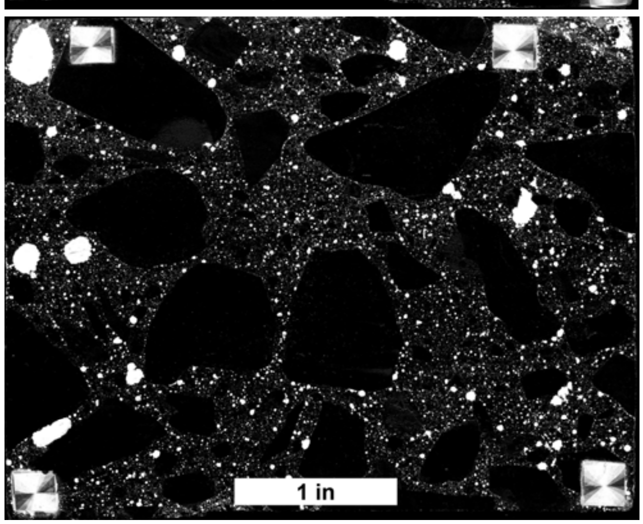


Figure 76: Scanned images of NE-3C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

5.27% air | 6.01% air

0.066mm SF | 0.053mm SF

6.67% air | 6.32% air

0.079mm SF | 0.077mm SF

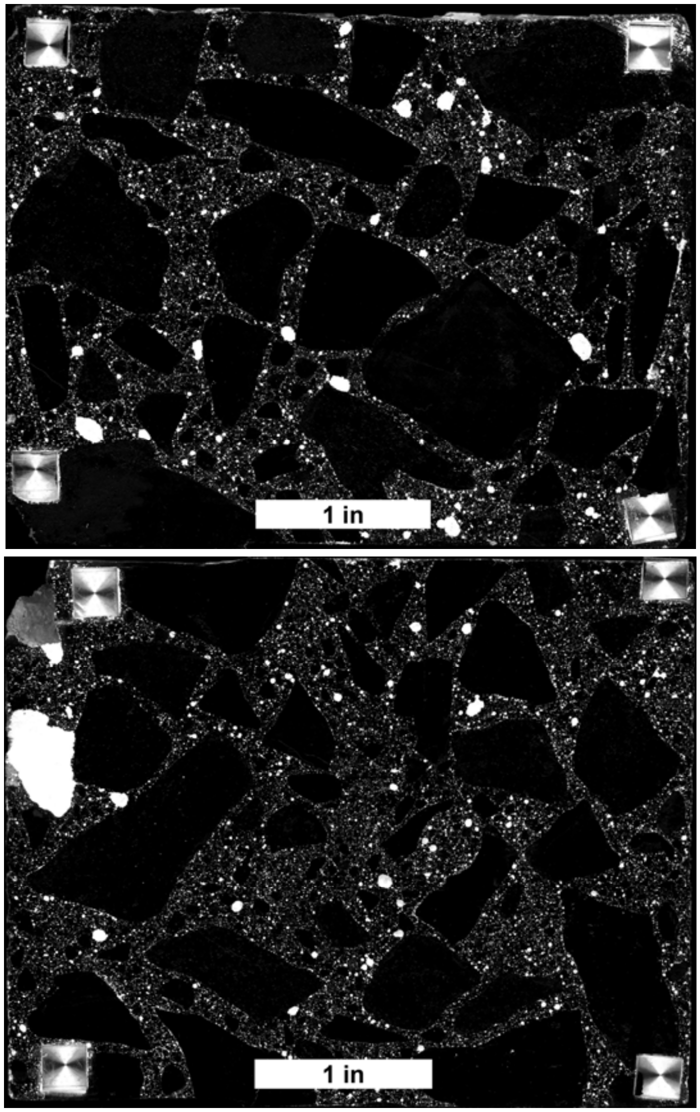


Figure 77: Scanned images of NE-1A slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

2.58% air | 4.83% air

0.097mm SF | 0.104mm SF

6.45% air | 6.34% air

0.140mm SF | 0.137mm SF

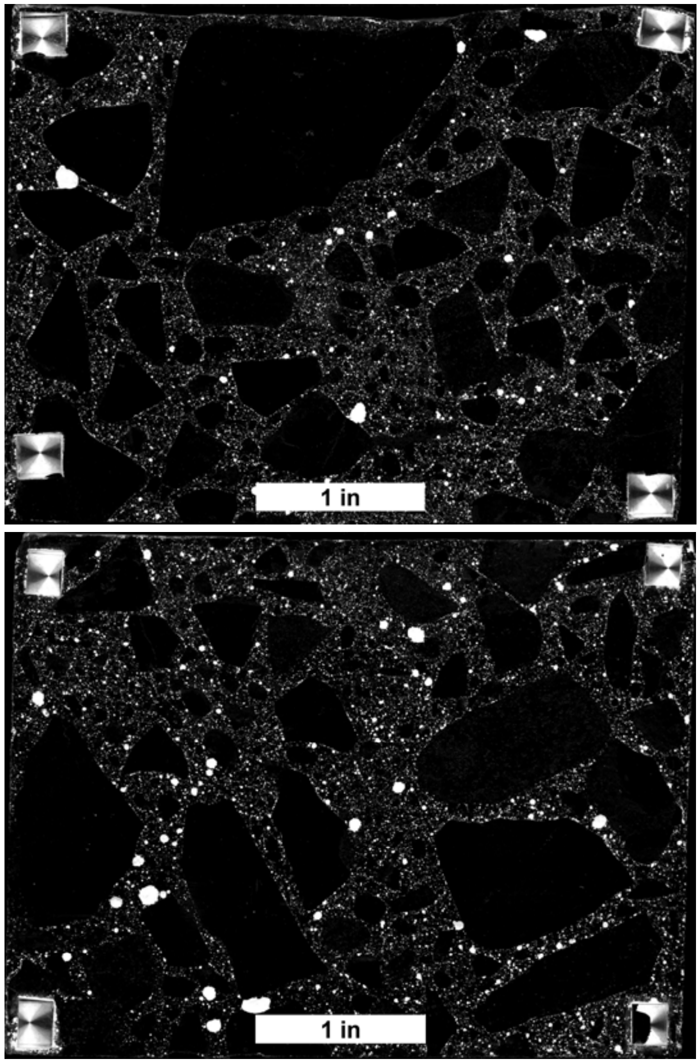


Figure 78: Scanned images of NE-1B slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

4.84% air | 6.34% air

0.148mm SF | 0.124mm SF

9.25% air | 9.53% air

0.054mm SF | 0.067mm SF

12.26% air | 10.58% air

0.098mm SF | 0.098mm SF

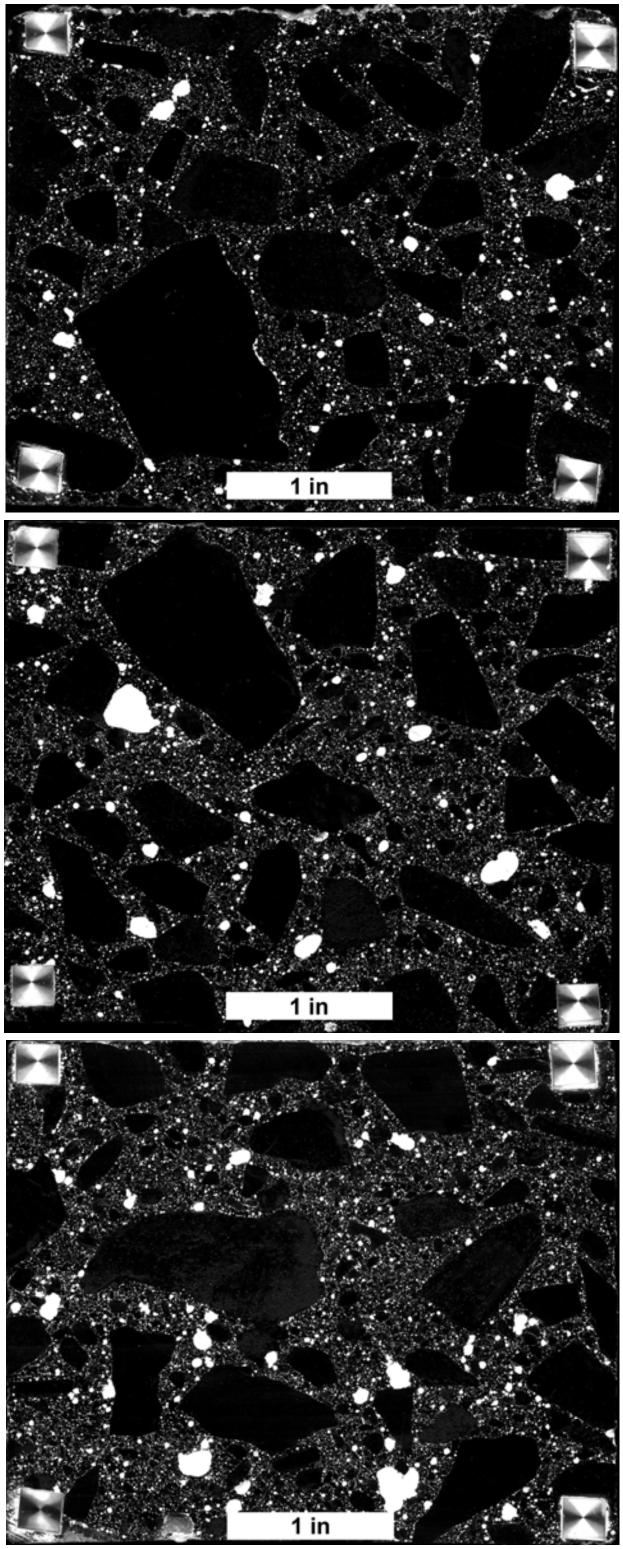


Figure 79: Scanned images of NE-1C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

6.88% air | 11.10% air

0.149mm SF | 0.084mm SF

7.20% air | 7.55% air

0.120mm SF | 0.123mm SF

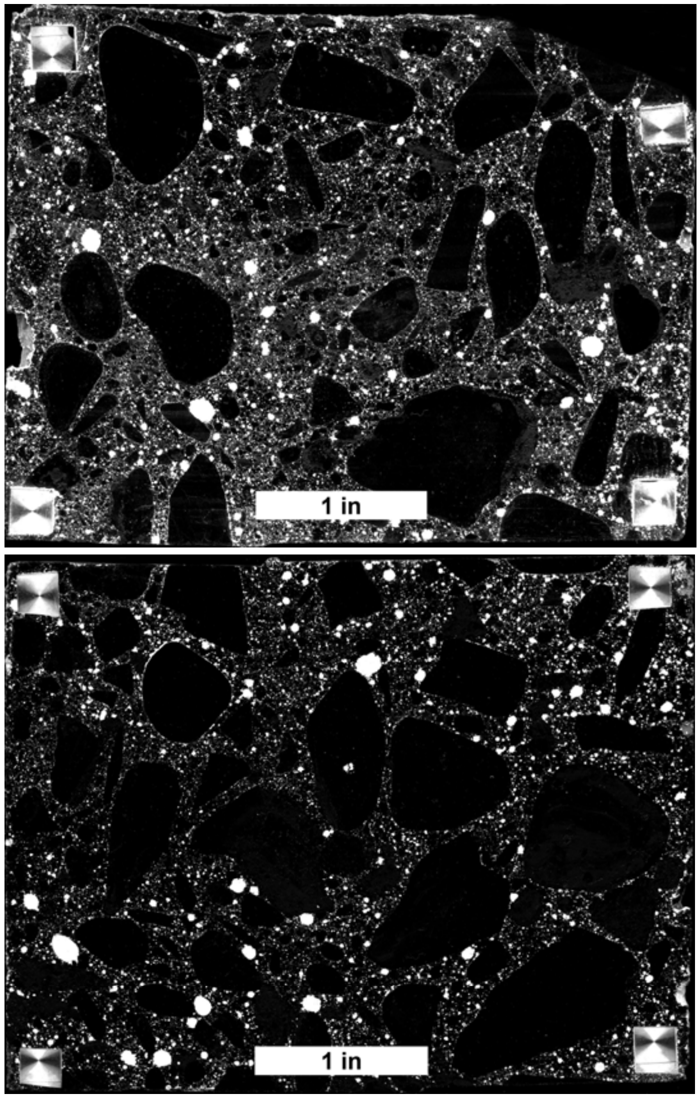


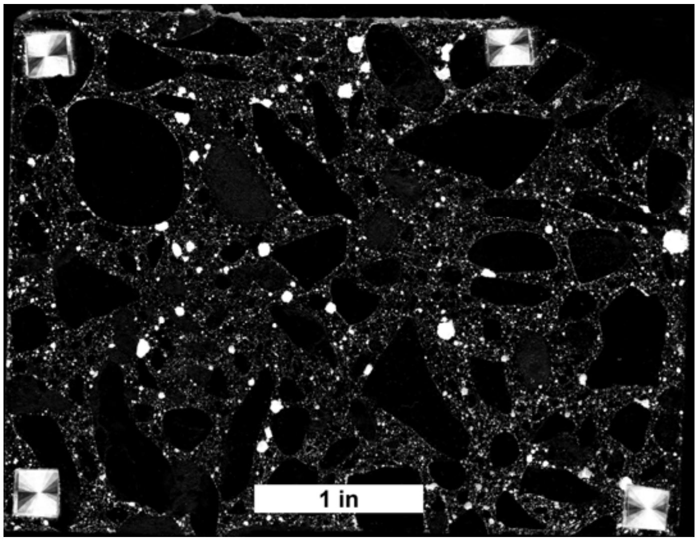
Figure 80: Scanned images of NW-1A slabs post contrast treatment analyzed using the automatic technique.

Manual

Automatic

4.41% air

0.122mm SF

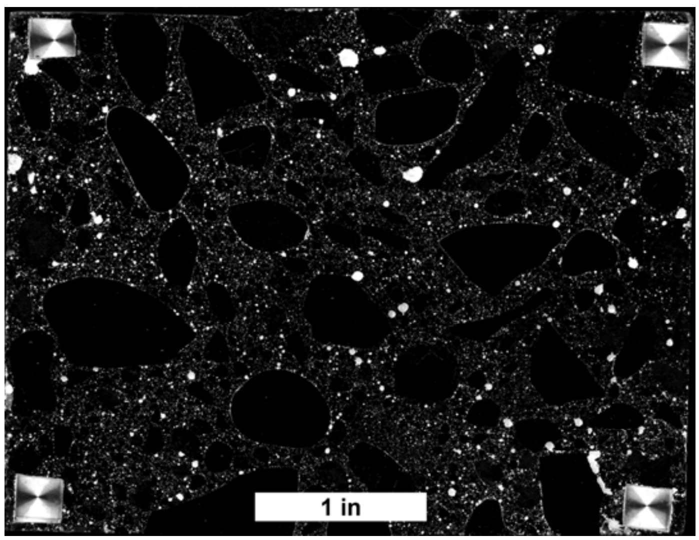


6.19% air

0.117mm SF

5.91% air

0.136mm SF

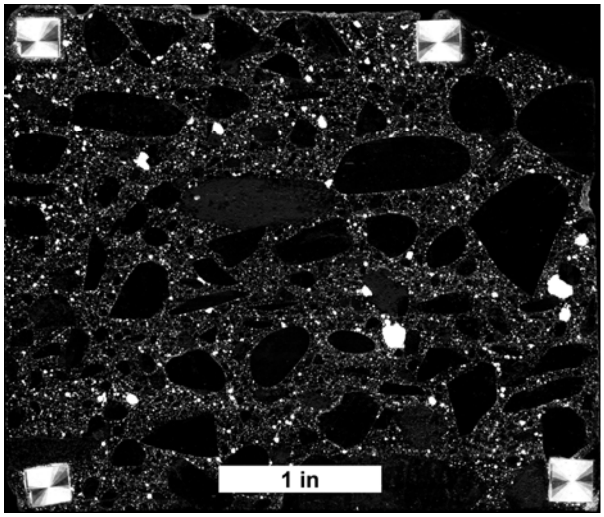


5.45% air

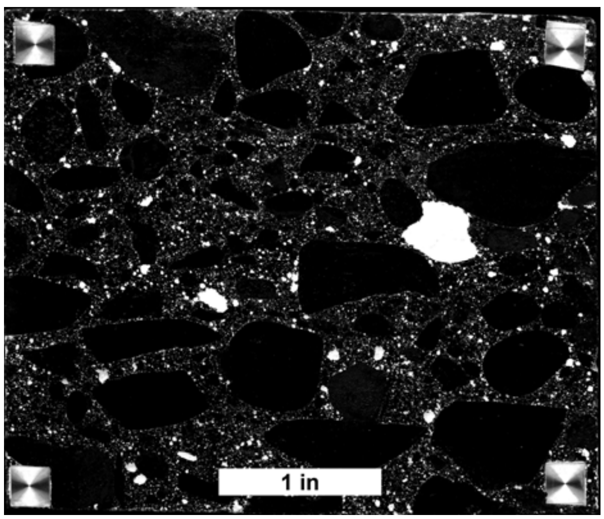
0.130mm SF

Figure 81: Scanned images of NW-1B slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
7.20% air	7.32% air
0.121mm SF	0.122mm SF



5.38% air	7.94% air
0.106mm SF	0.083mm SF



7.31% air	7.65% air
0.125mm SF	0.124mm SF

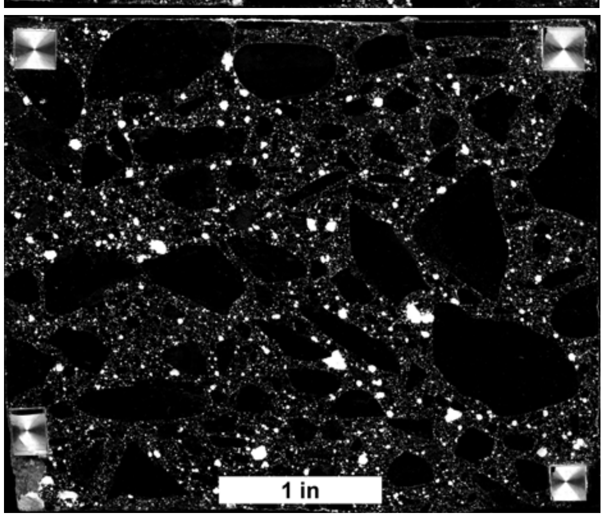


Figure 82: Scanned images of NW-1C slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

6.02% air | 6.34% air

0.092mm SF | 0.133mm SF

7.63% air | 6.62% air

0.117mm SF | 0.119mm SF

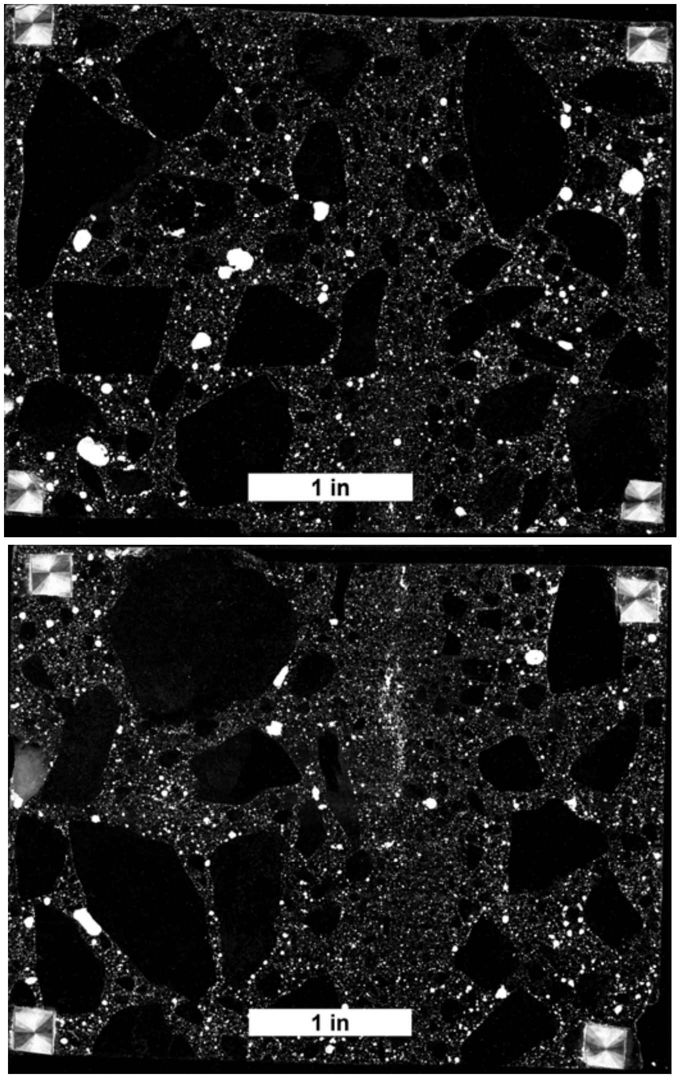
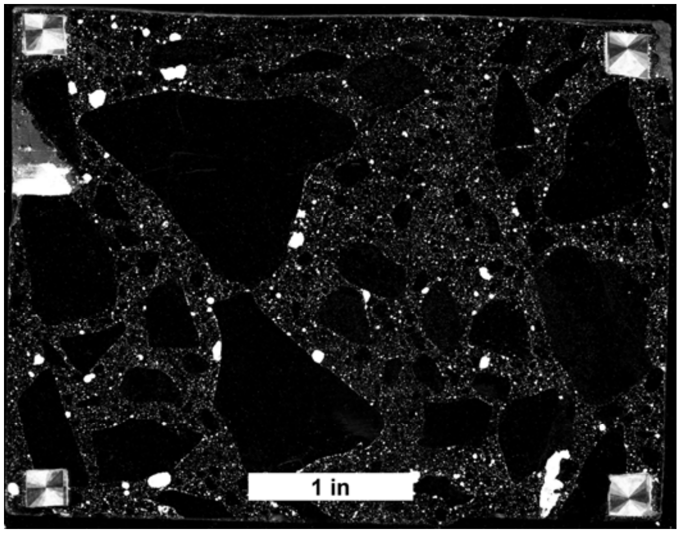


Figure 83: Scanned images of NE-1AA slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

6.34% air | 5.41% air

0.081mm SF | 0.117mm SF



7.63% air | 5.73% air

0.113mm SF | 0.103mm SF

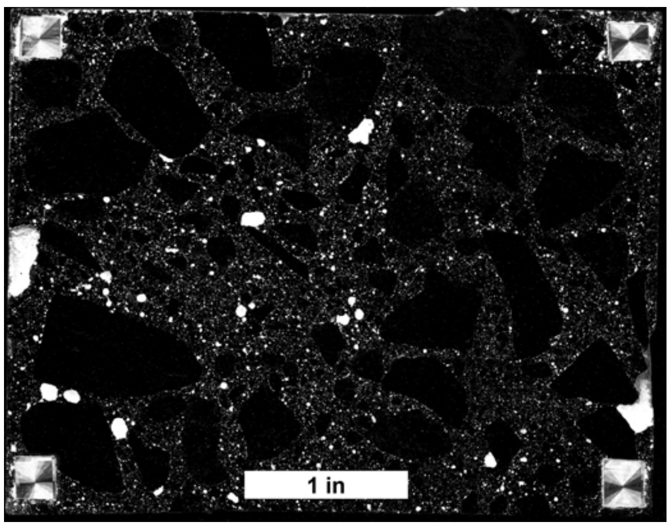


Figure 84: Scanned images of NE-1AB slabs post contrast treatment analyzed using the automatic technique.

Manual	Automatic
6.77% air	6.64% air
0.095mm SF	0.107mm SF
11.51% air	10.07% air
0.084mm SF	0.098mm SF
9.25% air	9.82% air
0.091mm SF	0.109mm SF

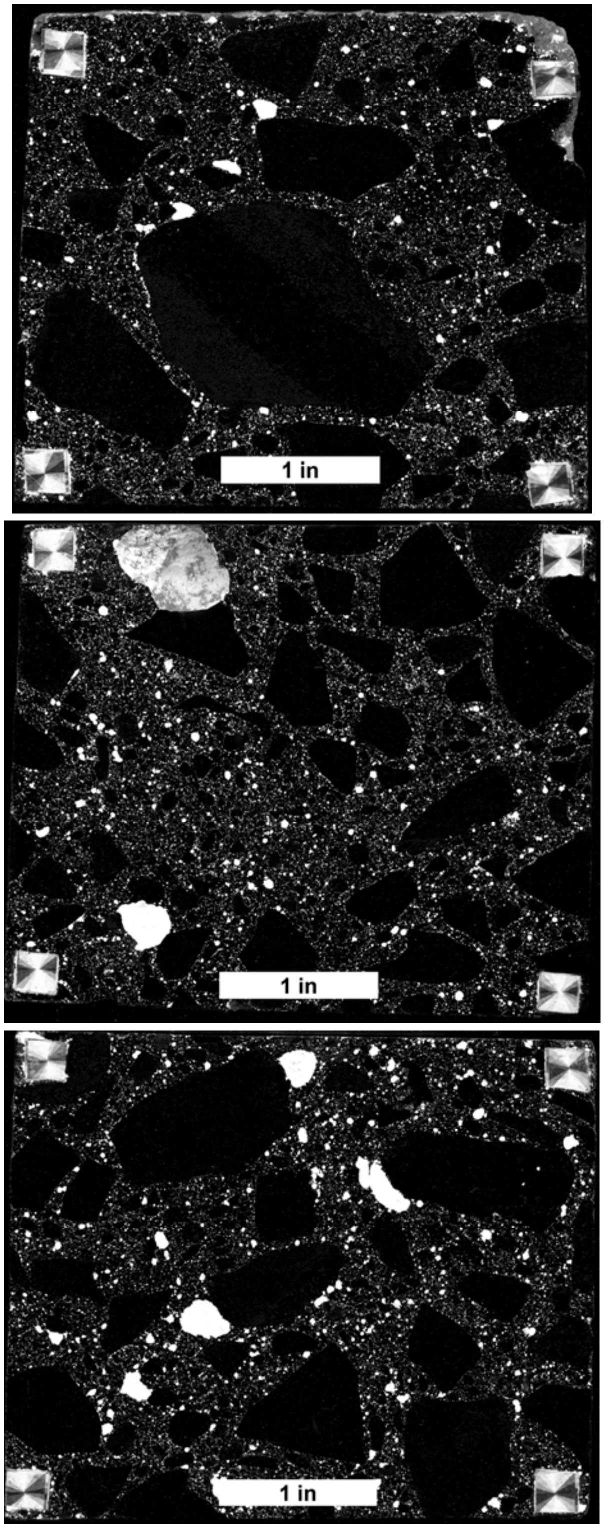


Figure 85: Scanned images of NE-1AC slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

8.39% air | 7.49% air

0.085mm SF | 0.122mm SF

6.24% air | 6.65% air

0.087mm SF | 0.113mm SF

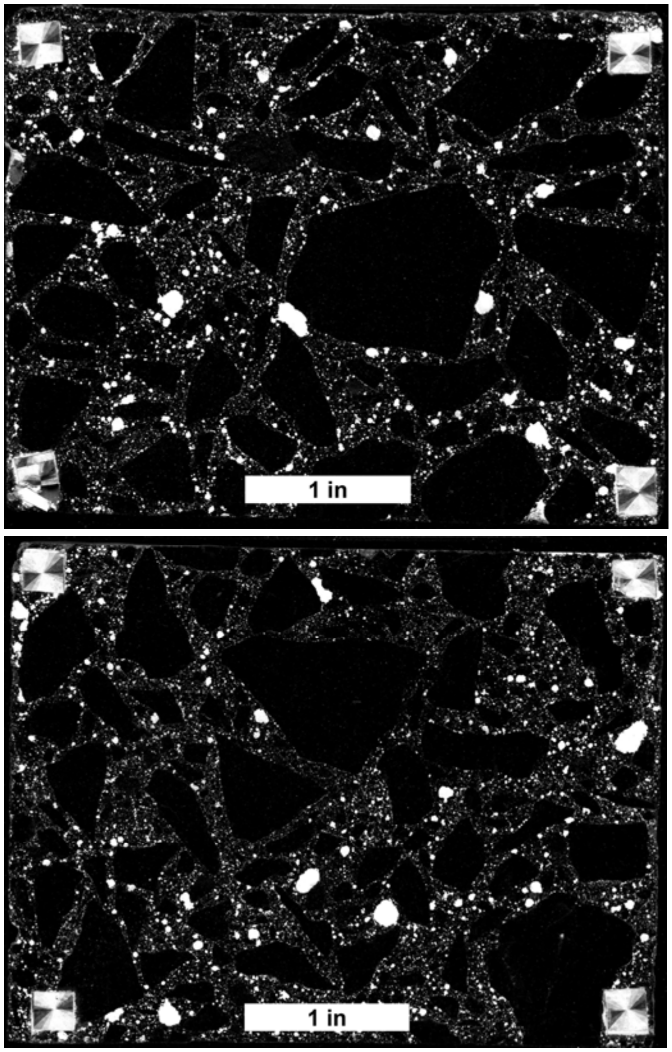


Figure 86: Scanned images of NC-2AA slabs post contrast treatment analyzed using the automatic technique.

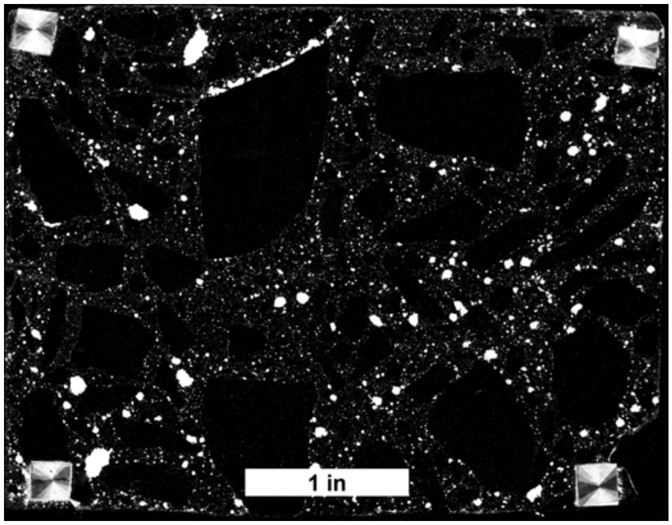
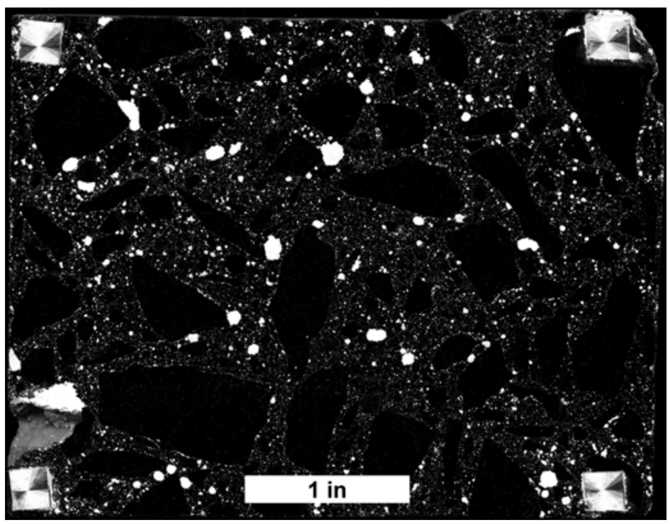
Manual		Automatic
5.48% air 0.143mm SF		5.26% air 0.203mm SF
5.91% air 0.135mm SF		6.13% air 0.174mm SF

Figure 87: Scanned images of NC-2AB slabs post contrast treatment analyzed using the automatic technique.

Manual | Automatic

6.24% air | 8.20% air

0.120mm SF | 0.123mm SF

7.96% air | 9.40% air

0.113mm SF | 0.112mm SF

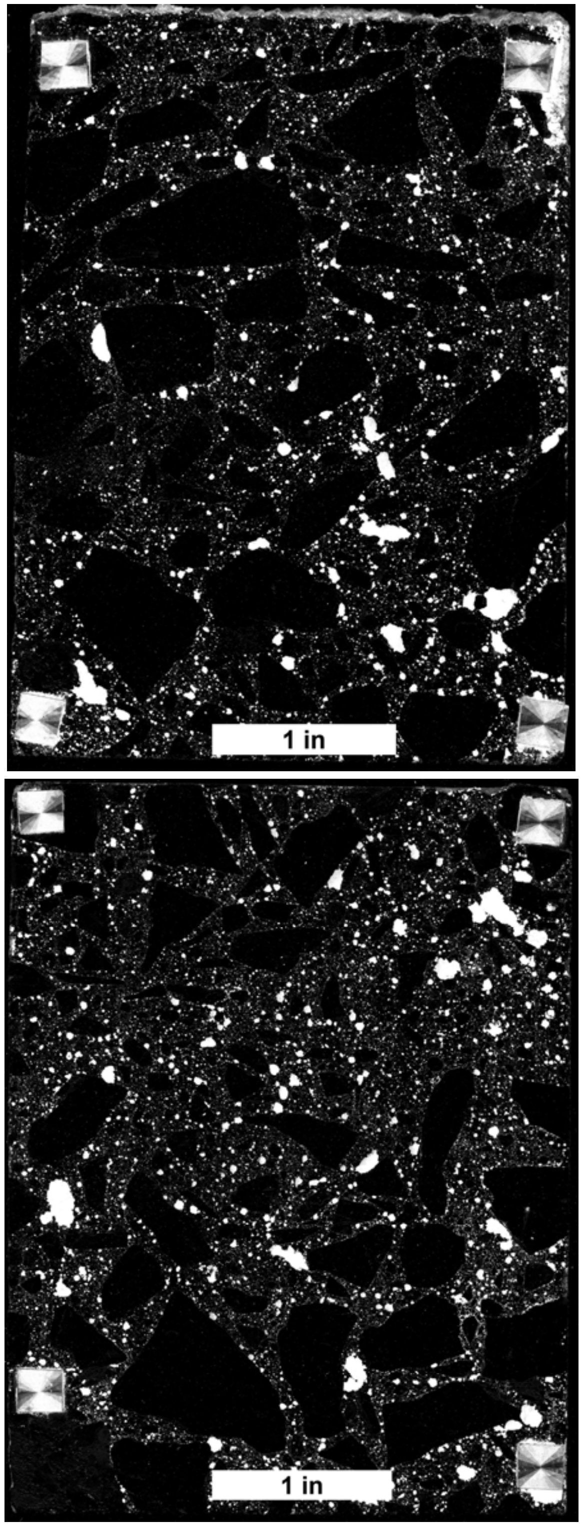


Figure 88: Scanned images of NC-2AC slabs post contrast treatment analyzed using the automatic technique.

Table 3: Results of automatic air-void analyses of individual slabs.

ID	Position	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
SW-1A	Top	2793	2284	0.818	11.66	0.070
SW-1A	Bot	2688	1274	0.474	7.10	0.097
SW-1B	Top	2740	1580	0.577	6.55	0.134
SW-1B	Bot	2656	1264	0.476	6.19	0.132
SW-1C	Top	2508	1058	0.422	5.53	0.144
SW-1C	Mid	2439	1018	0.417	6.70	0.144
SW-1C	Bot	2487	1318	0.530	8.68	0.110
SE-1A	Top	2740	1098	0.401	4.53	0.103
SE-1A	Bot	3062	1863	0.608	7.66	0.089
SE-1B	Top	2603	1220	0.469	5.95	0.119
SE-1B	Bot	2529	876	0.346	4.54	0.150
SE-1C	Top	2339	1520	0.650	8.82	0.044
SE-1C	Mid	2323	1061	0.457	6.68	0.124
SE-1C	Bot	2434	985	0.405	5.22	0.098
SW-3A	Top	2651	2346	0.885	15.41	0.065
SW-3A	Bot	2672	1932	0.723	8.96	0.095
SW-3B	Top	2798	2204	0.788	13.46	0.066
SW-3B	Bot	2592	1822	0.703	7.88	0.075
SW-3C	Top	2381	1726	0.725	12.60	0.065
SW-3C	Bot	2244	1517	0.676	10.87	0.082
SW-2A	Top	2756	1498	0.544	7.72	0.090
SW-2A	Bot	2714	1834	0.676	9.24	0.063
SW-2B	Top	2872	1383	0.481	6.13	0.109
SW-2B	Bot	2598	1494	0.575	6.52	0.104
SW-2C	Top	2339	1125	0.481	5.27	0.076
SW-2C	Mid	2476	1366	0.552	6.70	0.094
SW-2C	Bot	2445	1428	0.584	8.30	0.078
NC-1A	Top	2867	971	0.339	4.73	0.135
NC-1A	Bot	2571	1515	0.589	8.87	0.129
NC-1B	Top	2603	996	0.383	5.08	0.130
NC-1B	Bot	2624	1948	0.742	8.32	0.092
NC-1C	Top	2276	1100	0.483	7.87	0.121
NC-1C	Mid	2212	1122	0.507	8.45	0.124
NC-1C	Bot	2323	1609	0.693	11.62	0.088
SE-2A	Top	2582	1400	0.542	8.07	0.080
SE-2A	Bot	2592	1061	0.409	5.49	0.150
SE-2B	Top	2592	844	0.326	5.18	0.180
SE-2B	Bot	2561	860	0.336	4.65	0.121
SE-2C	Top	2571	767	0.298	5.97	0.150
SE-2C	Mid	2476	627	0.253	4.43	0.206
SE-2C	Bot	2550	700	0.274	6.48	0.204
NE-2A	Top	2239	1323	0.591	8.43	0.083
NE-2A	Bot	2233	1222	0.547	8.47	0.101
NE-2B	Top	2581	1377	0.533	6.90	0.111
NE-2B	Bot	2635	1643	0.624	7.86	0.110
NE-2C	Top	2397	1447	0.604	7.32	0.100

ID	Position	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
NE-2C	Mid	2434	785	0.323	4.59	0.126
NE-2C	Bot	2497	1170	0.468	7.18	0.130
NC-2A	Top	2656	1071	0.403	10.11	0.102
NC-2A	Bot	3036	1392	0.458	11.09	0.110
NC-2B	Top	2767	1294	0.468	8.59	0.124
NC-2B	Bot	2651	1745	0.658	9.94	0.105
NC-2C	Top	2286	1445	0.632	17.24	0.079
NC-2C	Mid	2064	1204	0.583	10.85	0.105
NC-2C	Bot	2466	1446	0.586	10.70	0.105
NE-4A	Top	2624	1197	0.456	5.41	0.112
NE-4A	Bot	2603	1531	0.588	7.27	0.110
NE-4B	Top	2577	1637	0.635	8.37	0.082
NE-4B	Bot	2645	1559	0.589	10.86	0.101
NE-4C	Top	2344	1266	0.540	8.70	0.079
NE-4C	Mid	2402	1204	0.501	8.95	0.089
NE-4C	Bot	2381	1248	0.524	6.98	0.126
NE-3A	Top	2724	1902	0.698	7.45	0.093
NE-3A	Bot	2550	680	0.267	3.58	0.176
NE-3B	Top	2814	1047	0.372	3.87	0.144
NE-3B	Bot	2709	857	0.316	3.36	0.160
NE-3C	Top	2434	949	0.390	5.87	0.115
NE-3C	Mid	2540	1330	0.524	8.59	0.086
NE-3C	Bot	2661	1034	0.389	6.49	0.141
NE-1A	Top	2592	1128	0.435	6.01	0.053
NE-1A	Bot	2577	1364	0.529	6.32	0.077
NE-1B	Top	2682	1219	0.454	4.83	0.104
NE-1B	Bot	2666	1175	0.441	6.34	0.137
NE-1C	Top	2392	1037	0.434	6.34	0.124
NE-1C	Mid	2466	1360	0.552	9.53	0.067
NE-1C	Bot	2376	1552	0.653	10.58	0.098
NW-1A	Top	2624	2116	0.806	11.10	0.084
NW-1A	Bot	2682	1209	0.451	7.55	0.123
NW-1B	Top	2629	1124	0.427	6.19	0.117
NW-1B	Bot	2582	1199	0.464	5.46	0.130
NW-1C	Top	2603	1480	0.569	7.32	0.122
NW-1C	Mid	2418	1102	0.456	7.94	0.083
NW-1C	Bot	2397	1179	0.492	7.65	0.124
NE-1AA	Top	2829	1250	0.442	6.34	0.133
NE-1AA	Bot	2708	1411	0.521	6.62	0.119
NE-1AB	Top	2523	1087	0.431	5.41	0.117
NE-1AB	Bot	2681	1306	0.487	5.73	0.103
NE-1AC	Top	2222	1104	0.497	6.64	0.107
NE-1AC	Mid	2745	1971	0.718	10.07	0.098
NE-1AC	Bot	2397	1253	0.523	9.82	0.109
NC-2AA	Top	2686	1037	0.386	7.49	0.122
NC-2AA	Bot	2697	1126	0.417	6.65	0.113
NC-2AB	Top	2787	796	0.286	5.26	0.203
NC-2AB	Bot	2481	921	0.371	6.13	0.174

ID	Position	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
NC-2AC	Top	1806	753	0.417	8.20	0.123
NC-2AC	Bot	2019	980	0.485	9.40	0.112

Table 4: Results of automatic air-void analyses of each specimen (cylinder or core).

ID	Traverse (mm)	Air-Void Intercepts	Void frequency (mm^{-1})	Air content (%)	Spacing Factor (mm)
SW-1A	5481	3558	0.649	9.42	0.057
SW-1B	5396	2844	0.527	6.37	0.089
SW-1C	7434	3394	0.457	6.97	0.090
SE-1A	5803	2961	0.510	6.19	0.079
SE-1B	5132	2096	0.408	5.26	0.107
SE-1C	7096	3566	0.503	6.88	0.056
SW-3A	5322	4278	0.804	12.17	0.036
SW-3B	5391	4026	0.747	10.77	0.039
SW-3C	4625	3243	0.701	11.76	0.043
SW-2A	5470	3332	0.609	8.47	0.048
SW-2B	5470	2877	0.526	6.31	0.062
SW-2C	7260	3919	0.540	6.78	0.054
NC-1A	5438	2486	0.457	6.69	0.106
NC-1B	5227	2944	0.563	6.71	0.080
NC-1C	6811	3831	0.562	9.34	0.069
SE-2A	5174	2461	0.476	6.78	0.107
SE-2B	5153	1704	0.331	4.92	0.130
SE-2C	7598	2094	0.276	5.64	0.208
NE-2A	4472	2545	0.569	8.45	0.052
NE-2B	5216	3020	0.579	7.39	0.071
NE-2C	7329	3402	0.464	6.37	0.095
NE-4A	5227	2728	0.522	6.34	0.063
NE-4B	5222	3196	0.612	9.63	0.064
NE-4C	7128	3718	0.522	8.21	0.064
NE-3A	5275	2582	0.490	5.58	0.086
NE-3B	5523	1904	0.345	3.62	0.143
NE-3C	7635	3313	0.434	6.99	0.098
NE-1A	5169	2492	0.482	6.17	0.059
NE-1B	5349	2394	0.448	5.58	0.109
NE-1C	7234	3949	0.546	8.82	0.064
NW-1A	5306	3325	0.627	9.30	0.082
NW-1B	5211	2323	0.446	5.83	0.112
NW-1C	7418	3761	0.507	7.63	0.090
NC-2A	5692	2463	0.433	10.64	0.089
NC-2B	5417	3039	0.561	9.25	0.078
NC-2C	6816	4095	0.601	12.94	0.063
NE-1AA	5537	2661	0.481	6.47	0.082
NE-1AB	5204	2393	0.460	5.58	0.081
NE-1AC	7363	4328	0.588	8.95	0.058
NC-2AA	5383	2163	0.402	7.07	0.082
NC-2AB	5268	1717	0.326	5.67	0.163
NC-2AC	3825	1733	0.453	8.83	0.099

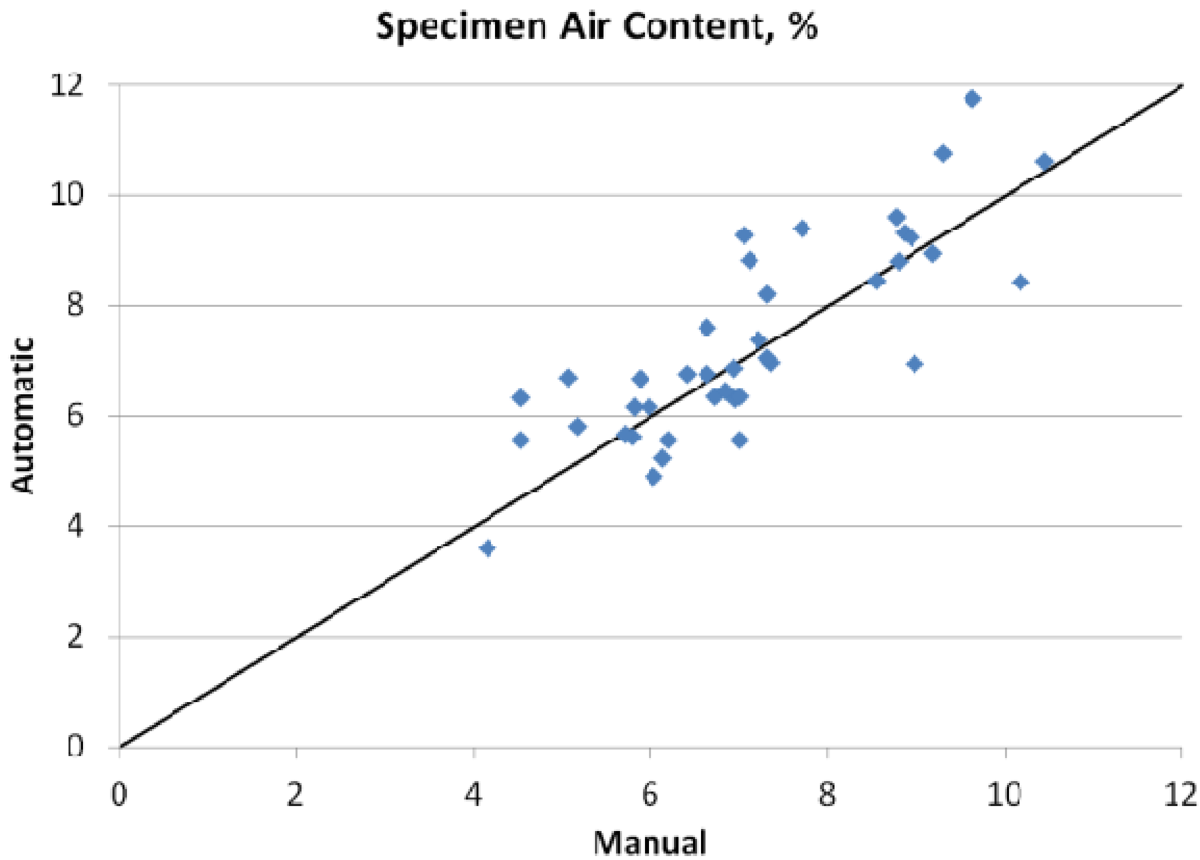


Figure 89: Comparison of air content determined manually and automatically for each specimen (cylinder or core).

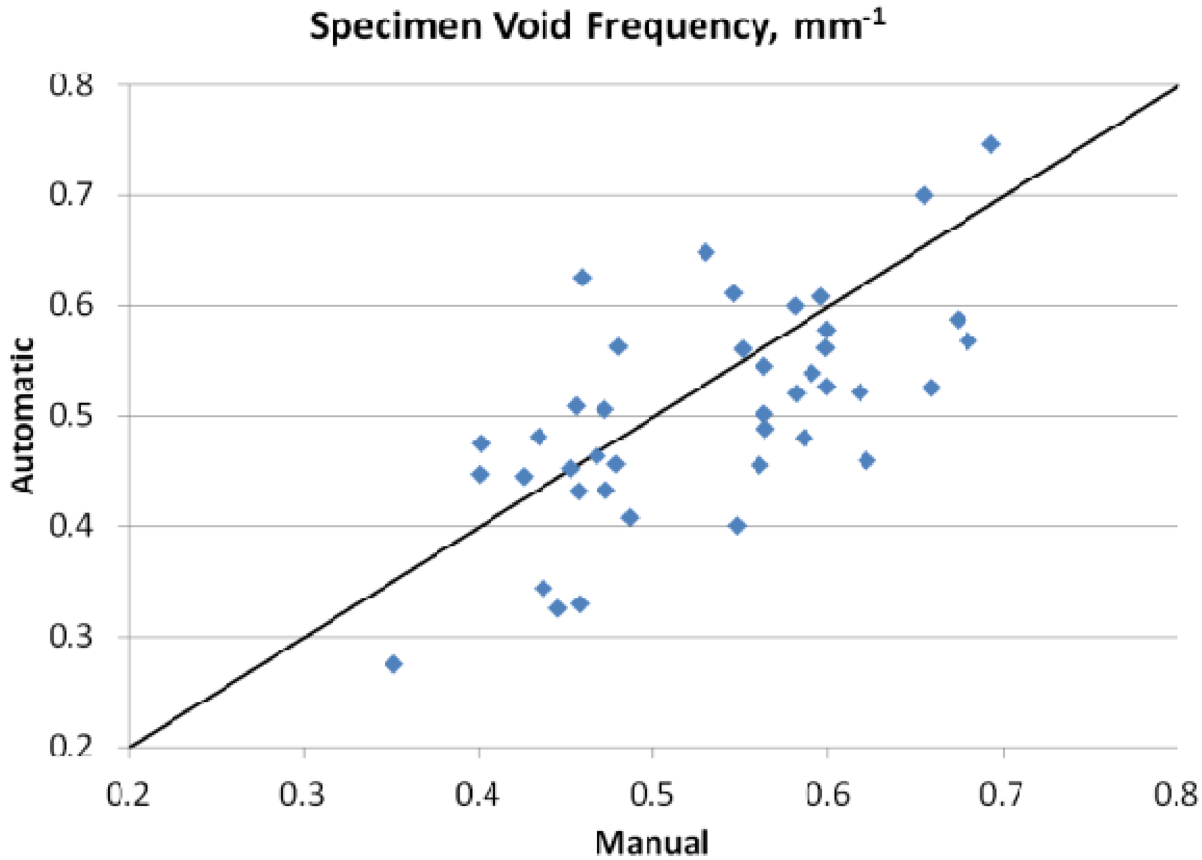


Figure 90: Comparison of void frequency determined manually and automatically for each specimen (cylinder or core).

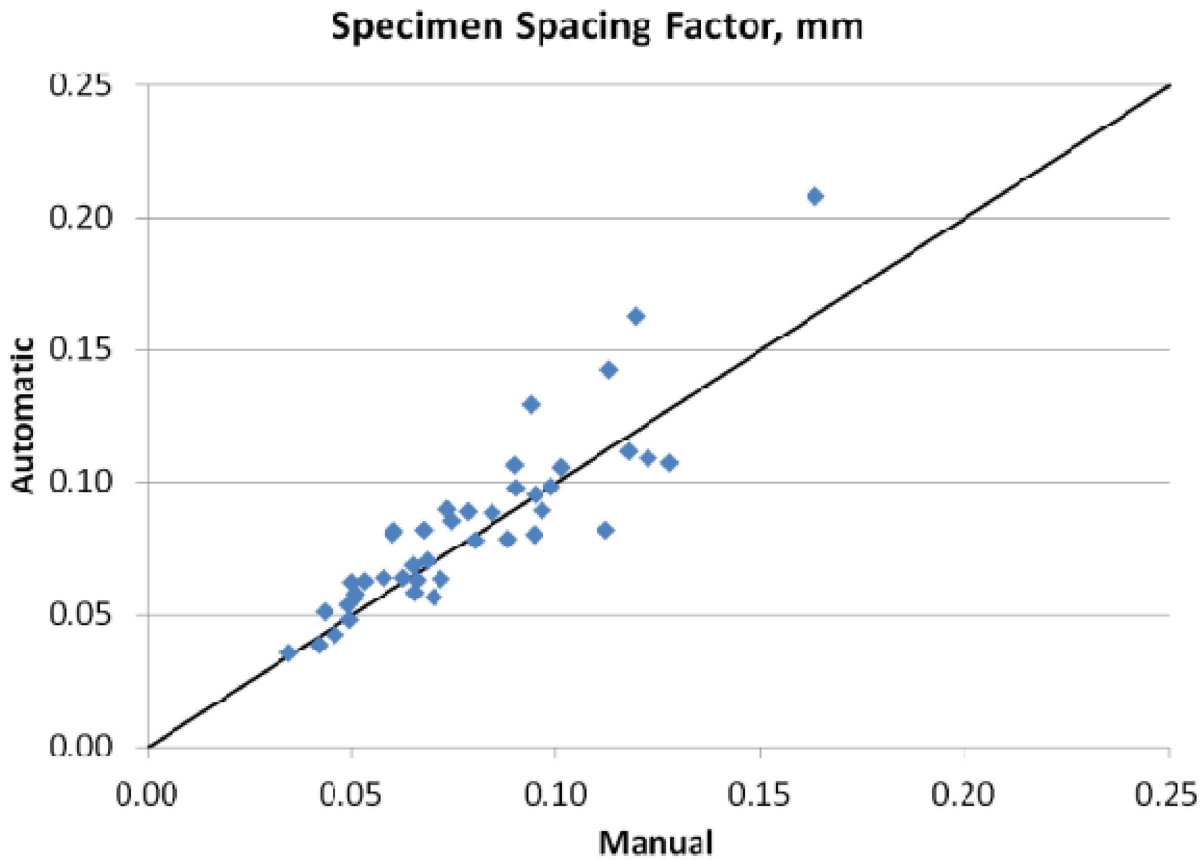


Figure 91: Comparison of spacing factor determined manually and automatically for each specimen (cylinder or core).

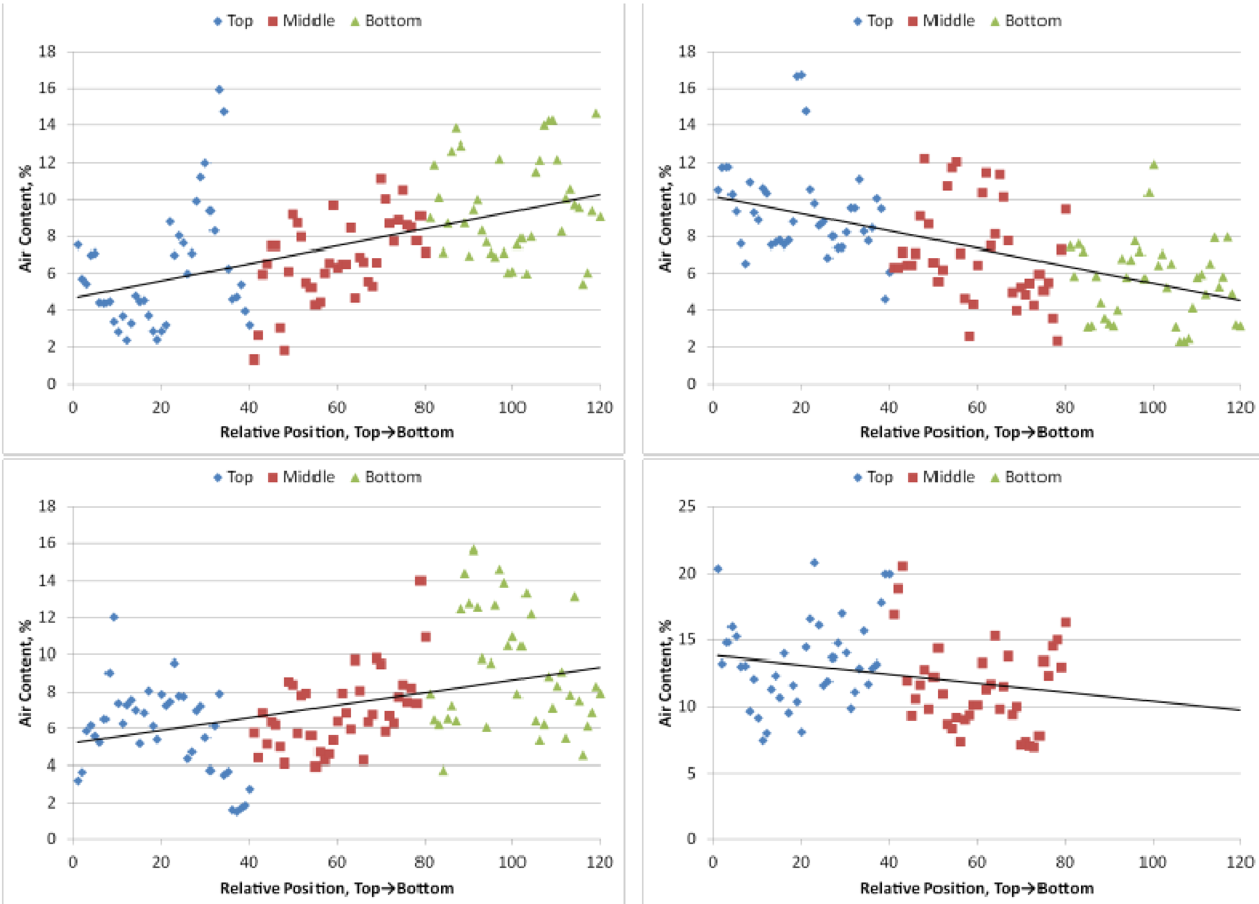


Figure 92: Plots of air content by relative depth in cores. Clockwise from top, left: SW-1C; SE-1C; SW-3C; SW-2C.

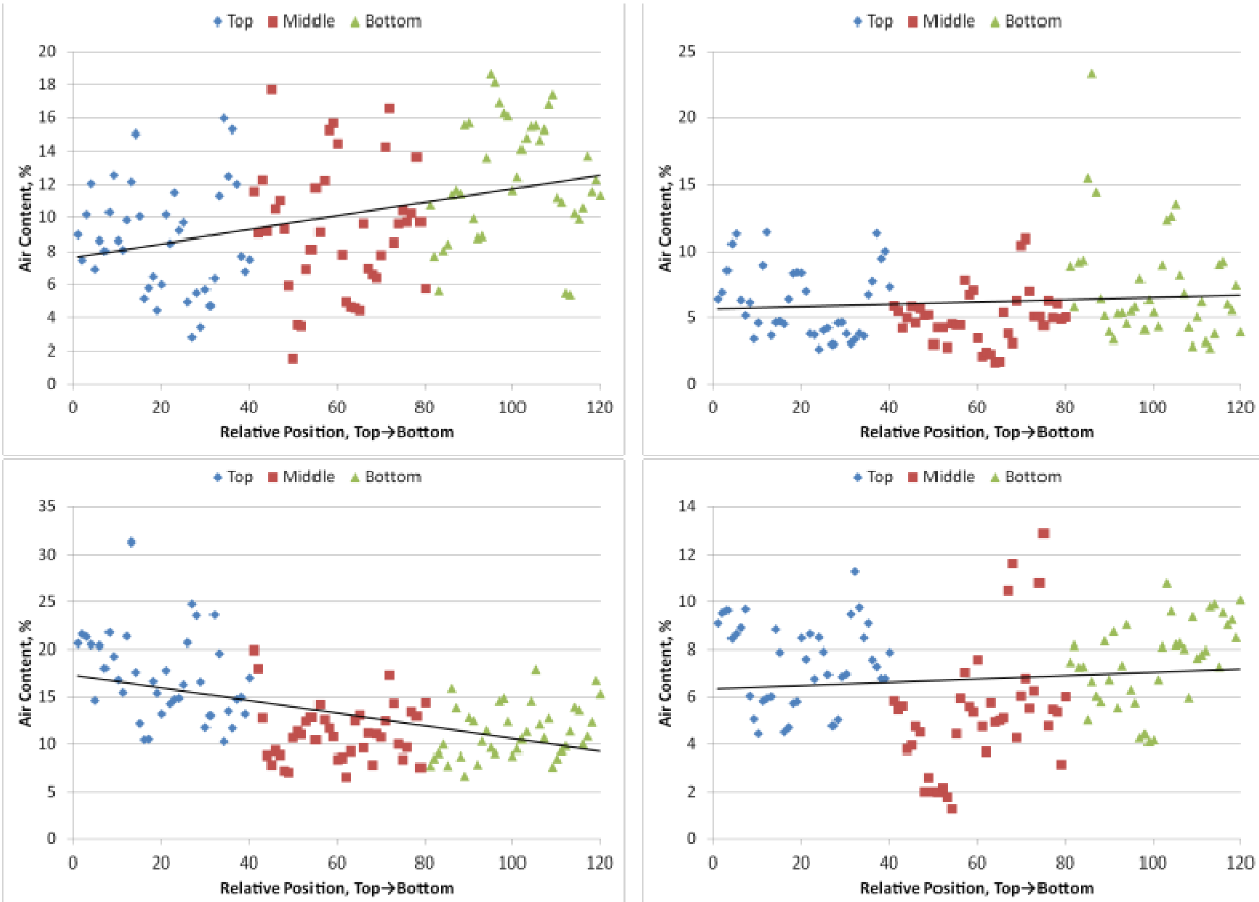


Figure 93: Plots of air content by relative depth in cores. Clockwise from top, left: NC-1C; SE-2C; NE-2C; NC-2C.

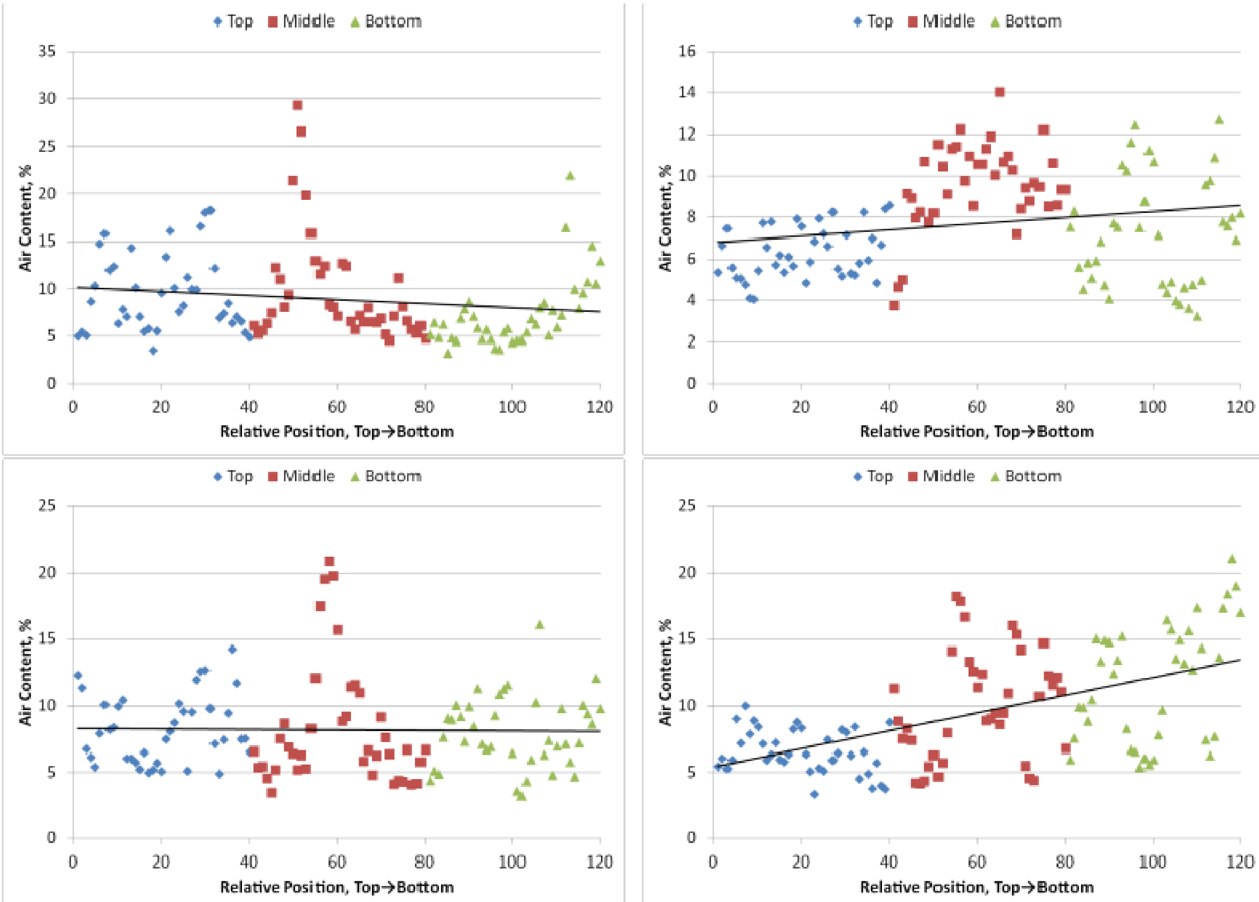


Figure 94: Plots of air content by relative depth in cores. Clockwise from top, left: NE-4C; NE-3C; NE-1C; NW-1C.

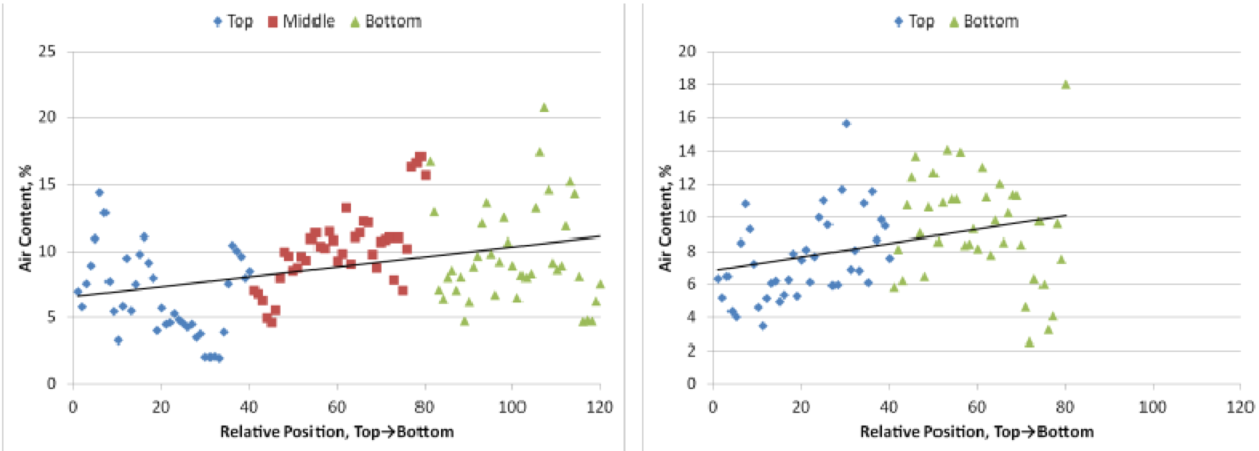


Figure 95: Plots of air content by relative depth in cores. NE-1AC (left) NC-2AC(right).

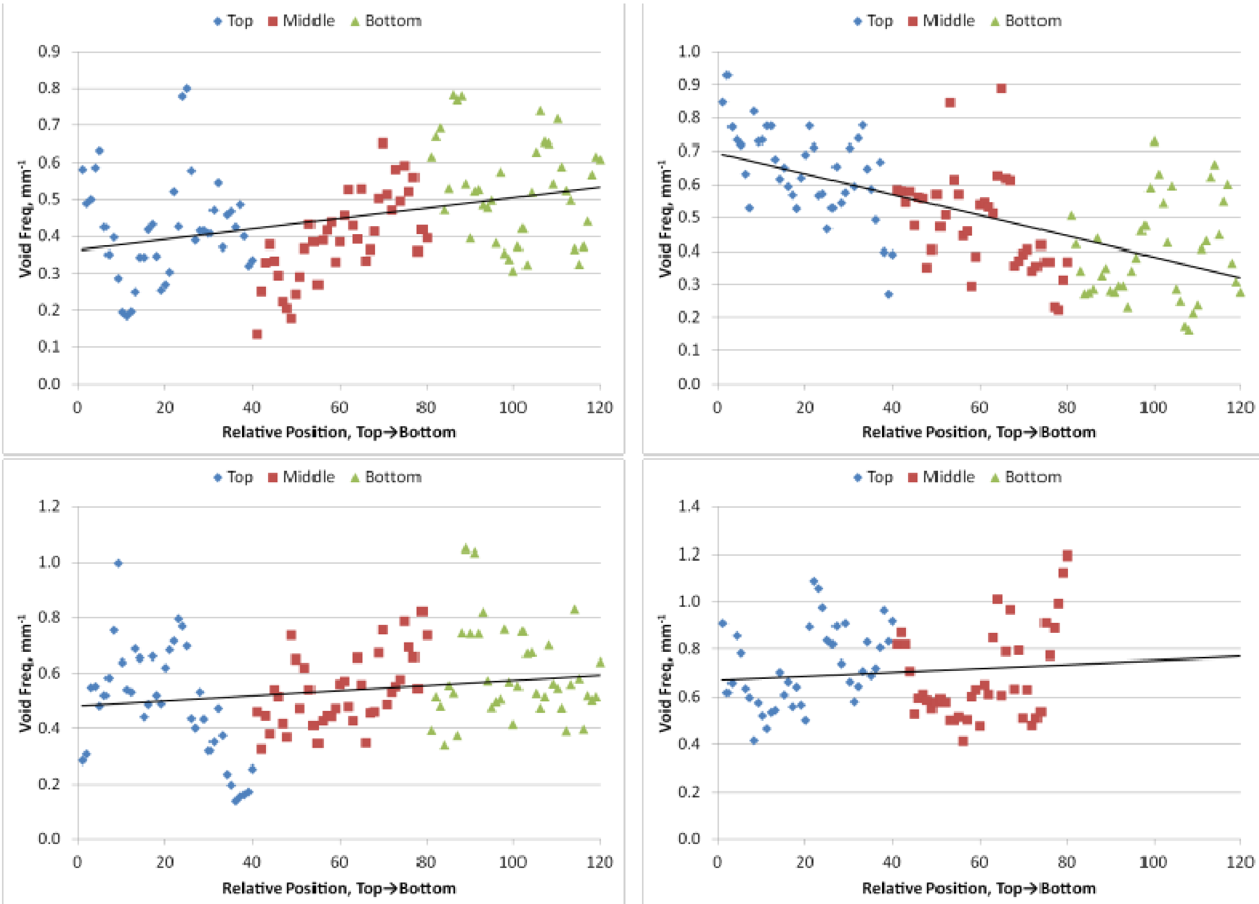


Figure 96: Plots of void frequency by relative depth in cores. Clockwise from top, left: SW-1C; SE-1C; SW-3C; SW-2C.

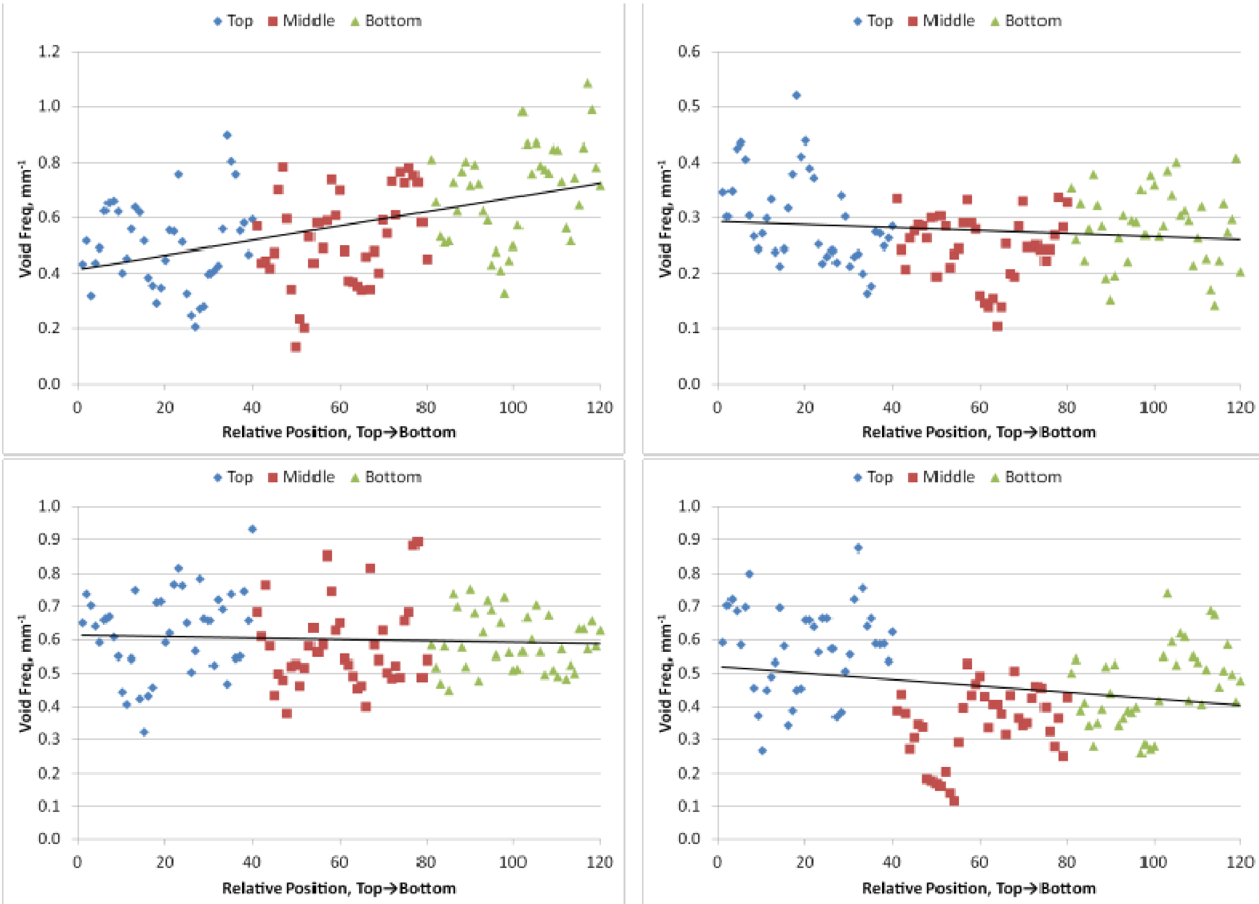


Figure 97: Plots of void frequency by relative depth in cores. Clockwise from top, left: NC-1C; SE-2C; NE-2C; NC-2C.

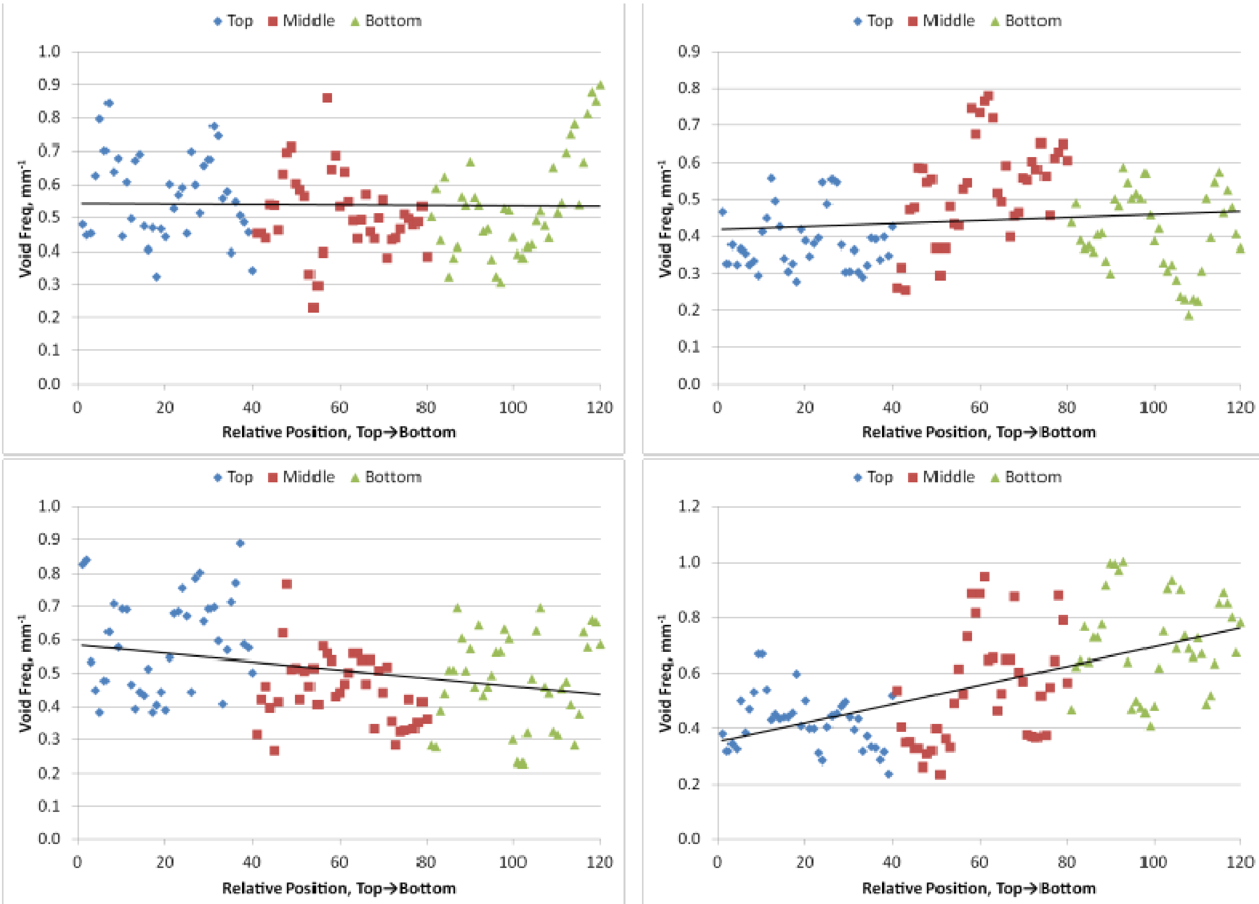


Figure 98: Plots of void frequency by relative depth in cores. Clockwise from top, left: NE-4C; NE-3C; NE-1C; NW-1C.

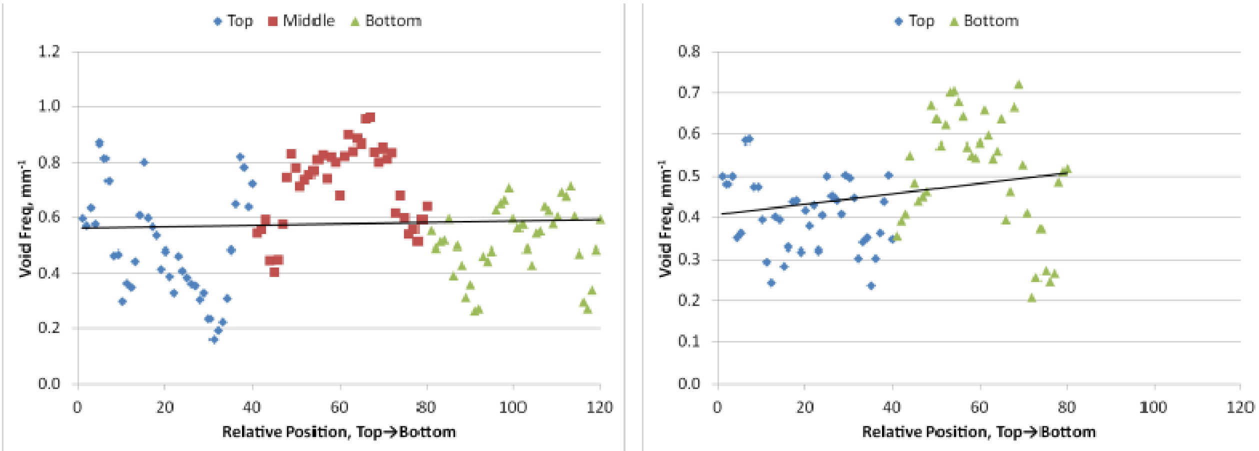


Figure 99: Plots of void frequency by relative depth in cores. NE-1AC (left) NC-2AC(right).

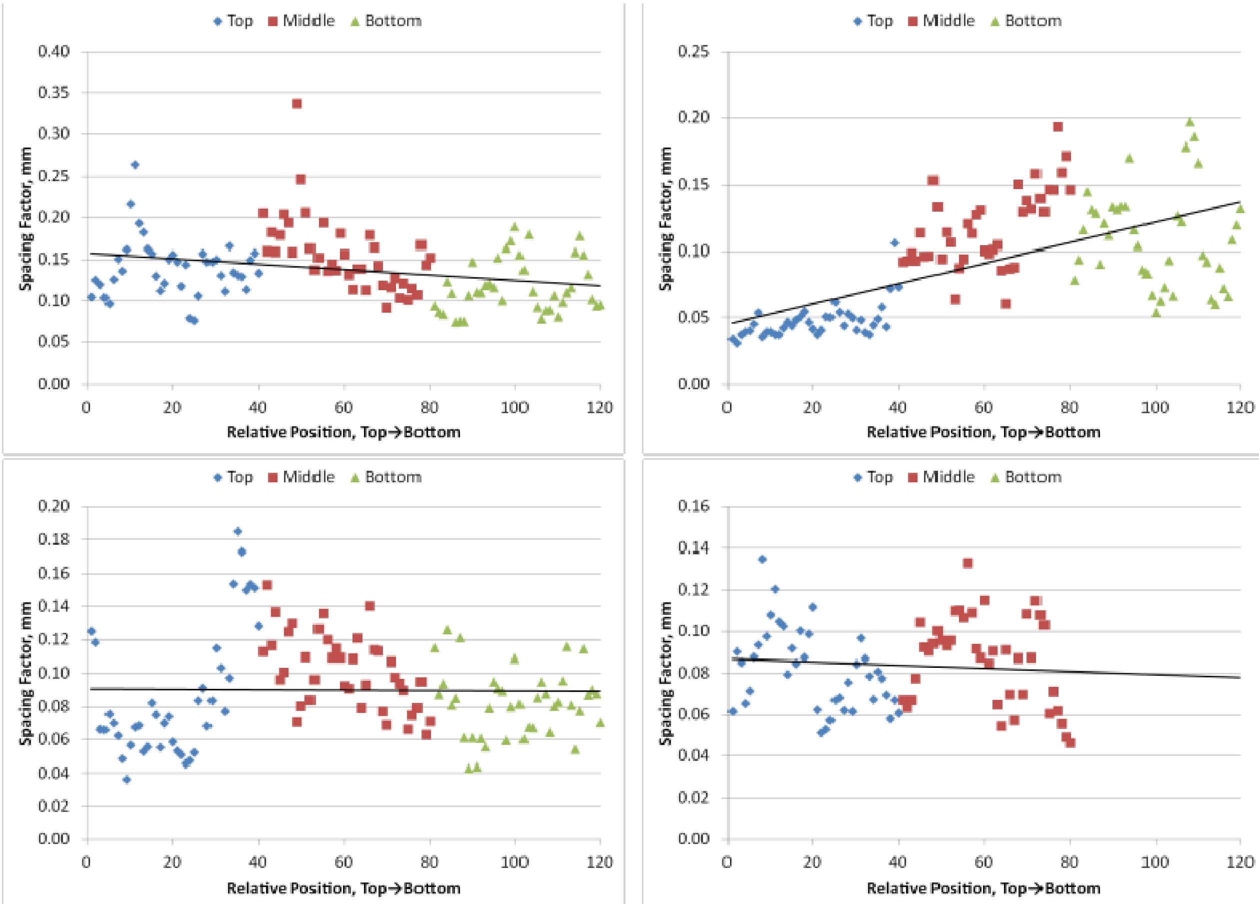


Figure 100: Plots of spacing factor by relative depth in cores. Clockwise from top, left: SW-1C; SE-1C; SW-3C; SW-2C.

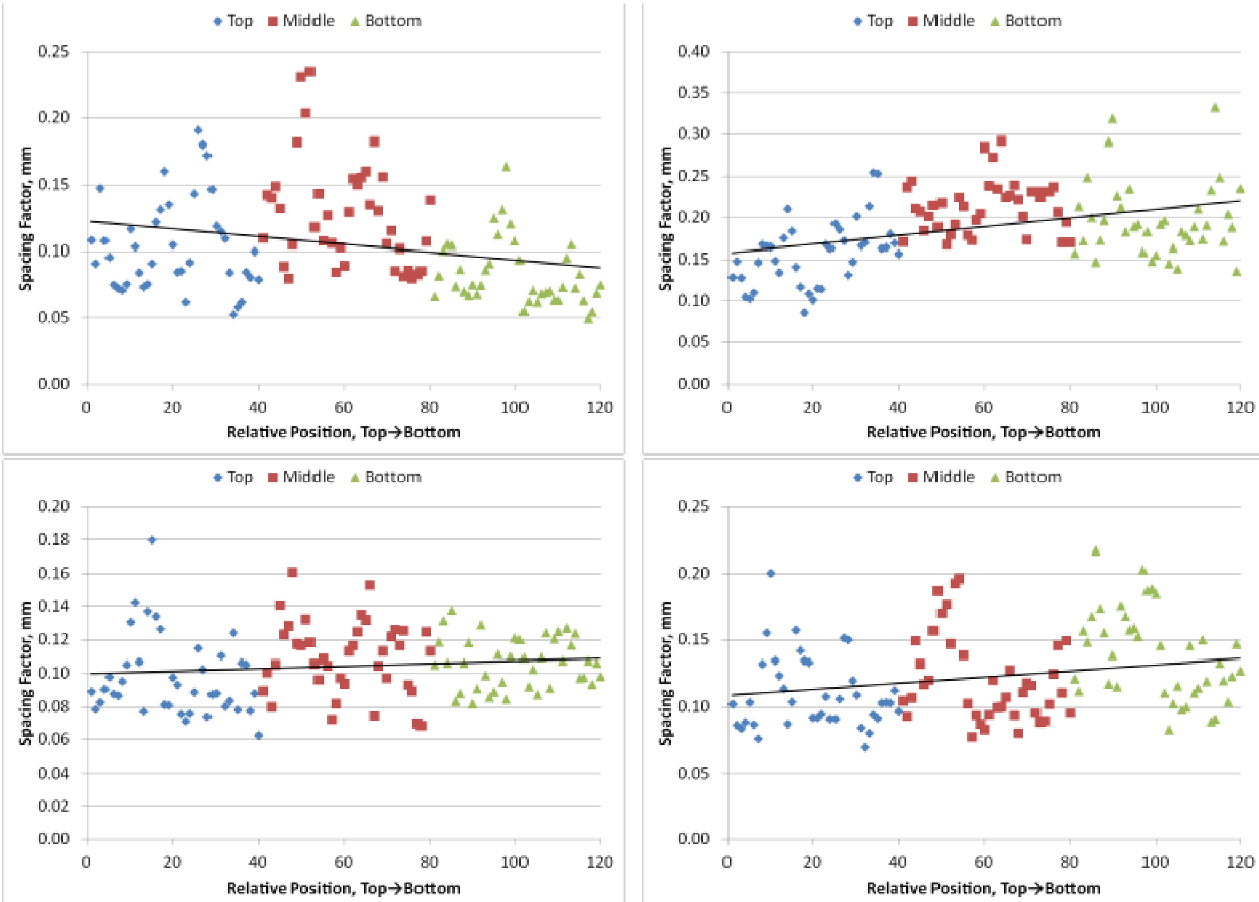


Figure 101: Plots of spacing factor by relative depth in cores. Clockwise from top, left: NC-1C; SE-2C; NE-2C; NC-2C.

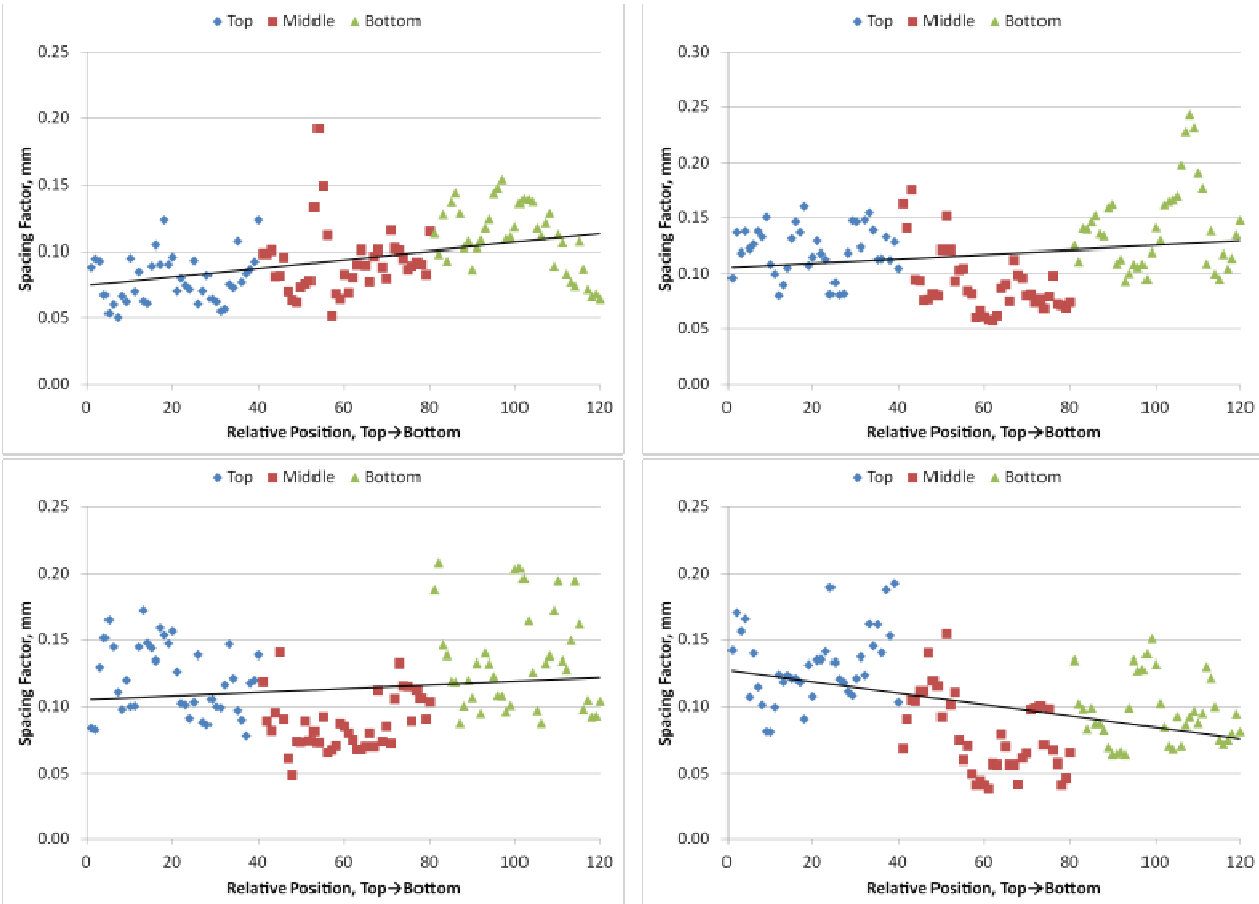


Figure 102: Plots of spacing factor by relative depth in cores. Clockwise from top, left: NE-4C; NE-3C; NE-1C; NW-1C.

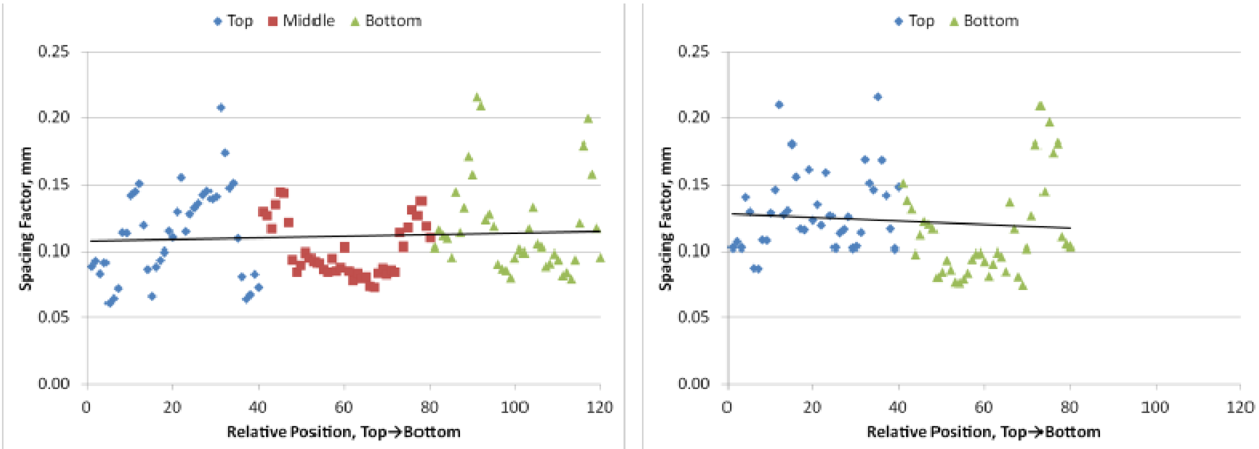


Figure 103: Plots of spacing factor by relative depth in cores. NE-1AC (left) NC-2AC(right).

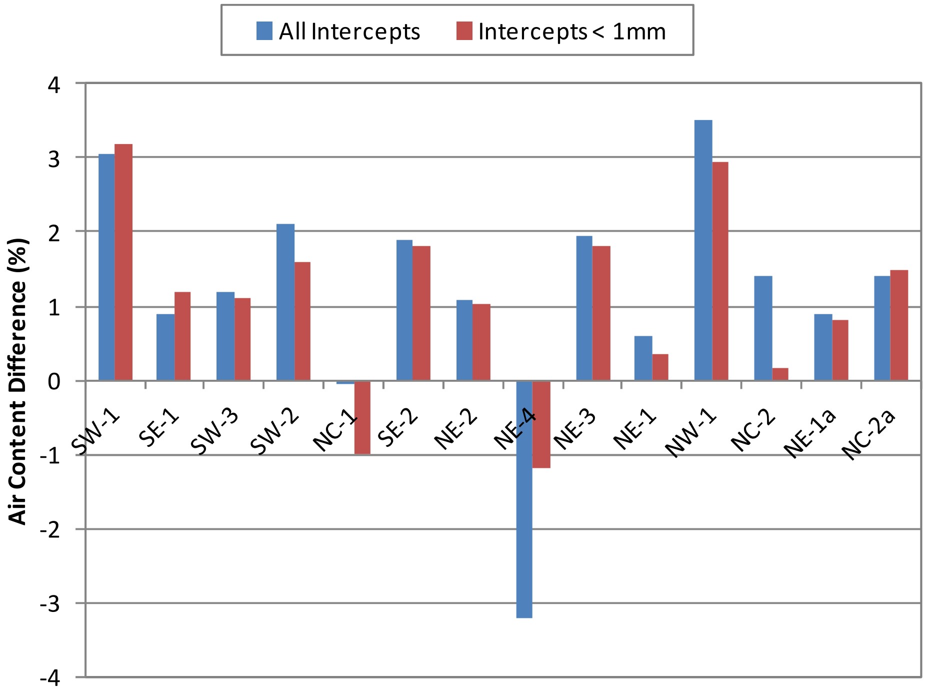


Figure 104: Difference in automatically determined air content between cylinders before paver and cylinders after paver (before % air – after % air).

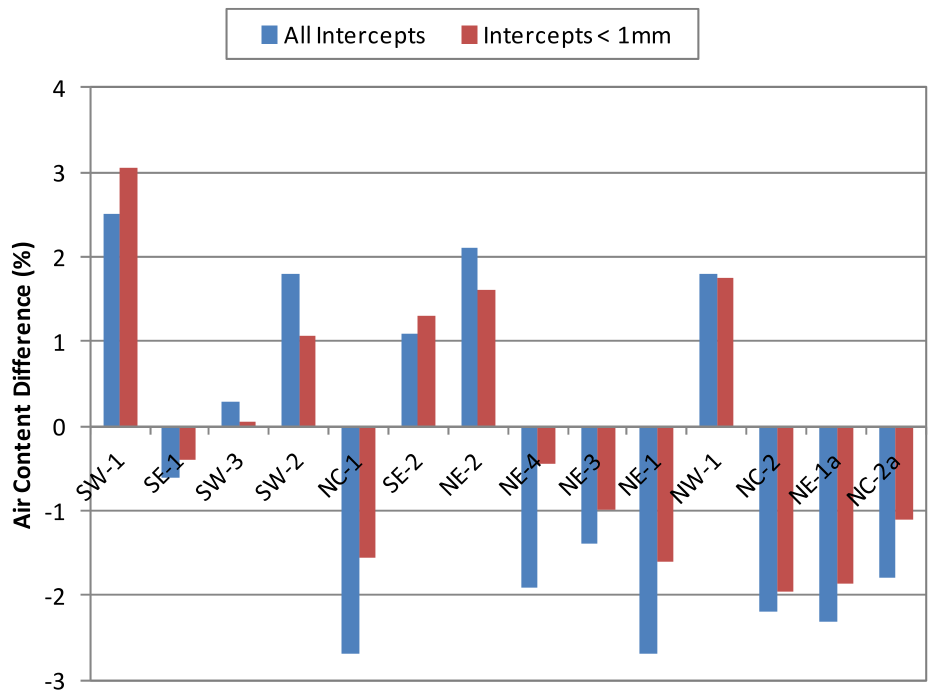


Figure 105: Difference in automatically determined air content between cylinders before paver and core after paver (before % air – after % air).

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