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CONCRETE DECK PERFORMANCE RELATIVE TO AIR ENTRAINMENT

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16. Abstract
Damage to concrete due to freeze-thaw (F-T) action is a serious concern for agencies in cold regions of the United States. The most effective method to protect concrete from F-T damage is through the addition of an air entraining agent as an admixture that creates a well distributed, closely spaced, small sized air void system in the concrete. Air content measurement in fresh concrete is a routine quality control and acceptance test procedure that helps to ensure good durability characteristics in the concrete structure. Most agencies, including the Colorado DOT (CDOT), in accordance with industry recommendations, perform the air content measurement at the point of placement in a concrete structure. Between 1993 and 2008, CDOT changed its specifications due to safety considerations of the field personnel. Air content measurements were performed at the point of delivery during this period. While structures built during this period did meet specifications, it is not clear whether the pumping and the placement operations altered the air void distribution. For planning future maintenance activities, CDOT was interested in evaluating the relative condition of bridge decks built under the point of delivery specification and verifying if they indeed possessed good F-T durability.

After a throrough review of 600 bridges in CDOT's database, six bridges in the Denver metro area in districts 1and 4 were selected for study. NBI ratings for the selected bridges ranged from 5 to 7. Three of the bridge decks were constructed before 1993 (using the point of placement specification), and three were constructed between 1993 and 2008 (using the point of delivery specification). Three cores from each structure were extracted, and two cores were tested as part of the forensic evaluation plan set up for this study. The tests included petrographic analysis as per ASTM C 856, air void analyses and total air content determination (including specific surface and spacing factor) as per ASTM C 457, and chloride profile measurement at three different depths as per ASTM 1152. The test results indicate that the bridge decks built under both specifications have an acceptable air void system and that the bridges built under the point of delivery specification have better F-T resistance than the structures built under the point of placement specification. This implies that good materials and construction practices were used and there is no alarming difference in the quality of bridge decks built under the two specifications. This does not suggest, however, that the point of delivery specification should be adopted. The sample size selected for this study is very small, and the results need to be interpreted with care.

Implementation
CDOT does not need any additional change of plans with bridge deck maintenance activities. However, CDOT has to take additional steps to ensure that bridge decks built in the future possess the air void distribution required for good durability. Also, the impact of other mix design and construction parameters on the air void system should be considered to achieve desired durability levels.

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CONCRETE DECK PERFORMANCE RELATIVE TO AIR ENTRAINMENT

by

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- Glenn Frieler, CDOT Region IV Resident Engineer
- Gary Dewitt, CDOT Region IV Materials Engineer
- Eric Prieve, CDOT Concrete Engineer
- Joe Rottman, CRMCA
- Brooke N. Smartz, Holcim US Inc.
- Matt Greer, FHWA
- Kenny Fong, FHWA
- Ali Harjali, CDOT Staff Bridge Project Engineer
- Aziz Khan, CDOT Research Branch Structure and Geotechnical Research Manager

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EXECUTIVE SUMMARY

Damage to concrete due to freeze-thaw (F-T) action is a serious concern for agencies in cold regions of the United States. The most effective method to protect concrete against F-T damage is through the addition of an air entraining agent as an admixture that creates a well distributed, closely spaced, small sized air void system in the concrete. Air content measurement in fresh concrete is a routine quality control and acceptance test procedure that helps to ensure good durability characteristics in the concrete structure. Most agencies, including the Colorado DOT (CDOT), in accordance with industry recommendations, perform the air content measurement at the point of placement in a concrete structure. Between 1993 and 2008, CDOT changed its specifications due to safety considerations of the field personnel. Air content measurements were performed at the point of delivery during this period. While structures built during this period did meet specifications, it is not clear whether the pumping and the placement operations altered the air void distribution. For planning future maintenance activities, CDOT was interested in evaluating the relative condition of bridge decks built under the point of delivery specification and verifying if they indeed possessed good F-T durability.

The primary objective of this study was to examine and compare the air void parameters of existing bridge decks that were built under the two different specifications – point of delivery and point of placement.

After a thorough review of 600 bridges in CDOT’s database, six bridges located in Regions 1 and 4 were selected for study. NBI ratings for the selected bridges ranged from 5 to 7. Three of the bridge decks were constructed before 1993 (using the point of placement specification), and three were constructed between 1993 and 2008 (using the point of delivery specification). Three cores from each structure were extracted, and two cores were tested as part of the forensic evaluation plan set up for this study. The tests included petrographic analysis as per ASTM C 856, air void analyses and total air content determination (including specific surface and spacing factor) as per ASTM C 457 and chloride profile measurement at three different depths as per ASTM 1152. The test results indicated that the bridge decks built under both specifications have an acceptable air void system and that the bridges built under the point of delivery specification have better F-T resistance than the structures built under the point of placement specification. This implies that good materials and construction practices were used and there is no alarming difference in the quality of bridge decks built under the two specifications. This does not suggest, however, that the point of delivery specification should be adopted. The sample size selected for this study was very small, and the results needed to be interpreted with care.

IMPLEMENTATION STATEMENT

CDOT does not need any additional change of plans with bridge deck maintenance activities. However, CDOT has to take additional steps to ensure that bridge decks built in the future possess the air void distribution required for good durability. The impact of other mix design and construction parameters on the air void system should be considered to achieve desired durability levels. The limitations in the study due to lack of necessary data and small sample size were recognized by the panel. For future work, the panel recommended the development of a specification that would require contractors to extract extra cores from the bridge decks after construction and deliver them to the research contractor, ARA, for testing and data analyses. This work plan was suggested for a span of five years.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Generally speaking, durability-related distresses in concrete are driven by either a chemical reaction or a physical phenomenon. Frost damage is a concrete durability distress that happens in the colder region caused by a physical mechanism involving volume expansion of freezing water in a critically saturated concrete.

Manifestations of Frost Damage

Freeze-thaw (F-T) deterioration of hardened cement paste results from an improper amount and/or distribution of air voids in the paste. When concrete is critically saturated and exposed to below-freezing temperatures, the water in the capillary pores freezes and occupies roughly 9% greater volume. The expansion in turn exerts excessive pore pressure which, when greater than the tensile strength of the concrete, dilates and ruptures the capillary channels. Successive F-T cycles and accumulation of expansive forces disturb the aggregate-paste interface, and the distress manifests over time. The condition is further exacerbated when deicing chemicals used for snow and ice removal infiltrate the concrete and come in contact with the reinforcement through the process of osmosis. Accumulation of moisture in the vicinity of steel can lead to corrosion of the steel. Figure 1 shows a classic F-T problem at Castlewood Canyon's structure on SH 83. F-T action has inflicted significant damage to the arch, causing the concrete to delaminate and exposing the reinforcing steel to corrosion.

D-cracking results from freezing and thawing of frost-susceptible coarse aggregate that manifests itself in the form of hairline cracks adjacent and nearly parallel to transverse and longitudinal joints and at the free edges of pavement slabs (see Figure 2). Frost-susceptible aggregates are of sedimentary rock origin and are composed primarily of limestone, dolomite, or chert aggregate. Bond failure between the aggregate and the cement paste and disintegration of the paste are major indications of D-cracking. Currently, the only ways to prevent D-cracking are to avoid frost-susceptible aggregate or to use a smaller nominal aggregate size, in which the hydraulic stresses developed are low. The aggregates used in Colorado rarely are prone to this problem; therefore, D-cracking is less critical in this study.

Figure 1. Freeze-thaw deterioration at Castlewood Canyon (Ardani, 2004)

Figure 2. Early development of D-cracking

Scaling normally is caused by excessive finishing of the concrete, causing the bleed water to be worked back into the upper surface of the concrete deck (see Figure 3). A higher water-cement (w/c) ratio results in lower strength at the surface of the concrete. In addition, excessive finishing results in lower air content, which in turn reduces the resistance of concrete to F-T deterioration.

Figure 3. Concrete surface scaling (PCA, 2008)

MOTIVATION FOR CURRENT RESEARCH

The ability of concrete to overcome F-T damage in cold regions is improved significantly by deliberately incorporating in the mix design entrained air through the use of air-entraining cement or air entraining admixtures (AEA), the latter being more common. AEA introduces a stable system of discrete air bubbles that allows freezing pore waters to freely expand throughout the concrete mass. The key is to provide a good distribution of small-sized entrained air bubbles rather than entrapped air, which is larger in size. Entrained air is of the order of 0.004-0.04 inch (0.01-1.0 mm) in size, spaced 0.004 to 0.01 in (0.1 to 0.25 mm) apart, and occupies about 3 to 4 percent of the volume. Entrapped air, which occupies about 2% of the volume, 0.05-0.16 inch (1-4 mm) sized, and more dispersed, also makes no contribution in the F-T resistance of the concrete.

Clearly this offers Materials Engineers the flexibility to design a mix for a specific climate. Therefore, highway agencies such as CDOT specify air content requirements in the concrete mixture used on bridge decks, pavements, and other structures. (It is worth noting that concrete in extremely cold climates where the temperatures remain below freezing for extended periods of time is less susceptible to F-T damage than concrete in climates that experience multiple temperature swings throughout the year, such as the Denver area.)

Entrained air is produced during the mixing of the concrete, and the role of the AEA is to stabilize them and keep them from escaping the mix or dissolving in the water. However, although a mix design can be developed and accepted for project use, construction practices can significantly alter the level of air entrainment achieved in the concrete placed in the field. Over-consolidating can disturb the size and distribution, as can the process of transporting and pumping from the concrete truck to the structure.

Both the quality of the AEA used and the skill level of the pump operator have an impact on the stability of the entrained air. Under normal pump pressures, it is typical for mixes with acceptable quality AEA to hold up the entrained air during the pumping operations while sufficient pressures exist. However, as the mix goes into a vacuum state in the hose, stability can be lost under certain circumstances. This implies that the bubble is stable and uniform while under pressure, but under free fall conditions the vacuum or reduced pressure conditions created cause the air bubble to expand. Eventually, when the mix goes back under pressure, the air bubble can snap due to contraction.

This discussion suggests that air content measurements for the same concrete mix can provide different results when tested at the point of delivery (i.e., before the concrete is pumped to the structure) and the point of placement (i.e., after the concrete is pumped into the structural form work). The definition of the point of testing in an agency specification can be critical for obtaining the required air content in the as-built structure. A specification for air content requirements at the point of placement also shifts the responsibility from the mix producer to the contractor.

CDOT Air Void Testing Practices for Quality Assurance

Until about 1993, CDOT's air content specifications were applicable to the mixture at the point of placement. From 1993 until 2008, the specifications were modified such that concrete mixtures were specified to meet air content requirements at the point of delivery. The change back to the point of placement specification in 2009 was based on the fact that concrete mixes could lose up to 2% of their air void during transportation. In addition, testing the air content using a point of delivery specification did not follow the recommendations of the American Concrete Institute (ACI) for testing and acceptance of air void systems in fresh concrete. The air content specifications from 2005 (point of delivery) and the revised specifications from 2009 (point of placement) are included in Appendix A. The mix design and strength requirement specifications have not undergone significant changes over this period.

The basis for using a point of delivery specification between 1993 and 2008 was due to safety considerations for personnel performing quality control (QC) and quality assurance (QA) testing. However, the impact of this specification on the effective air content of concrete structures built during that period, especially bridge decks, is unknown. While in many cases this will have no effect on the physical properties of the concrete, the impact on durability could be significant. CDOT recognizes that this modification also has led to uncertainty in the required level of total air content and, therefore, generated legitimate questions about the quality and integrity of the bridge concrete deck structures constructed during this time period.

Generally speaking, CDOT designs bridges with a life expectancy of 75 to 100 years. However, if the concrete used for these bridges lacks adequate air voids to withstand the detrimental impact of F-T cycles, these bridges may fail before meeting their expected designed life. This prompted CDOT's Oversight Team for Pavement Research to undertake Study 22.80 examining the impact of the modified specification, if any, for air void testing on durability of the structures constructed within the last 15 years. If the performance of these structures is determined to be substandard and deviate from the 75 year design life of conventional bridges, CDOT can use this information to plan future maintenance activities and allocate appropriate fund to maintain these structures.

TEST METHODS TO MEASURE AIR CONTENT

The air content of fresh concrete is performed as part of routine QC/QA and is often an acceptance quality characteristic for agencies. The total air content, which includes both entrapped and entrained air, is measured using in-situ test methods—ASTM C 231 (pressure method), ASTM C 173 (volumetric method), or ASTM C 138 (gravimetric method). The pressure meter method is the most commonly used protocol.

While the total air content is a good indicator of the overall extent of air introduced in the mixture, it does not characterize the size and spatial distribution of air bubbles in the mix or its resistance to F-T damage adequately. Parameters that provide this information and have been better correlated to performance are:

- Spacing factor, *L*, the distance the freezing water must traverse to reach a void and relieve stresses. Small *L*-values are desirable, and specifications limit *L* to 0.008 in (0.2 mm).
- Specific surface area, which is the surface area of the void per unit volume and is a relative measure of the number and size of air bubbles for a given volume of air. A larger number for specific surface is desirable, as it indicates a larger number of smaller bubbles. Specific surface area values of 600 to 1100 in^2/in^3 (24 to 44 mm^2/mm^3) are recommended for good F-T durability.

The standard protocol to measure air void distribution parameters is ASTM C 457, applicable for hardened concrete. This protocol uses both the linear traverse and point count techniques to determine the above air void parameters, as well as the total air content. The ASTM C 457 procedure has been automated in the recently developed device called *RapidAir* 457 and is essentially based on the same principle.

While the manual test procedure can be time-consuming and subjective, this automation assists in bringing objectivity and eliminates operator-introduced variability. These tests can be performed only on hardened concrete, at a stage perhaps too late to make changes to the mix design or construction. However, they can be used to make improvements to agency practices.

The air-void analyzer (AVA) can provide air void parameters in fresh concrete and serves as a QA/QC tool. Tests are performed on-site using samples extracted from the newly placed concrete, and adjustments in concrete batching can be made in real time to meet specifications. Several concerted efforts to adopt the AVA are underway in the concrete materials community, and an American Association of State Highway and Transportation Officials (AASHTO) test method has been developed for this device.

OBJECTIVES OF THE STUDY

The primary objectives of this study were to identify, evaluate, and compare significant factors that affect the performance, durability, and formation of distresses in selected CDOT bridge structures built with “point of delivery” and “point of placement” specifications, to find solutions to mitigate any resultant negative effects observed, and to address the following questions:

- Is there any statistically significant difference in total air content between the concrete deck of structures that performed successfully and unsuccessfully?
- Is the air content that is lost, if any, the beneficial entrained air, or just entrapped air?
- Do these concrete structures have the correct amount of entrained air to resist damage caused by F-T cycling?
- What is the current condition of these structures in relation to the amount of actual air entrainment in the concrete?

The ultimate goal of the study is to improve the longevity and performance of bridge decks in Colorado by providing the necessary information to predict future maintenance needs.

TECHNICAL APPROACH ADOPTED

The project essentially involved an in-depth examination of the effective quality of air void systems on a sample set of bridges constructed under both the point of delivery and point of placement specifications to assess the impact of these specification changes. A literature review was conducted on the effect of varying air content in concrete mix designs and the effects it has on concrete durability. Next, after a review of CDOT bridge databases and partial construction information, six bridges in the Denver metro area were selected that included three bridges built under each of the specifications. Core samples from these bridges were used in petrographic analyses, air void parameters determination through petrographic examination, and chloride penetration tests to assess the impact of these specifications.

REPORT ORGANIZATION

Chapter 1 introduces the research subject and lists the study objectives and scope of work. Chapter 2 presents a summary of the literature review. Chapter 3 describes the site selection and test sample collection practice adopted for this study. Chapter 4 contains the data analyses and discussion of results. Chapter 5 summarizes the project and presents the conclusions.

The report has three appendices. Appendix A includes the specifications to measure air content on field at the point of delivery and the point of placement. Appendix B contains the reports for the hardened concrete air void analyses conducted on the samples. Appendix C contains the petrographic analyses conducted by the laboratory.

CHAPTER 2. LITERATURE REVIEW

A lower w/c ratio in conjunction with an air content of 5 to 8 percent generally is considered adequate to overcome the detrimental effects of F-T actions and deicing chemicals in an environment like Colorado’s. Many factors affect the air content of concrete, including the transportation and handling of the concrete. Approximately 1 to 2 percent of the air is lost during transporting, and the same air loss is possible during pumping. The reduction in air content could have a dramatic effect on the ability of the concrete to resist F-T action.

The change in resulting entrained air in concrete can be confounded by the effects of several other factors, such as material, mix design, production procedures, construction practices, and environment for the control of air content in concrete (Thomas & Wilson, 2002; Whiting & Startk, 1983; Whiting & Nagi, 1998). For example, the use of higher contents of fly ash in colder temperatures can cause delayed setting of the concrete and can show increased signs of surface scaling. Concrete mixes with a lower w/c ratio that have been cured adequately have lower permeability and are less prone to F-T damage and corrosion because of the absence of pathways for moisture to travel to the steel reinforcement. A summary of typical parameters of interest to this study and the associated change is presented in Table 1.

A recent National Cooperative Highway Research Program (NCHRP) study found that the AEA type has a statistically significant effect on the concrete air void system and spacing factor (Nagi et al., 2006).

For more than 50 years, neutralized Vinsol resin has been used effectively for air entrainment. More recently, other AEAs have been introduced, and their use has increased primarily because of the higher cost and limited supply of Vinsol. However, many concretes incorporating these newer products have exhibited unacceptable properties when used in bridge decks, pavements, and other structures.

Table 1. Effect of concrete mixture components, mix design, and construction parameters on resultant entrained air in concrete (Thomas & Wilson, 2002; Whiting & Startk, 1983; Whiting & Nagi, 1998)

Material, Mix Design, Construction Practice	Change and Associated Effect on Entrained Air
Cement	Increase in cement content (D), Increase in fineness (D), Increase in alkali content (I)
Supplementary Cementitious Materials	Fly Ash (especially with high carbon) (D**), Silica Fume (D**), Slag with increasing fineness (D), Metakaolin (N)
Aggregates	Increase in maximum size (D), Sand content (I),
Chemical Admixtures	Water reducers (I), Retarders (I), Accelerators (N), High-range water reducers (I)
w/c ratio	Increase W/CM (I),
Slump	Increase in slump up to 6 in (150 mm), (I), High slump >6 in [150 mm] (D), Low slump concrete [<3 in (75 mm)] (D)
Production, Transport, and Delivery	Transport (D), Long hauls (D), Retempering (I),
Placing and finishing	Belt conveyors (D), Pumping (D), *Wet-mix shotcrete (D), Prolonged internal vibration (D), Excessive finishing (D)

Note: D-decreases , I-increases, N-No change, **-Significantly impacts

A laboratory study conducted by Kozikowski et al. (2005) linked air-void clustering (AVC) to certain types of AEAs and late addition of water to concrete. According to this study, AVC in concrete is a randomly occurring phenomenon that can result in a significant decrease in compressive strength. As the name implies, AVC is the concentration of entrained air voids around coarse aggregate particles at the paste/aggregate interface, creating a localized zone of weakness. Such mixes could possess lower compressive strengths because applied loads cannot be transferred effectively between the paste and aggregate particles. Figure 4 depicts examples of concrete with and without AVC.

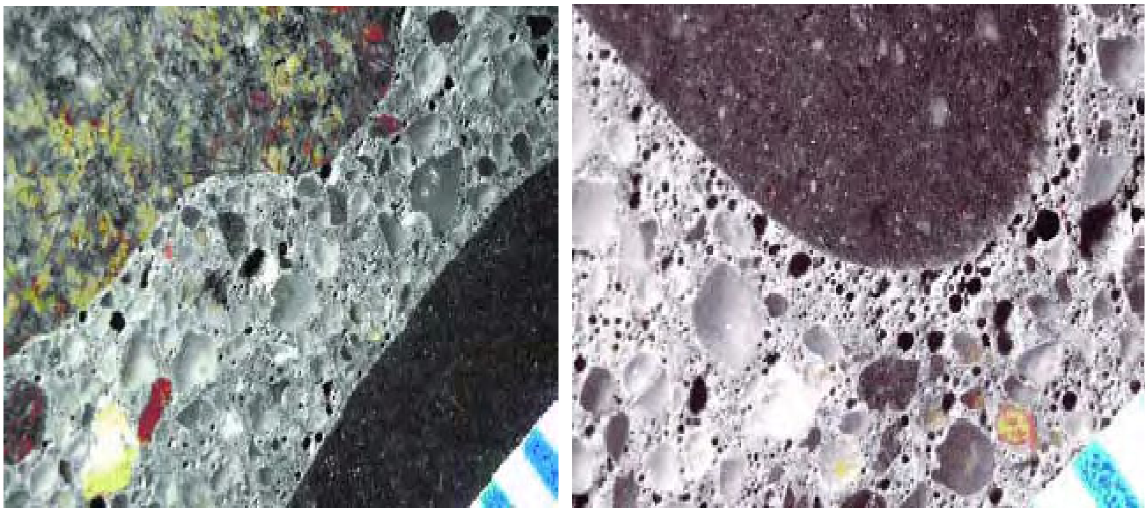


Figure 4. Concrete with and without AVC (Kozikowski et al., 2005)

The main findings on AVC are:

- AVC did not occur in concrete mixes made with Vinsol resin based admixtures.
- A late addition of water to concrete mixes containing non-Vinsol resin admixtures regularly caused clustering to occur.
- The severity of the AVC increased when the retempered concrete was mixed for a longer time.

The amount of air to be used in air-entrained concrete depends on a number of factors: type of structure, climatic conditions, number of F-T cycles, extent of exposure to deicers, and the design life of the structure. The ACI 318 building code states that concrete that will be exposed to moist freezing and thawing or deicer chemicals shall be air entrained with the target air content shown in Table 2. Furthermore, the w/c ratio should not exceed 0.45 (Kosmatka et al., 2002).

ACI 318 allows a one percentage point reduction in target air contents for concrete with strength over 5,000 psi (34 MPa) and presumably very low w/c ratio.

Table 2. Recommended total air content for concrete (Kosmatka, 2002)

Nominal maximum aggregate size, in. (mm)	Air content, percent*		
	Severe exposure**	Moderate exposure†	Mild exposure††
< 3/8 (< 9.5)	9	7	5
3/8 (9.5)	7-1/2	6	4-1/2
1/2 (12.5)	7	5-1/2	4
3/4 (19.0)	6	5	3-1/2
1 (25.0)	6	4-1/2	3
1-1/2 (37.5)	5-1/2	4-1/2	2-1/2
2 (50)‡	5	4	2
3 (75)‡	4-1/2	3-1/2	1-1/2

* Project specifications often allow the air content of the concrete to be within -1 to +2 percentage points of the table target values.

** Concrete exposed to wet-freeze-thaw conditions, deicers, or other aggressive agents.

† Concrete exposed to freezing but not continually moist, and not in contact with deicers or aggressive chemicals.

†† Concrete not exposed to freezing conditions, deicers, or aggressive agents.

‡ These air contents apply to the total mix, as for the preceding aggregate sizes. When testing these concretes, however, aggregate larger than 1-1/2 inch (37.5 mm) is removed by handpicking or sieving and air content is determined on the minus 1-1/2 inch (37.5 mm) fraction of mix. (Tolerance on air content as delivered applies to this value.)

Both F-T and salt scaling deterioration are of interest in cold climates. These mechanisms are controlled significantly by the permeability of the concrete. Permeability influences all forms of durability-related distress. It is widely reported that the use of supplementary cementitious materials at dosage greater than those likely to be appropriate for process of additions will reduce permeability in well-cured concrete (Taylor, 2008).

Concrete containing low-calcium (Class F) fly ash generally requires a higher dose of AEA to achieve a satisfactory air void system, mainly due to the presence of unburned carbon, which absorbs the admixture. Consequently, higher doses of AEA are required as either the fly ash content of the concrete increases or the carbon content of the fly ash increases (Thomas, 2007). The carbon content of fly ash usually is measured indirectly by determining its loss-on-ignition.

Entrained air increases concrete resistance to F-T damage by providing local release for the hydraulic and osmotic pressure produced when water within the concrete expands before and during freezing (water expands about 9% just before freezing). Water moves through the concrete into these voids, and the air voids must be closely spaced so that the pressure can be released before freezing occurs (Lawler et al., 2007).

The critical distance that water can be expected to move without causing freezing damage in typical paste is approximately 0.010 in (0.2544 mm). Therefore, the effectiveness of the entrained air at providing F-T resistance to the concrete is governed by the volume and spacing of the air bubbles within the concrete.

A Federal Highway Administration study evaluated the F-T resistance of several mixes with "marginal" air void systems with two different types of AEAs—a Vinsol resin and a synthetic admixture (Tanesi & Meininger, 2006). 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 F-T performance when the Vinsol resin based AEA was used. The synthetic admixture did not show the same good performance (Tanesi & Meininger, 2006).

Consolidation practices at the time of construction could have a profound effect on the quality and quantity of the air voids in fresh concrete. A study conducted by CDOT (Ardani et al., 2003) demonstrated the development of vibrator trails caused by malfunctioning of the internal vibrators. Vibrators working at high frequencies (in excess of 10,000 vpm) over-consolidate the concrete mix, causing non-uniform dispersion of the aggregate, lowering the air content, and forming vibrator trails. Laboratory investigation of cores extracted on and adjacent to the vibrator trails clearly confirmed this phenomenon. The cores obtained on the vibrator trails had consistently lower air content than cores obtained 18 inches away, in the center of the lane.

Air void stability can be evaluated using the foam drainage test. In general, a stable air void system has a lower drainage rate and retains more water than an unstable system (Nagi et al., 2007). Figure 5 shows the evaluation of three different AEAs using a foam drainage test for a South Dakota study (Cross et al., 2000).

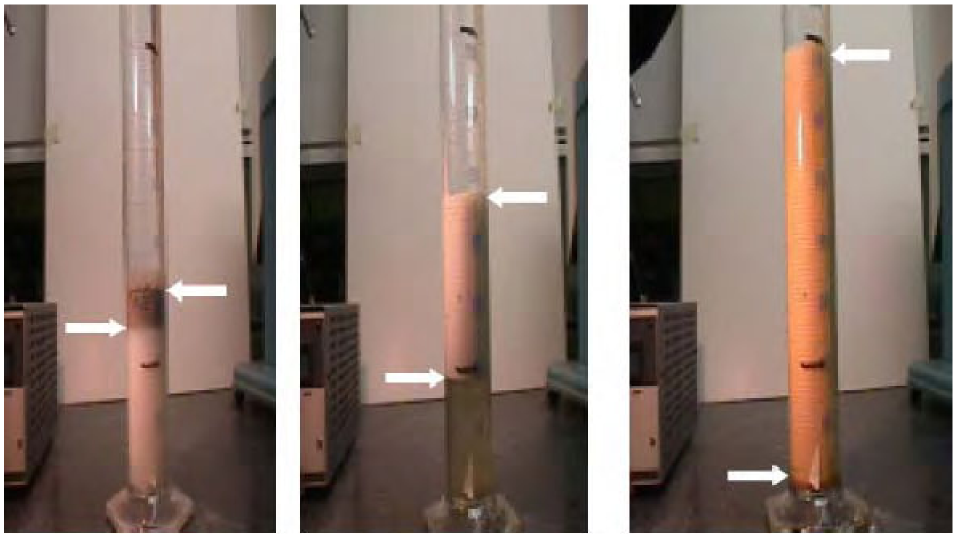


Figure 5. Foam drainage testing of three different AEAs (Cross et al., 2000).

Recently, transportation agencies have been experimenting with the AVA system in monitoring the air void characteristics of fresh concrete mixes. The AVA, shown in Figure 6 is a portable device that measures the air content, specific surface, and spacing factor of fresh concrete in real time, taking approximately 30 minutes. The results correlate closely with ASTM C 457 values obtained on hardened concrete. The Kansas Department of Transportation has been using this technology since April 2001 and has developed a State specification that it uses routinely (AASHTO, 2006). The formation of an AASHTO Technology Implementation Group (TIG) and the subsequent round robin tests conducted under this effort has led to the implementation of this technology by other agencies.

With the use of AVA, QC adjustments in concrete batching can be made in real time to improve the air void system and thus increase F-T durability. This technology offers many advantages over current practices for evaluating air in concrete (Grove et al., 2006). At least 16 States used AVA on a limited basis in 2005, including Arkansas, California, Delaware, Iowa, Kansas, Minnesota, Missouri, Nebraska, Nevada, New York, North Carolina, North Dakota, Oklahoma, Pennsylvania, Texas, and Utah (USDOT, 2006).

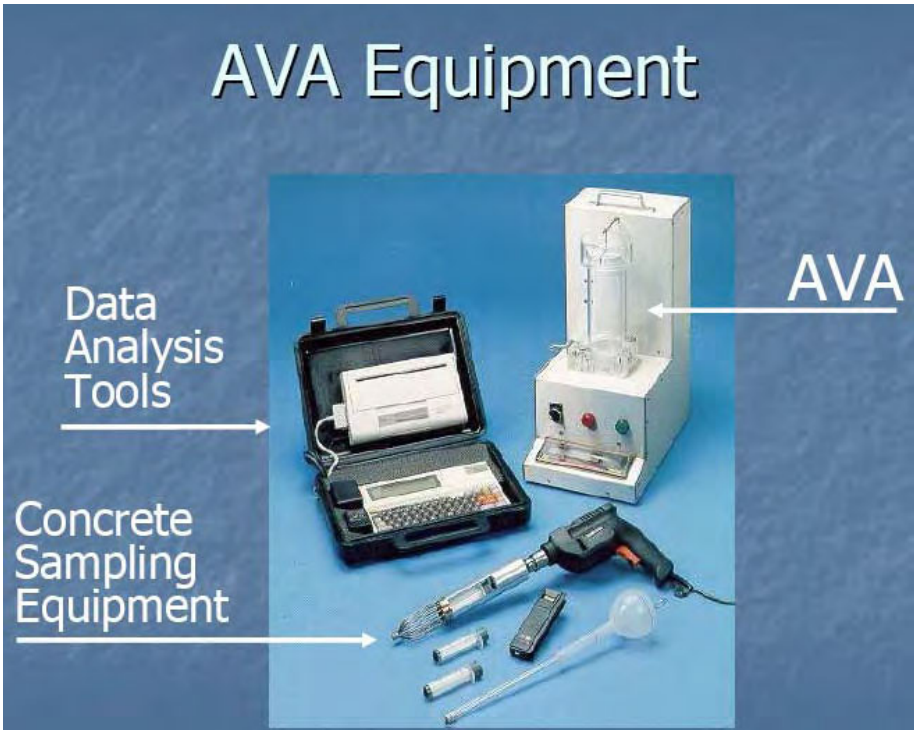


Figure 6. AVA system (courtesy National Concrete Pavement Technology Center)

ASTM C 666-97, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," is used to evaluate the resistance of concrete specimens to rapidly repeated cycles of F-T in the laboratory by two different methodologies. Method A examines the rapid F-T of the concrete specimen (a 4 x 4 x 16 in [100 x 100 x 400 mm] specimen) in water, and method B evaluates the rapid freezing of the concrete specimen in air and thawing in water. Normally, 300 cycles constitute a complete test. Both procedures are intended for use in determining the effects of variations in the properties of concrete on the resistance of the concrete to the F-T cycles specified in the particular procedure. Neither procedure is intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete.

CHAPTER 3. SITE SELECTION AND FIELD SAMPLING

SITE SELECTION

The field sampling was limited to the metro Denver area, which includes CDOT Regions 1, 4, and 6. A database of over 600 in-service existing bare concrete decks in these Regions was obtained from the CDOT Bridge Branch, and 20 of these bridges were selected for visual investigation of the decks in the field. Of these, six were shortlisted for forensic investigation by personnel from the research team and the study panel. The National Bridge Inventory (NBI) and Pontis systems were use to identify and rate the bridges. The NBI ratings for the selected bridges ranged from 5 to 7.

The selected structures are scattered in the eastern plains and mountainous area of Colorado. Half of the structures were constructed before 1993 (using the point of placement specification), and half were constructed after 1993 (using the point of delivery specification). Two of the selected bridges were in Region 4 and four were in Region 1. None of the Region 6 bridges was selected due to high traffic and difficulties in closing lanes.

Eighteen cores (3 per bridge deck) were extracted and sent to American Engineering Testing, Inc., in Florida for forensic evaluation, which included petrographic analysis, total air content determination (including specific surface and spacing factor), and chloride profile measurement at three different depths. Traffic control for the coring operations was provided by the Region's maintenance forces, and coring was conducted by CDOT Research Branch (Figure 7).

A brief description of each bridge deck is presented in the following sections.

Figure 7. Bridge deck coring

Structure C-15-AK (Point of Placement)

Structure C-15-AK was built in 1977 over the Big Thompson River and provides access to a small residential area from SH 34. Only 60 vehicles cross this bridge every day. Approximately 10% of the surface shows signs of shallow spalling, with minor transverse cracking. The deeper spalls have been patched with cement grout. Figure 8 shows the deck's surface condition.

Structure D-14-I (Point of Placement)

Structure D-14-I, built in 1973, is located on SH 7 over St. Vrain Creek, approximately 10 miles southeast of the town of Estes Park. SH 7 at this location is a mountainous, curvy two-lane route with an average daily traffic of 1900 vehicles. Of all the bridge decks investigated for this study, structure D-14-I is the one that exhibited possible signs of F-T with moderate to severe spalling and scaling of the surface (Figure 9). Some of the deeper spalls were patched with asphalt. However, as described in the data analysis section of this report, the petrographic analysis of the cores obtained from the deck of this bridge did not reveal any signs of F-T distress.

Figure 8. Structure C-15-AK

Figure 9. View of scaling on structure D-14-I

Structure F-20-BU (Point of Placement)

Structure F-20-BU, with average daily traffic of 5750 vehicles, is located on eastbound I-70 over Rattle Snake Creek at milepost 320.215, approximately 4.4 miles (7 km) east of the town of Byer. The structure was built in 1989 and presently is in fairly good condition with isolated transverse cracking. The bridge is shown in Figure 10.

Figure 10. Structure F-20-BU

Structure F-15-BZ (Point of Delivery Specification)

Structure F-15-BZ over Clear Creek was built in 1999 and currently carries 428 vehicles per day. The structure is the on-ramp to I-70 eastbound, located just west of Idaho Springs (Figure 11). Distresses at this location included transverse cracking that covered the entire deck’s surface in approximately 2 to 4-ft (0.6 to 1.2-m) intervals with no visible signs of F-T (Figure 12).

Figure 11. Structure F-15-BZ west of Idaho Springs

Figure 12. View of transverse cracking at structure F-15-BZ

Structure G-22-BY (Point of Delivery)

Structure G-22-BY , built in 2000 over the Big Sandy Creek, is located at milepost 376.481, immediately south of the town of Limon. With an average daily traffic of 4600 vehicles per day, the deck exhibited shallow map cracking with isolated areas of scaling, as shown in Figure 13.

Figure 13. View of a scaling area on structure G-22-BY

Structure G-22-BZ (Point of Delivery Specification)

Structure G-22-BZ, built in 2000, is located on US 24 at milepost 376.63 over a railroad, immediately south of the town of Limon. With an average daily traffic of 4600 vehicle per day, the deck of this bridge exhibited irregular diagonal cracking with isolated minor scaling, as shown in Figure 14.

Figure 14. Structure G-22-BZ

General Comments on Site Selection

A summary of the selected bridges is provided in Table 3. Generally speaking, all of the bridge decks selected for field investigation exhibited moderate to severe distresses, primarily in the form of map and transverse cracking. None of the decks inspected clearly showed signs of F-T problems; however, surface delamination, spalling, and potholes were observed on some of the decks, which could indicate possible F-T distresses.

Table 3 also indicates that the bridges considered under the two specifications belong to distinctly different periods. Bridges under the point of delivery specification were built in 1999-2000, while the bridges under point of placement specification were built much earlier during 1973-1989. While the two different specifications and the distress ratings were considered into the experimental design, it is to be recognized that there could be confounding effects from other parameters, known and unknown. (Please note that construction or QA records were not available at CDOT). Clearly the period between 1973 and 2000 witnessed changes in material specifications for mix designs, mix constituents, supplementary cementitious materials, quality of admixtures, strength requirements for construction and other placement practices. Since these parameters could finally influence the test results obtained, it is to be recognized that any differences or similarities observed need not be fully as a result of air content testing specifications.

Table 3. Summary of selected structures for field sampling and laboratory testing

Specification	Bridge	Highway	Region and Maintenance	Year Built	Delivery Method	Concrete Deck	ADT (veh./day)	ADT Year	NBI Deck Rating
Point of Placement	C-15-AK	0034A	4,1	1977	Unknown	Cast in place	60	2006	6
	D-14-I	0007A	4,1	1973	Unknown		1900	2005	5
	F-20-BU	0070A	1,5	1989	Unknown		5750	2005	7
Point of Delivery	F-15-BZ	0070A	1,5	1999	Unknown		428	2005	7
	G-22-BY	0024G	1,5	2000	Unknown	Deck panels cast in place	3000	2005	7
	G-22-BZ	0024G	1,5	2000	Unknown		4600	2005	7

ADT = average daily traffic

Tests Performed on Cores from Selected Structures

Test samples were prepared from two of the three extracted cores, thereby providing a test replicate for each bridge deck selected. Petrographic examination was performed in accordance with ASTM C 865, and air content testing also was conducted using ASTM C 457. In addition, ASTM C 1152 was used to establish a chloride profile in intervals of 1 inch from the upper 3 inches of the cores. Chapter 4 documents the analysis of all the laboratory tests conducted on core samples.

CHAPTER 4. TEST DATA, ANALYSES, AND DISCUSSION OF RESULTS

SAMPLE COLLECTION

Three cores were extracted and sent to the laboratory for petrographic and chloride ion testing. Cores typically were 4 inches in diameter but occasionally were extracted with reduced diameter of 2¾ inches to accommodate closely spaced deck reinforcement. The length of the cores ranged from 2¾ to 9 inches. Figures 15 through 20 show photos of the extracted cores that were received by the testing laboratory for the six selected structures. Two of the three cores were randomly selected for testing.

It was important to perform all three tests—ASTM C 457, ASTM C 865, and ASTM C 1152—on each of the cores so that the air void distribution at the sampled location could be compared against chloride penetration. In each core, a thin ½-inch specimen was sliced longitudinally (along the axis) from the middle to perform the petrographic tests. The thin slice was polished on both sides to provide two surfaces at least 3 inch by 3 inch in area, or a cumulative area of 18 inch^2. The petrographic tests revealed the extent of durability damage, as well as the effective distribution of entrained air. These parameters can be correlated directly to the distresses observed in the visual surveys.

Next, the remaining two halves of the core were sliced transversely into three pieces, providing specimens for chloride penetration investigation at three depths. Mortar samples were extracted from each of the three slices to test the material for chloride ion penetration. These tests indicated if, for a given level of air entrainment, the distresses have led to the infiltration of chloride ions. Obtaining the profile is critical to determining penetration depth. This method of obtaining test specimens, illustrated in Figure 21, also provided replicate samples for all tests.
The statistical sampling adopted in this study, however, poses a major limitation. The number of bridges selected for field evaluation and the number of samples considered for laboratory testing

were controlled by the project budget and scope of work CDOT considered appropriate for this study. It is recognized that the selected sample size is very small, and its ability to represent the true population mean is questionable. Therefore, all data analyses, discussions, and conclusions should be considered preliminary in nature, forming the basis for research or actions that CDOT can pursue in this area in the future.

Figure 15. Core samples received by the laboratory for Structure C-15-AK

Figure 16. Core samples received by the laboratory for Structure D-14-1

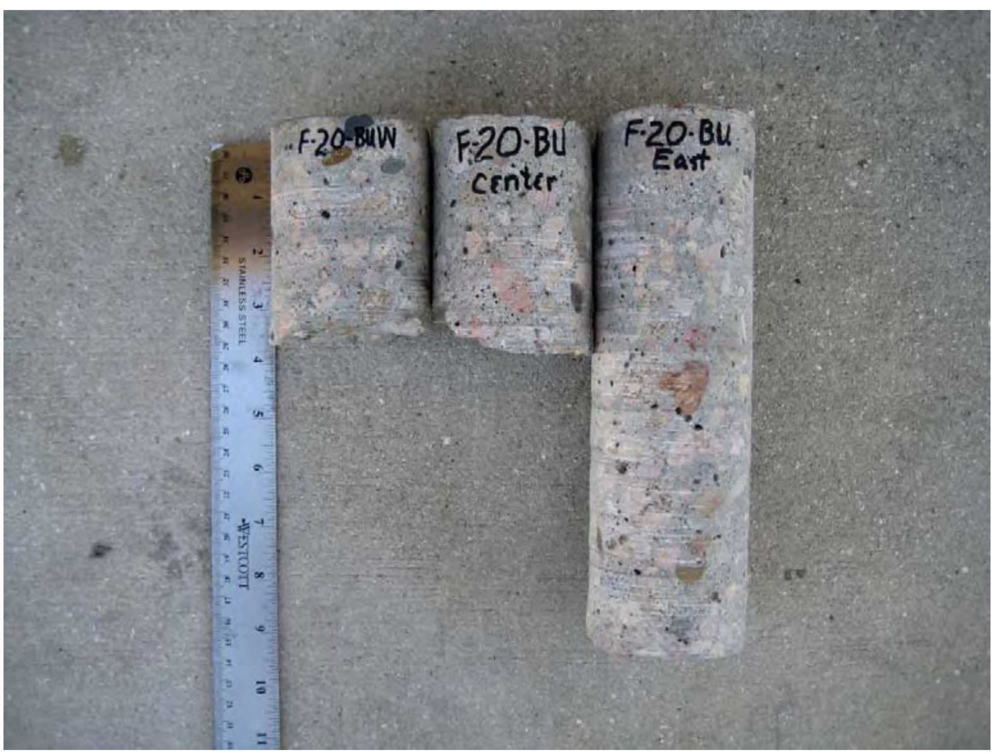


Figure 17. Core samples received by the laboratory for Structure F-20-BU

Figure 18. Core samples received by the laboratory for Structure F-15-BZ

Figure 19. Core samples received by the laboratory for Structure G-22-BY

Figure 20. Core samples received by the laboratory for Structure G-22-BZ

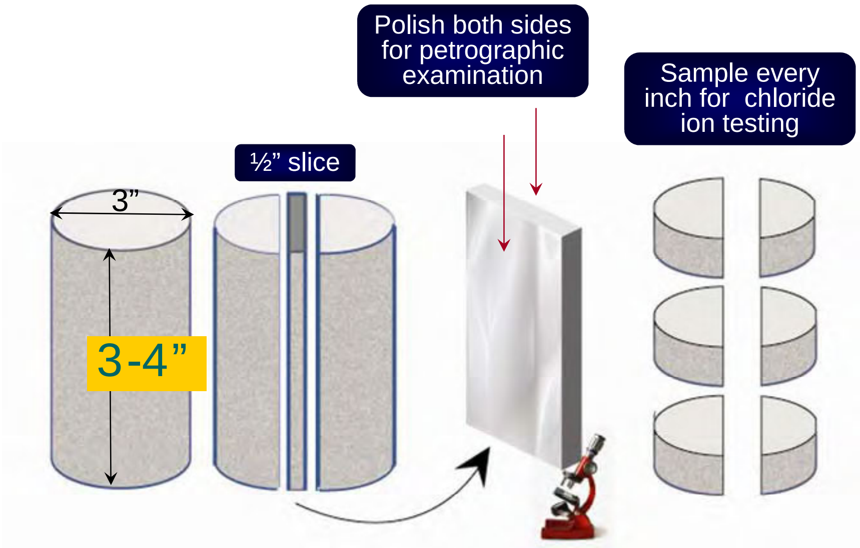


Figure 21. Samples obtained from each core for petrographic and chloride testing

Note: All dimensions are minimum effective lengths measured on the cores

RESULTS OF ASTM C 457AIR VOID ANALYSES

The air void analysis reports for all samples are included in Appendix B of this report. Table 4 summarizes the results of the air void analyses in the two cores for the six structures, and Table 5 presents the average values for each structure. Note that Table 5 also presents the average results for each specification type based on results from the three structures that were selected in each category. A close review of the data presented in Table 4 suggests that the variability between the samples within a structure generally is higher than the variability across structures or between the two specification types used.

Table 6 presents sample mean percent deviation from the average presented in Table 5. It appears that the point of delivery specification has produced relatively more consistent air void characteristics based on the results from two cores. However, statistically, it is appropriate to consider an average between the samples within a structure, as the cores have been sampled from the same structure (same mix, same design, construction practice, workmanship, etc.).

The data in Table 4 and 5 suggest that the results more or less meet the conventional limit that specifies a spacing factor of less than 0.008 in (0.2 mm) and specific a surface greater than 600 in^2/in^3 (24 to 44 mm^2/mm^3) to maintain F-T durability. Additionally, the entrained air content is between 3 and 4 percent in majority of the cases in Table 4. Table 5 also shows that air void analysis results across the structures and between the specifications are fairly close. The closeness of these values indicates no practical difference. If there was a significant difference, this would indicate that the change in specification resulted in a change in the quality of concrete placed. It is worth noting that the point of delivery specification, in general, shows better air void characteristics, perhaps attributable to improved mix designs and admixture quality during the period when the point of delivery specification was used relative to the period when the bridges under the point of placement specification was in effect. Thus, there is no evidence that the change in specification resulted in a lower quality of air entrainment achieved during the period of 1993-2008.

Table 4. Summary of air void analysis results for selected structures

Structure and specification		Sample/ Core 1							Sample/Core 2						
		ID	Total air content, %	Entrained air, %	Entrapped air, %	Spacing factor, in (mm)	Specific surface (in^2/in^3)	Paste content (%)	ID	Total air content, %	Entrained air, %	Entrapped air, %	Spacing factor, in (mm)	Specific surface (in^2/in^3)	Paste content (%)
Point of Placement	**C-15-AK**	N	3.9	3.3	0.6	0.00035 (0.009)	585	26	C	2.2	1.6	0.6	0.00051 (0.013)	515	26
	D-14-I	1	6.1	3.8	2.3	0.00023 (0.006)	685	26	2	3.9	2.5	1.4	0.00035 (0.009)	590	26
	F-20-BU	E	6.4	3	3.4	0.00039 (0.01)	425	26	C	3.3	2.2	1.1	0.00035 (0.009)	615	26
Point of delivery	**F-15-BZ**	1	4.7	3.2	1.5	0.00031 (0.008)	625	26	2	5.3	4.4	0.9	0.00027 (0.007)	690	26
	G-22-BY	S	5.9	4.3	1.6	0.00039 (0.01)	450	26	N	4.3	3.1	1.2	0.00031 (0.008)	650	26
	G-22-BZ	S	5.1	4.1	1	0.00027 (0.007)	700	26	N	3.5	2.8	0.7	0.00031 (0.008)	680	26

Entrained air is <0.04 in (1 mm), entrapped air is > 0.04 in (1 mm)

Table 5. Average results from air void analyses of all structures

	Structure/ Specification	Total air content, %	Entrained air, %	Entrapped air, %	Spacing factor, in, (mm)	Specific surface (in^2/in^3)	Paste content (%)
Point of Placement	C-15-AK	3.05	2.45	0.6	0.00043 (0.011)	550	26
	D-14-I	5	3.15	1.85	0.00029 (0.0075)	637.5	26
	F-20-BU	4.85	2.6	2.25	0.00037 (0.0095)	520	26
Point of delivery	F-15-BZ	5	3.8	1.2	0.00029 (0.0075)	657.5	26
	G-22-BY	5.1	3.7	1.4	0.00035 (0.009)	550	26
	G-22-BZ	4.3	3.45	0.85	0.00029 (0.0075)	690	26
Average Point of placement		4.3	2.73	1.567	0.00036 (0.0093)	569.2	26
Average Point of delivery		4.8	3.65	1.15	0.00031 (0.008)	632.5	26

Table 6. Percent mean sample deviation from average results in air void analyses

	Structure/ Specification	Total air content	Entrained air content	Entrapped air content	Spacing factor	Specific surface	Paste content
Point of Placement	C-15-AK	27.9	34.7	0.0	18.2	6.4	0.0
	D-14-I	22.0	20.6	24.3	20.0	7.5	0.0
	F-20-BU	32.0	15.4	51.1	5.3	18.3	0.0
Point of delivery	F-15-BZ	6.0	15.8	25.0	6.7	4.9	0.0
	G-22-BY	15.7	16.2	14.3	11.1	18.2	0.0
	G-22-BZ	18.6	18.8	17.6	6.7	1.4	0.0

RESULTS OF ASTM C 1152 CHLORIDE ION PENETRATION TESTING

Chloride ion penetration was measured using mortar samples collected from each core at depths of 0-1 in (0-25 mm), 1-2 in (25-50 mm), and 2-3 in (50-75 mm). Results from each core are presented in Table 7, and the average results are presented in Table 8. As expected, the chloride levels decrease along the depth of the slab. Also listed in the tables are the gradients that indicate the rate of change in chloride levels along the slab depth and signify the level of permeability in the concrete. Higher gradients typically are indicative of lower permeability and vice versa. Figure 22 shows the gradient in chloride content variation per inch of slab depth.

Table 7 and 8 suggest that there is no significant difference between the two specifications, especially considering that the chloride levels are within critical levels. Note that, while the average chloride ion concentration in the top 1 inch of the slab is higher in the structures built under the point of placement specification, the gradient is higher as well, indicating there is a larger drop in the chloride ion concentration as the second inch is sampled. It is also clear that Structure D-14-1 has a higher concentration in the top inch, which results in the higher average for the structures considered under the point of placement specification. D-14-1 is the oldest of the structures included in the study and, as indicated in the previous chapter, the surface of this deck appeared to be most affected by F-T related durability issues.

In general, the chloride levels that trigger corrosion are not well defined because they depend on whether the chloride was introduced into the system during mixing of the concrete or after hardening. The temperature and humidity conditions, the use of deicer chemicals or salts during winter months, and the carbonation in the concrete also play a vital role in the effective chloride content measured in hardened concrete. In general, chloride levels lower than 0.35 percent are considered harmless, while chloride-induced corrosion is significant for levels greater than 0.6 percent.

Table 7. Summary of chloride ion penetration results for selected structures, percent chloride by weight

Structure and specification		Sample/ Core 1							Sample/Core 2						
		ID	Cl_2, 0-1 in	Cl_2, 1-2 in	Cl_2, 2-3 in	Gradient 1-2 in	Gradient 2-3 in	Gradient 1-3 in	ID	Cl_2, 0-1 in	Cl_2, 1-2 in	Cl_2, 2-3 in	Gradient 1-2 in	Gradient 2-3 in	Gradient 1-3 in
Point of Placement	C-15-AK	N	0.15	0.103	0.069	0.047	0.034	0.041	C	0.252	0.217	0.19	0.035	0.027	0.031
	D-14-I	1	0.308	0.039	0.004	0.269	0.035	0.152	2	0.261	0.094	0.013	0.167	0.081	0.124
	F-20-BU	E	0.089	0.006	0.004	0.083	0.002	0.043	C	0.12	0.005	0.005	0.115	0	0.058
Point of delivery	F-15-BZ	1	0.105	0.034	0.01	0.071	0.024	0.048	2	0.094	0.025	0.005	0.069	0.02	0.045
	G-22-BY	S	0.171	0.059	0.008	0.112	0.051	0.082	N	0.14	0.037	0.005	0.103	0.032	0.068
	G-22-BZ	S	0.275	0.223	0.098	0.052	0.125	0.089	N	0.159	0.064	0.012	0.095	0.052	0.074

The gradient in chloride ion concentration in units of percent chloride per inch is shown for all structures in Figure 22 at depths of 0-1 in (0-25 mm), 1-2 in (25-50 mm), and 2-3 in (50-75 mm). Clearly, there is no striking difference between structures built under the two specifications. However, Structure D-14-1, which was built in 1973, shows a relatively higher drop in concentration, indicating a smaller ingress of chloride ions within the top 2 inches (50 mm). Also, Structure G-22-BZ, a relatively newer structure built in 2000, shows a consistent drop in chloride ion concentration across the entire slab depth.

Table 8. Average chloride ion concentration of all structures, percent chloride by weight

	Structure/ Specification	Cl_2, 0-1 in	Cl_2, 1-2 in	Cl_2, 2-3 in	Gradient 1-2 in	Gradient 2-3 in	Gradient 1-3 in
Point of Placement	C-15-AK	0.201	0.160	0.130	0.041	0.031	0.036
	D-14-I	0.285	0.067	0.009	0.218	0.058	0.138
	F-20-BU	0.105	0.006	0.005	0.099	0.001	0.050
Point of delivery	F-15-BZ	0.100	0.030	0.008	0.070	0.022	0.046
	G-22-BY	0.156	0.048	0.007	0.108	0.042	0.075
	G-22-BZ	0.217	0.144	0.055	0.074	0.089	0.081
Average Point of placement		0.197	0.077	0.048	0.119	0.030	0.075
Average Point of delivery		0.157	0.074	0.023	0.084	0.051	0.067

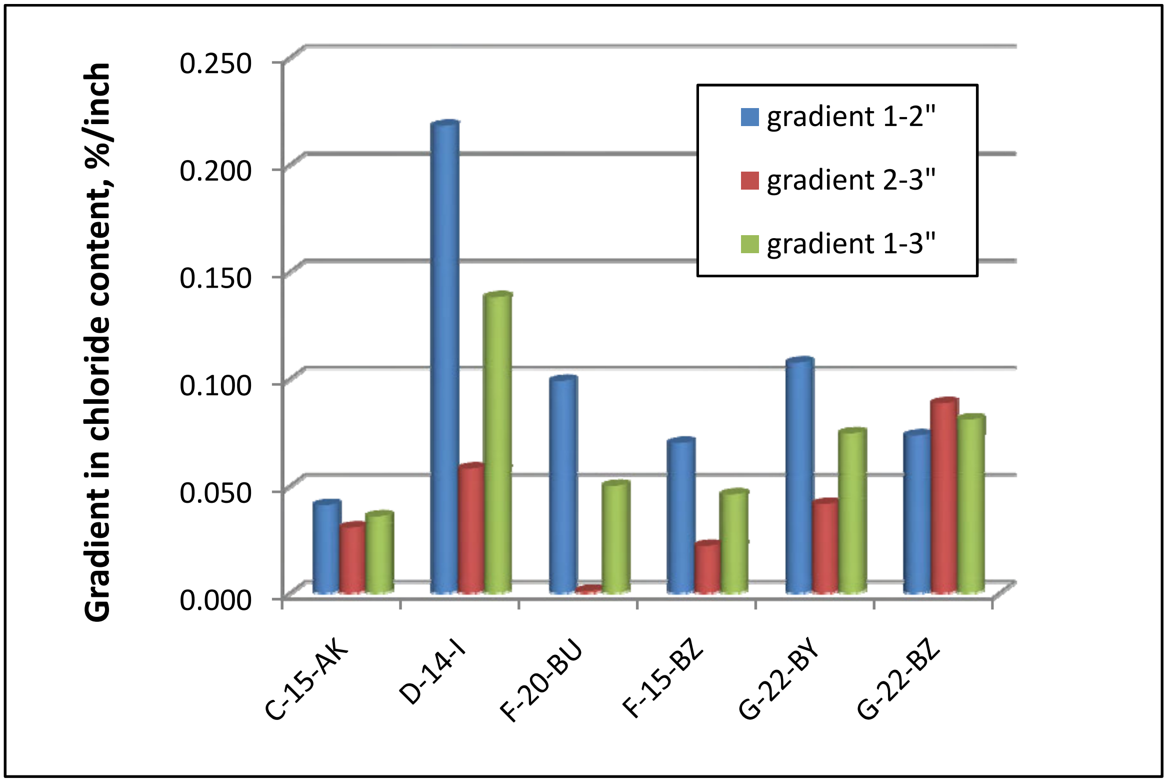


Figure 22. Chloride ion content gradient at three levels in the selected structures

Figure 23 shows the chloride ion distribution along the slab depth as measured in the two cores extracted from each structure. The plots show that, for a majority of cases, both cores within a structure follow the same trend.

Structures C-15-AK and G-22-BZ show higher variability within the structure. However, the gradients are the same between the two cores from the structure. Also, as discussed previously, the chloride contents are within critical levels and do not signify a difference in durability of the mix or the performance of the structure. The plots shown on the same scale also illustrate the relative chloride ion contents across all structures and across specifications. The results suggest, again, that there is no significant difference in the chloride ion penetration in structures constructed under the two specifications.

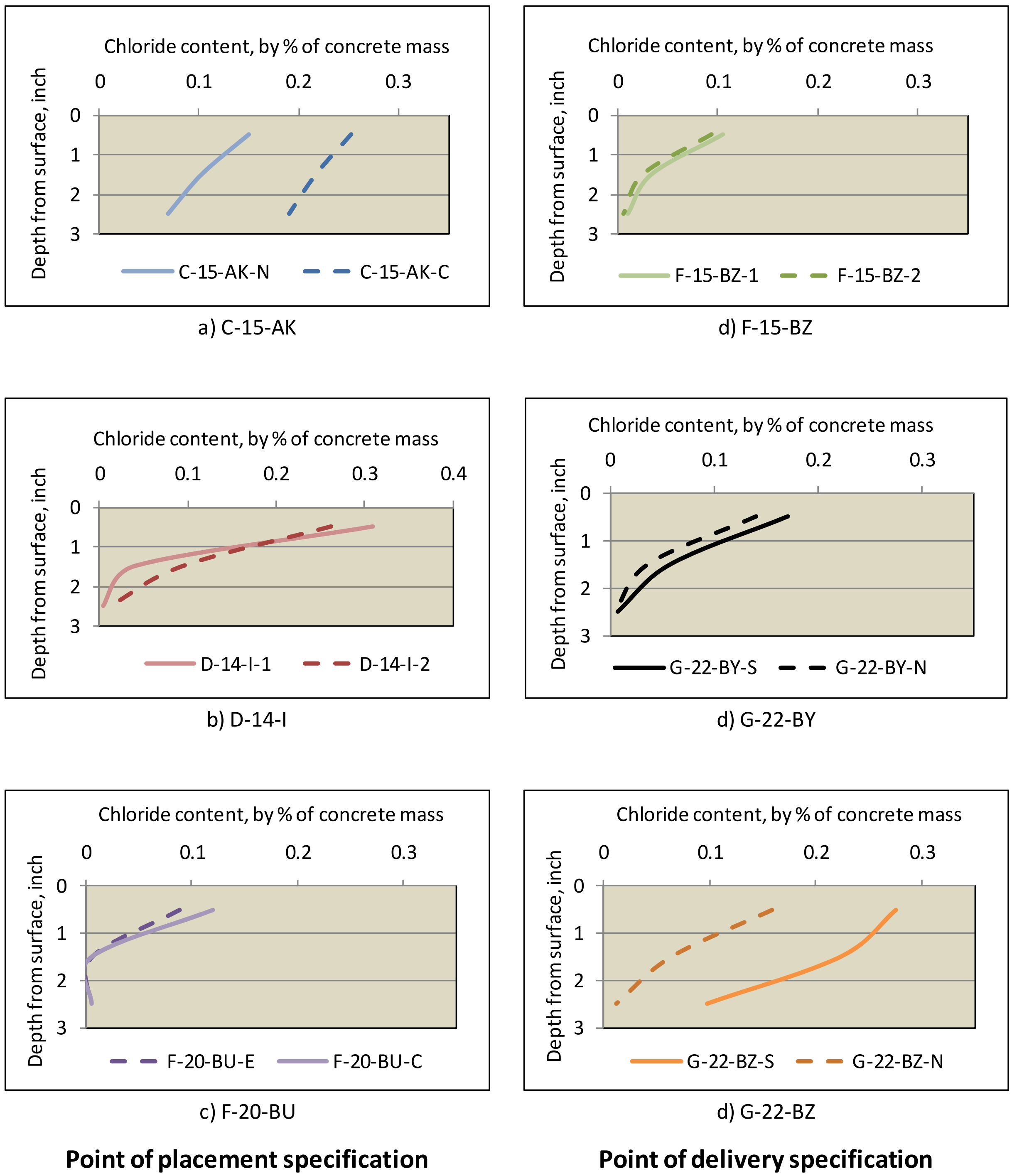


Figure 23. Chloride ion distribution along slab depth in selected structures from two cores

As with the air void analyses results, it is reasonable to consider the average from the two samples to represent the general condition of each structure. Figure 24 presents the average chloride ion content for each structure. While all structures are within reasonable limits, there are no clear trends in the distribution that could indicate any change in durability due to the change in specification. Structure D-14-1 shows a higher concentration near the surface, but perhaps it has a low permeability mix design that has maintained low chloride levels at lower depths, comparable to those in the relatively newer structures. Also, it is reasonable to say that the chloride analysis results are consistent with the findings of the air void analysis testing.

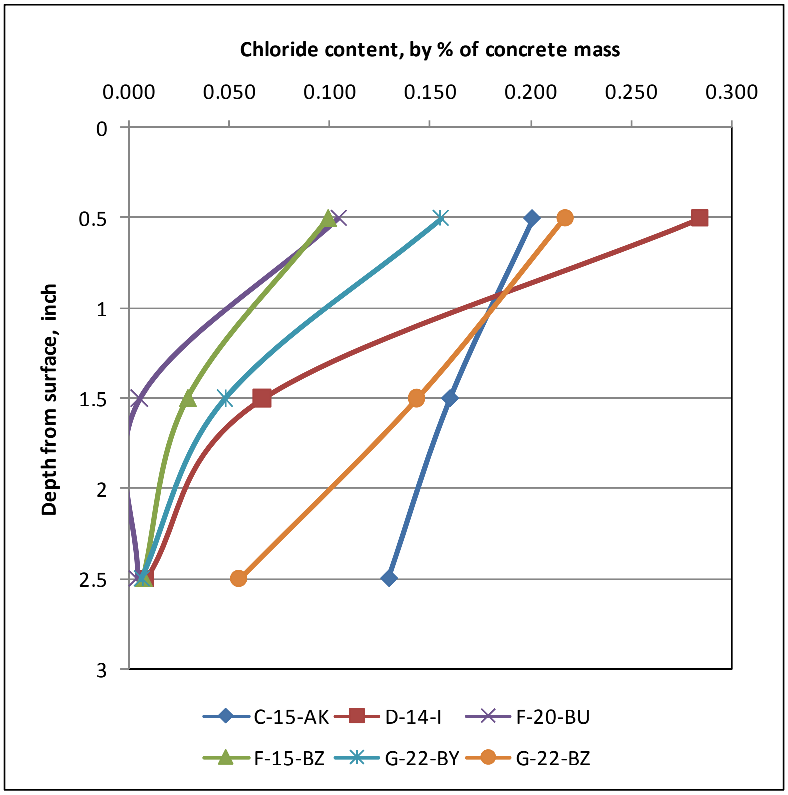


Figure 24. Average chloride ion concentration for all structures

RESULTS OF ASTM C 856 PETROGRAPHIC EXAMINATION OF SAMPLES

A routine petrographic examination was conducted on the samples extracted for air void analyses in accordance with ASTM C 856. Detailed petrographic reports of each sample are included in Appendix C. This section presents some of the key observations and a brief summary of the test results for each structure. In general, the two cores taken from each structure were very consistent with each other.

C-15-AK – Point of Placement Specification

Magnified images of the two cores are presented in Figures 25, 26, and 27. The cores from this structure had a rough mortar eroded surface on the top with exposed coarse aggregate surfaces. Carbonation extended about 0.16 to 0.32 in (4 to 8 mm) from the surface (see Figure 25a, 26a). Several drying shrinkage microcracks were observed up to depths of 0.48 to 0.6 in (12 to 15 mm), and finer air voids at depths below an inch were filled with secondary ettringite (Figure 26c and 27b). This concrete was rated as having limited to poor F-T resistance.

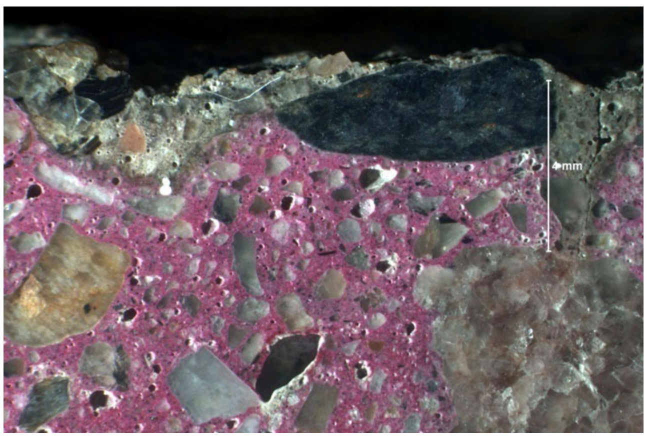
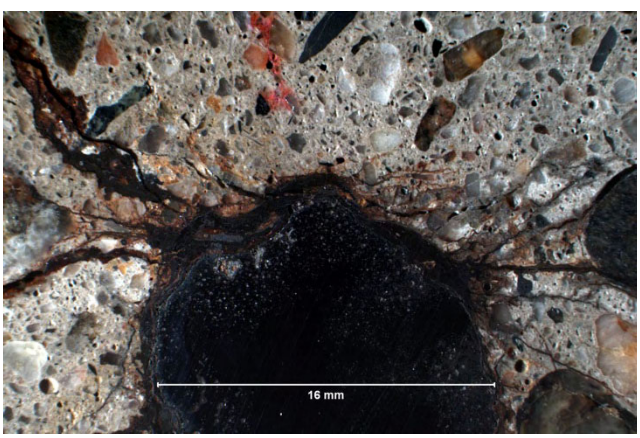
	**a)** **SAMPLE**: C-15-AK, C **DESCRIPTION:** Carbonation (unstained) proceeds up to 0.16 in (4 mm) depth from the mortar eroded top surface, along sub-vertical microcracking **MAG**: 5X
	**b)** **SAMPLE**: C-15-AK, C **DESCRIPTION:** Moderate corrosion of the rebar at depth in the sawcut and lapped cross section of core. (Note corrosion product-filled radiating micro and macrocracks) **MAG**: 5X

Figure 25. Magnified images of sample C-15-AK, C under petrographic examination

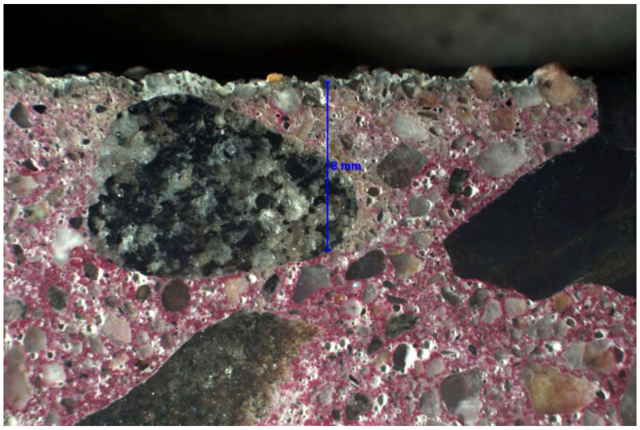
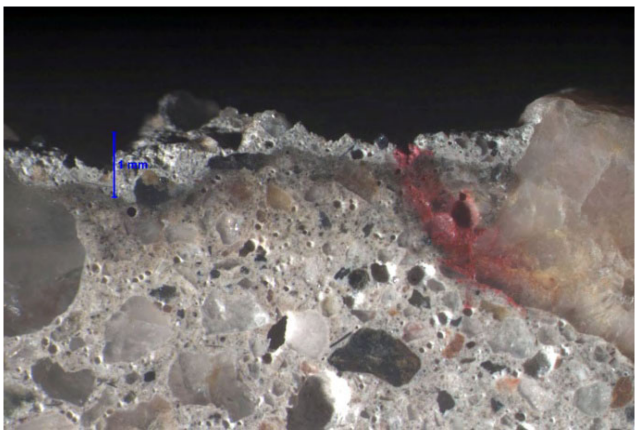
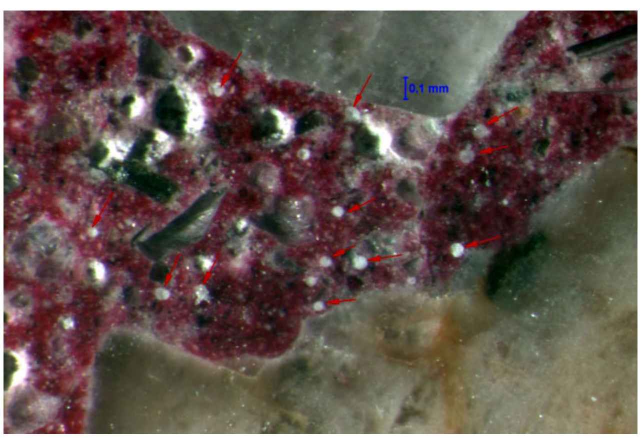
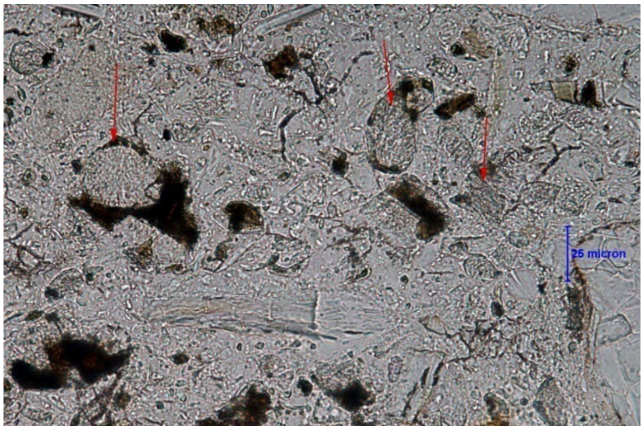
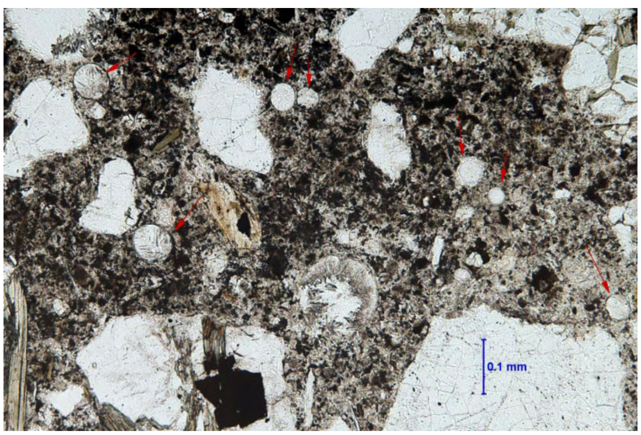
	**a)** **SAMPLE**: C-15-AK, N **DESCRIPTION:** Carbonation (unstained) ranges from negligible up to 0.32 in (8 mm) depth from the mortar eroded top surface. **MAG**: 5X
	**b)** **SAMPLE**: C-15-AK, N **DESCRIPTION:** The top up to 0.04 in (1 mm) on the concrete was characterized by a very soft, white paste. **MAG**: 15X
	**c)** **SAMPLE**: C-15-AK, N **DESCRIPTION:** White, ettringite-filled entrained air void spaces in phenolphthalein-stained paste at 0.71 in (18 mm) depth from the top surface of the core. **MAG**: 50X

Figure 26. Magnified images of sample C-15-AK-N under petrographic examination

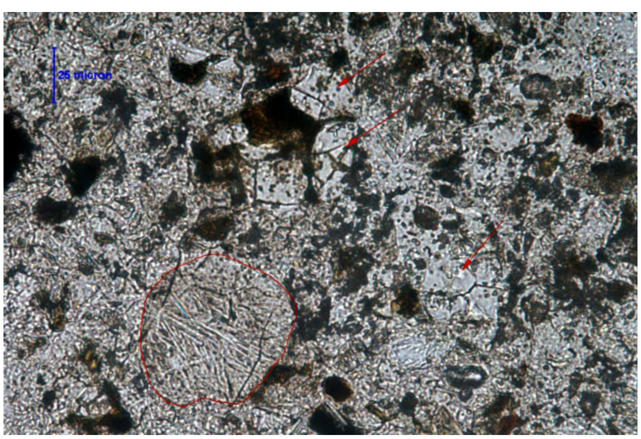
Also, there was evidence of corrosion products filling microcracks radiating from the corroding member (Figure 25b). Coarse aggregate was ¾-in (19 mm) maximum sized natural gravel which consisted mostly of granite, gneiss, schist, quartzite, sandstone, and some shale. w/c ratio was estimated to be 0.45 to 0.5, and the alites and belites were fully hydrated. (Figures 27a, 27c)



a)
SAMPLE: C-15-AK, N
DESCRIPTION: Fully hydrated belites portland cement clinker relicts in thin section of concrete paste under plane polarized light.
MAG: 400X



b)
SAMPLE: C-15-AK, C
DESCRIPTION: Ettringite-filled entrained air void spaces (arrows) in thin section of concrete paste under plane polarized light
MAG: 100X



c)
SAMPLE: C-15-AK, C
DESCRIPTION: Fully hydrated alites (arrows) and belites (circled) portland cement clinker relicts in thin section of concrete paste under plane polarized light.
MAG: 400X

Figure 27. Examination under plane polarized light for structure C-15-AK

D-14-I – Point of Placement Specification

Magnified images of the two cores are presented in Figures 28, 29, and 30. The cores from this structure had a rough mortar eroded surface exposing fine aggregate particles on the top. They indicated the placement of a thin bituminous overlay on the portland cement concrete (PCC) deck. As evidenced by the other test results, this structure showed remarkable resistance to chloride ion permeability and F-T damage (see Figure 24 and Table 5). Accordingly, the petrographic results indicated a very well consolidated mix with good air entrainment. Drying shrinkage microcracks were observed up to depths of 0.16 in (4 mm) in one core and 0.63 in (16 mm) in another core. This variability could be a result of small inconsistencies in workmanship (curing) or change in construction weather across the two ends of the bridge. Likewise, one of the cores showed evidence of excessive bleed water (Figure 28b).

Carbonation extended from a depth of 0.08 to 0.75 in (2 to 19 mm) as seen in Figures 28a and 29a. The finer air voids were free of ettringite formation (Figure 29b), indicating again a low permeability mix and good temperature management or placement during cooler weather conditions. This structure was rated to have good F-T resistance under severe exposure conditions.

Coarse aggregate was 1-in (25 mm) maximum sized crushed trap rock composed of felsites, and well graded and uniformly distributed. The w/c ratio was estimated to be between 0.43 and 0.48, and the alites and belites were well to fully hydrated (see Figure 30).

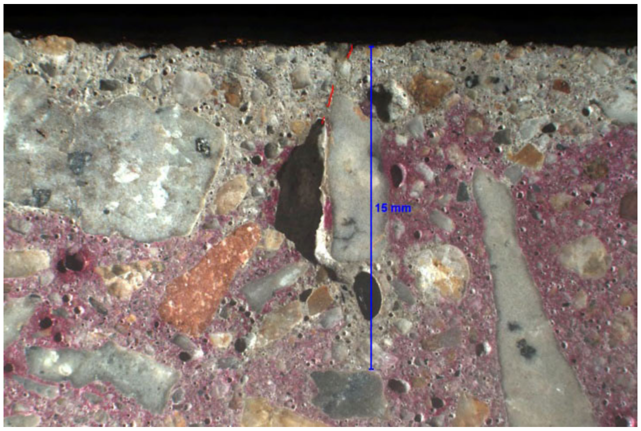
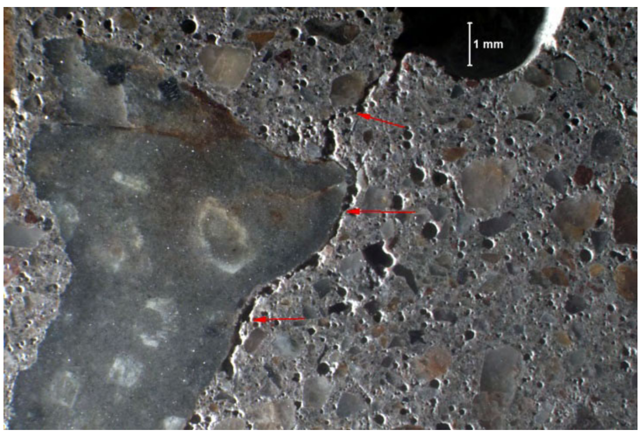
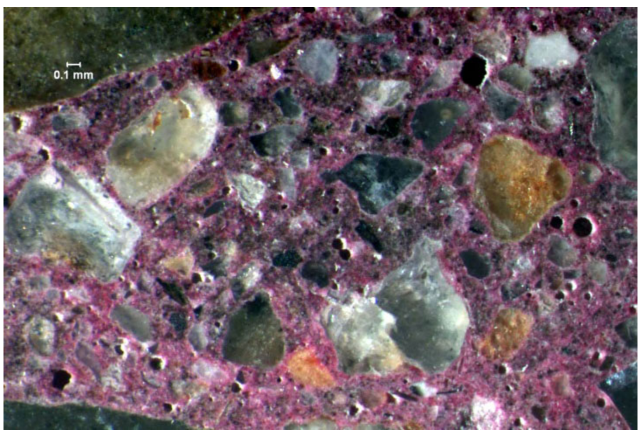
	**a)** **SAMPLE**: D-14-I (1) **DESCRIPTION:** Carbonation (unstained) proceeds up to 0.63 in (16 mm) depth from the mortar eroded top surface, along consolidation void space. Microcrack is mapped in red dash line. **MAG**: 5X
	**b)** **SAMPLE**: D-14-I (1) **DESCRIPTION:** Sinuous bleed water void space/channel proceeds along paste-coarse aggregate boundary at depth in the core. **MAG**: 10X

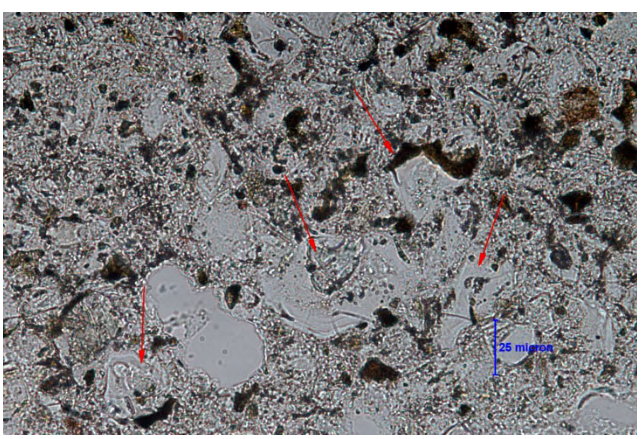
Figure 28. Magnified images of sample D-14-I (1) under petrographic examination

a)
SAMPLE: D-14-I (2)
DESCRIPTION: Carbonation (unstained) proceeds up to 0.75 in (19 mm) depth from the mortar eroded top surface, along sub-vertical microcracking and consolidation void space. Microcrack is mapped in red dash line.
MAG: 5X



b)
SAMPLE: D-14-I (2)
DESCRIPTION: Fine air void spaces relatively clean and free of secondary ettringite fillings.
MAG: 30X

Figure 29. Magnified images of sample D-14-I (2) under petrographic examination

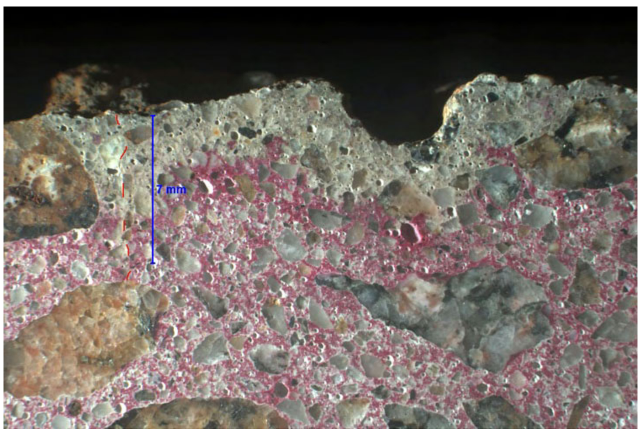


a)
SAMPLE: D-14-I (1)
DESCRIPTION: Well to fully hydrated alites portland cement clinker particles in thin section of concrete paste under plane polarized light
MAG: 400X

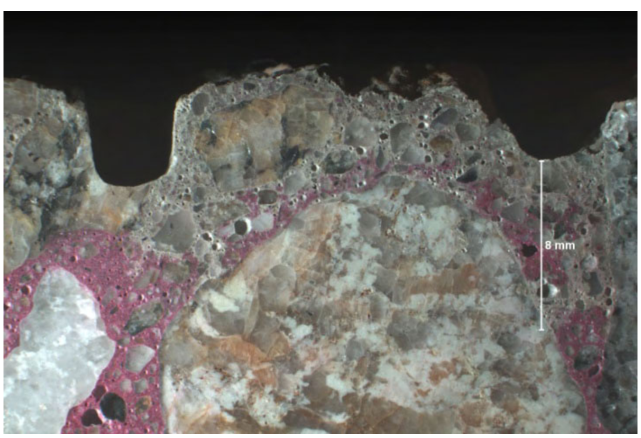
Figure 30. Examination under plane polarized light for structure D-14-I

F-20-BU – Point of Placement Specification

Magnified images of the two cores are presented in Figures 31 and 32. The cores from this structure had a rough mortar eroded surface with exposed fine aggregates. The cores also showed evidence of diamond sawn transverse tining, 0.16 in (4 mm) wide and 0.10 in (2.5 mm) deep. Drying shrinkage microcracks were observed up to comparable depths in both cores, 0.47 in (12 mm) in one core and 0.60 in (15 mm) in the other. Carbonation was not extensive in this structure, but where observed, it extended 0.28 to 0.35 in (7 to 9 mm) deep (see Figure 31). The concrete was considered to offer only limited F-T resistance.



a)
SAMPLE: F-20-BU, E
DESCRIPTION: Carbonation (unstained) ranges from negligible up to 0.28 in (7 mm) depth, intermittently, from the top surface of the core.
MAG: 5X



b)
SAMPLE: F-20-BU, C
DESCRIPTION: Carbonation (unstained) ranges from negligible up to 0.28 in (7 mm) depth, intermittently, from the top surface of the core.
MAG: 5X

Figure 31. Magnified images of structure F-20-BU under petrographic examination

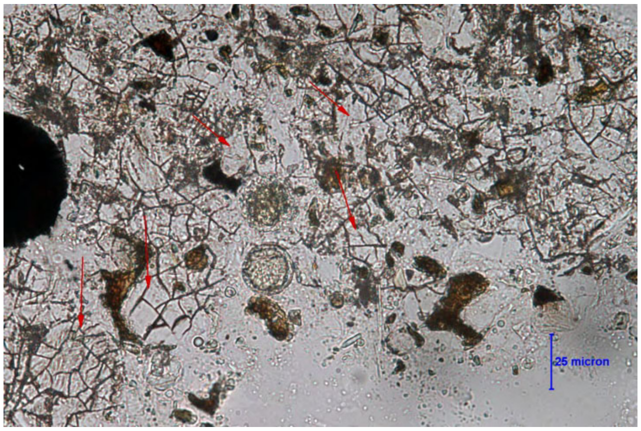
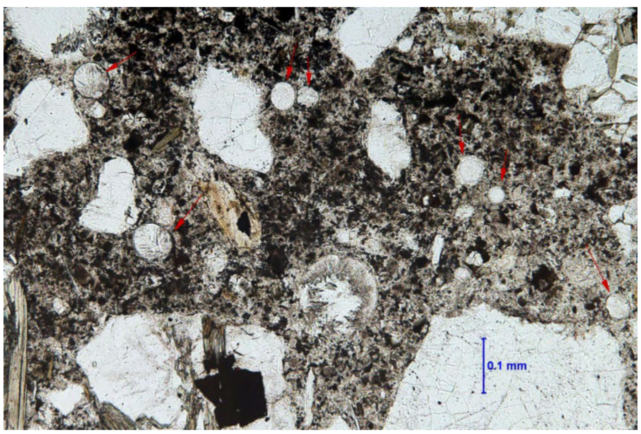
	**a)** **SAMPLE**: F-20-BU, E **DESCRIPTION:** Well to fully hydrated alites portland cement clinker particles in thin section of concrete paste under plane polarized light. Note spherical fly ash pozzolan particles. **MAG**: 400X
	**b)** **SAMPLE**: F-20-BU, C **DESCRIPTION:** Well to fully hydrated portland cement clinker particles in thin section of concrete paste under plane polarized light. Note spherical fly ash pozzolan particles. **MAG**: 100X

Figure 32. Examination under plane polarized light for structure F-20-BU

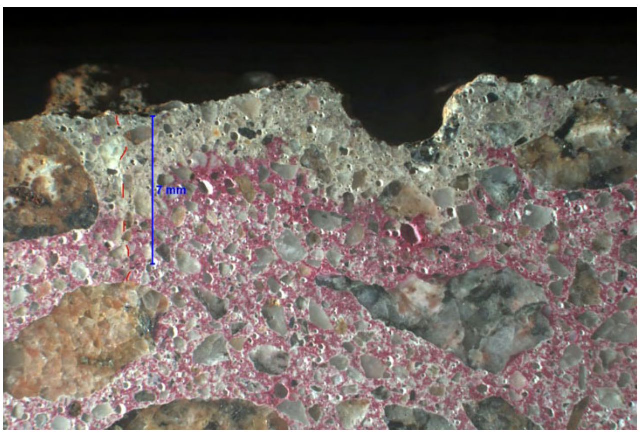
Coarse aggregate was ¾-in (19 mm) maximum sized crushed natural granite rich gravel, with small amounts of basalt, sandstone, and quartzite. The w/c ratio was estimated to be between 0.38 and 0.43, and the alites were fully hydrated, while the belites were moderately hydrated (see Figure 32).

F-15-BZ – Point of Delivery Specification

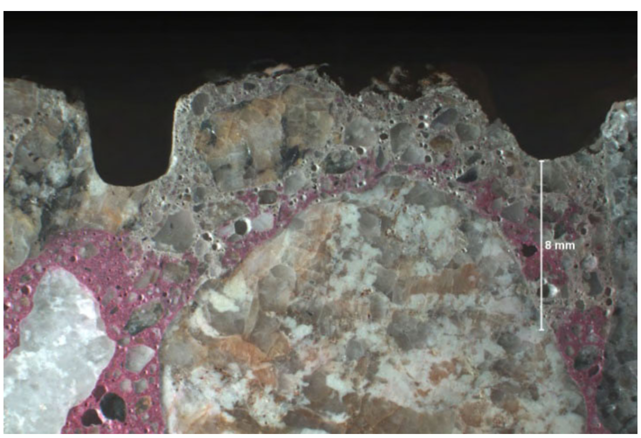
Magnified images of the two cores are presented in Figures 33 and 34. The cores from this structure had a rough mortar eroded surface with exposed coarse aggregates. The cores also showed evidence of diamond sawn transverse tining, 0.16 in (4 mm) wide, and 0.12 to 0.16 in (3 to 4 mm) deep. Drying shrinkage microcracks appeared to varying degrees in this structure—

from 0.08 to 2.75 in (2 to 70 mm) depth. Carbonation extended from 0.08 to 0.28 in (2 to 7 mm) deep (Figure 33). The concrete was considered to offer F-T resistance under severe exposure conditions.

Coarse aggregate was ¾-in (19 mm) maximum sized crushed natural granite rich gravel, with small amounts of basalt, sandstone, and quartzite. The w/c ratio was estimated to be between 0.42 and 0.47, and the alites and belites were mostly fully hydrated (see Figure 34).

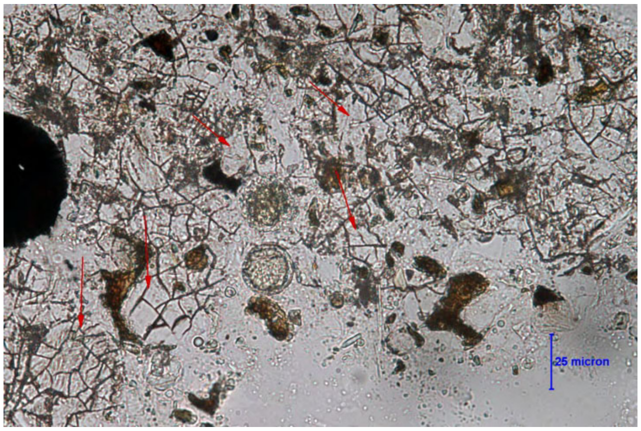


a)
SAMPLE: F-15-BZ (1)
DESCRIPTION: Carbonation (unstained) ranges from 0.08 in (2 mm) up to 0.28 in (7 mm) depth from the top surface of the core.
MAG: 5X



b)
SAMPLE: F-15-BZ(2)
DESCRIPTION: Carbonation (unstained) proceeds up to 0.32 in (8 mm) depth from the top surface of the core.
MAG: 5X

Figure 33. Magnified images of structure F-15-BZ under petrographic examination



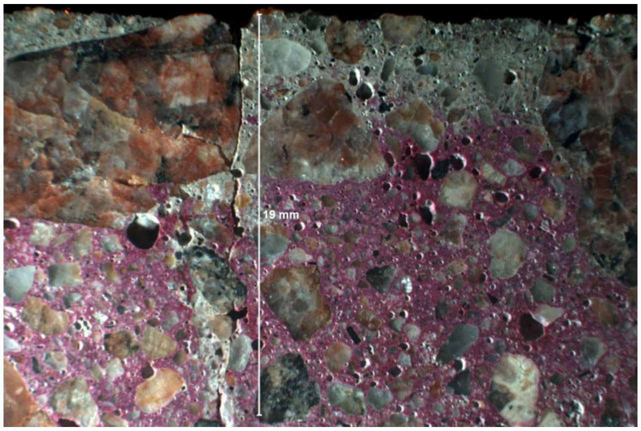
a)
SAMPLE: F-15-BZ (1)
DESCRIPTION: Well to fully hydrated portland cement clinker particles in thin section of concrete paste under plane polarized light. Note spherical fly ash pozzolan particles.
MAG: 400X

Figure 34. Examination under plane polarized light for structure F-15-BZ

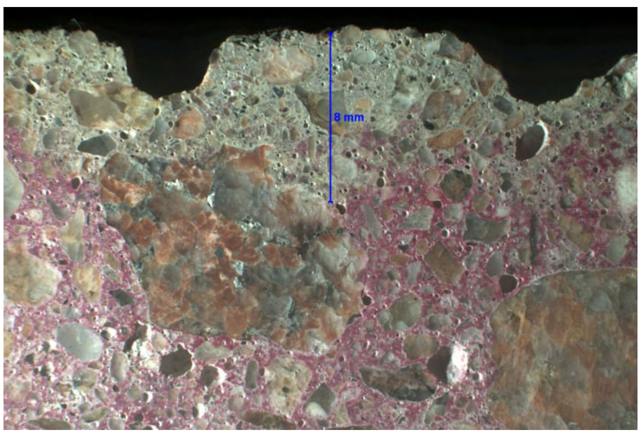
G-22-BY – Point of Delivery Specification

Magnified images of the two cores are presented in Figures 35, 36, and 37. The top surface of this structure has undergone moderate mortar erosion exposing fine aggregate particles. The cores also showed evidence of diamond sawn transverse tining 0.12 in (3 mm) deep (see Figure 36). Drying shrinkage microcracks appeared to a depth of 3.35 in (85 mm), but the cracks were wider in the top 1.18 in (30 mm) as seen in Figure 35. Carbonation extended up to 0.32 in (8 mm) deep (see Figure 35) in one core and up to 0.75 in (19 mm) deep in the other. The concrete was considered to offer limited F-T resistance.

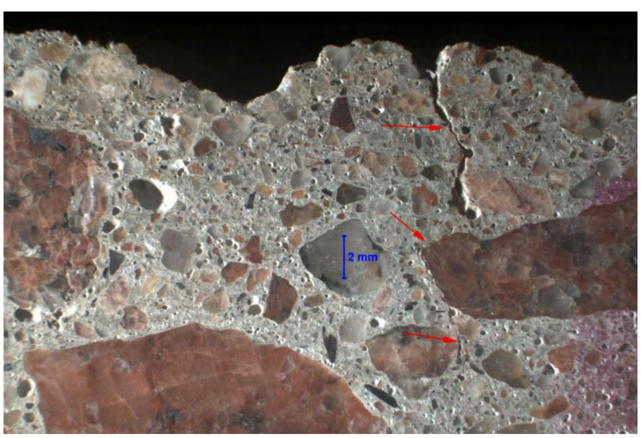
Coarse aggregate was ¾-in (19 mm) maximum sized crushed granite with well graded and uniform distribution. The w/c ratio was estimated to be between 0.39 and 0.44, and the alites and belites were mostly fully hydrated (see Figure 37).



a)
SAMPLE: G-22-BY, N
DESCRIPTION: Carbonation (unstained) proceeds up to 0.75 in (19 mm) depth, intermittently from the top surface of the core, along sub-vertical microcracking.
MAG: 5X

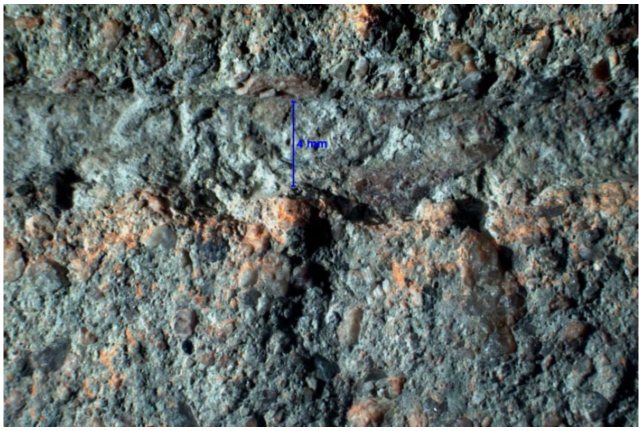


b)
SAMPLE: G-22-BY, S
DESCRIPTION: Carbonation (unstained) proceeds up to 0.32 in (8 mm) depth from the top surface of the core
MAG: 5X



c)
SAMPLE: G-22-BY, S
DESCRIPTION: Plastic shrinkage macrocrack proceeds intermittently from the top surface of the core.
MAG: 5X

Figure 35. Magnified images of structure G-22-BY under petrographic examination

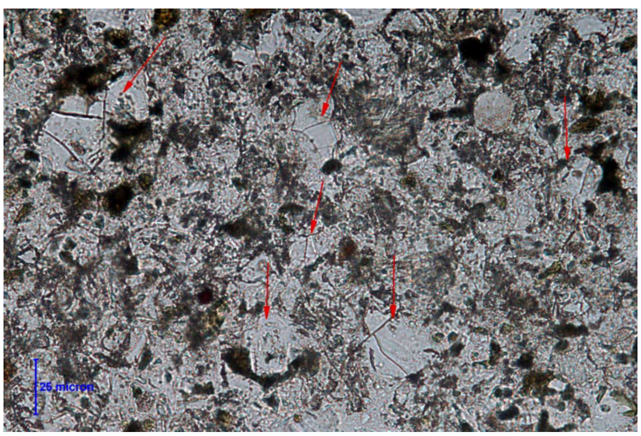


SAMPLE: G-22-BY, S

DESCRIPTION: 0.16 in (4-mm)-wide diamond sawn transverse tining in mortar eroded top surface of the core.

MAG: 5X

Figure 36. Transverse tining visible in the magnified image for structure G-22-BY



a)
SAMPLE: G-22-BY, S
DESCRIPTION: Fully hydrated alites portland cement clinker relicts in thin section of concrete paste under plane polarized light.
MAG: 400X

Figure 37. Examination under plane polarized light for structure G-22-BY

G-22-BZ – Point of Delivery Specification

Magnified images of the two cores are presented in Figures 38 and 39. Mortar in the top surface of this structure has undergone erosion, exposing fine aggregate particles. Diamond sawn transverse tining 0.16 in (4 mm) wide and 0.16 in (4 mm) deep was observed in the cores. Drying shrinkage microcracks appeared to a depth of 2.75 in (70 mm) in one core and up to 1 in (25 mm) in the other. Carbonation extended up to a depth of 0.28 in (7 mm) in both cores (see

Figure 38). The concrete was considered well consolidated and rated as offering good F-T resistance under severe exposure conditions.

Coarse aggregate was ¾-in (19 mm) maximum sized crushed granite with well graded and uniform distribution. The w/c ratio was estimated to be between 0.39 and 0.45, and the alites and belites were generally well to fully hydrated (see Figure 39).

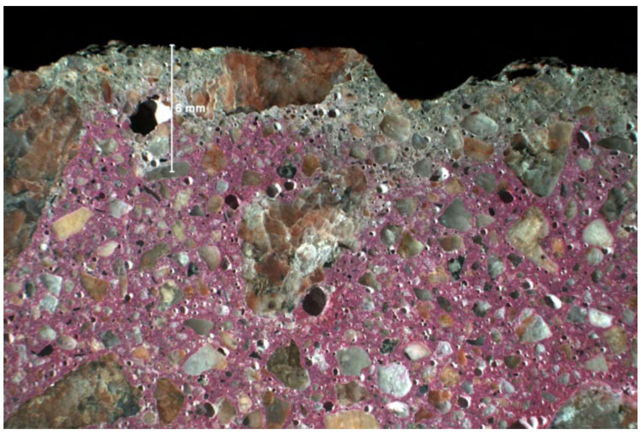
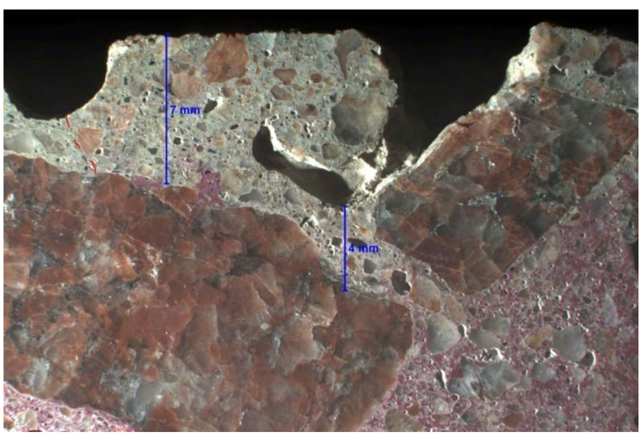
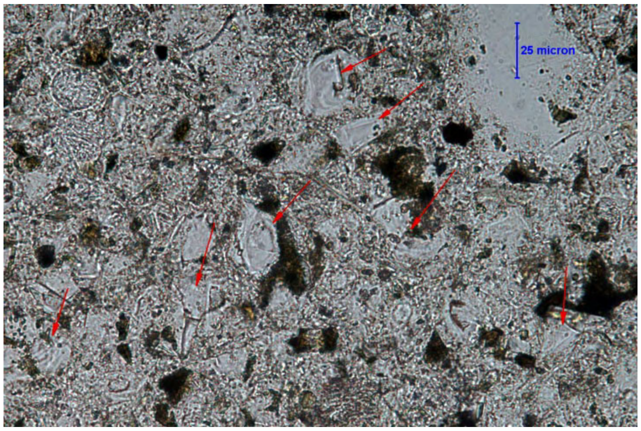
	**a)** **SAMPLE**: G-22-BZ, N **DESCRIPTION:** Carbonation (unstained) proceeds up to 0.24 in (6 mm) depth from the top surface of the core. **MAG**: 5X
	**b)** **SAMPLE**: G-22-BZ, S **DESCRIPTION:** Carbonation (unstained) proceeds up to 0.28 in (7 mm) from the mortar eroded top surface of the core. Note additional carbonation depth along consolidation void space. **MAG**: 5X

Figure 38. Magnified images of structure G-22-BZ under petrographic examination



a)
SAMPLE: G-22-BZ, S
DESCRIPTION: Fully hydrated alites portland cement clinker relicts in thin section of concrete paste under plane polarized light
MAG: 400X

Figure 39. Examination under plane polarized light for structure G-22-BZ

Summary of Findings from Petrographic Examination

A summary of the results obtained from the petrographic examinations of all the cores is presented in Table 9. These results do not indicate any specific trends that suggest different durability characteristics between structures built under the two specifications.

Using the point of placement specification, two bridges were rated as having limited resistance, and one bridge was rated as being resistant to a severe F-T environment. Using the point of delivery specification, one bridge was rated as being resistant to a severe F-T environment; however, only one of the replicates showed limited resistance to F-T damage. Although the point of delivery specification shows a higher number of concrete placements with better resistance to F-T damage, the data relative to the sample size used are not adequate to draw significant conclusions on the effectiveness of one specification over the other.

It is therefore reasonable to conclude that the change in specification did not result in a change in quality of PCC. This is perhaps because the workmanship and the quality of the PCC mix, including its durability characteristics, did not change—or perhaps even improved—during the period when the specification changed from point of placement to point of delivery. It is apparent that CDOT has used good materials and consistent construction practices through the years.

Table 9. Summary of results from petrographic tests for all bridges

Structure and specification		Carbonation depth, mm	Drying shrinkage depth, mm	Other observations	Coarse aggregates max size & w/c ratio	F-T resistance
Point of Placement	C-15-AK	4 to 8	12 to 15	Finer voids with secondary ettringite	¾” 0.45 – 0.50	Limited to poor
	D-14-I	16 to 19	4 and 16	Bleed water, good consolidation	1” 0.43 – 0.48	Good under severe exposure
	F-20-BU	7 to 9	12 and 15	Tining, Belites partly hydrated	¾” 0.38 – 0.43	Limited
Point of delivery	F-15-BZ	2 to 7	2 to 70	Tining, fly ash	¾” 0.42 – 0.47	Good under severe exposure
	G-22-BY	8 and 19	85 (wide up to 30)	Tining, well consolidated, finer voids ettringite	¾” 0.39 – 0.44	Limited and Good under severe exposure
	G-22-BZ	Up to 7	25 and 70	Tining, well consolidated	¾” 0.39 – 0.45	Good under severe exposure

CHAPTER 5. SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

SUMMARY

Damage to concrete due to frost action is a serious concern to agencies in cold regions all over the world. While frost damage can be related to the complex microstructure of concrete, the mix characteristics, as well as the specific environment in the project location, play a significant role in the extent and nature of damage. Frost damage manifests itself typically in the form of cracking and spalling, D-cracking, and scaling, depending on the type of structure, quality and properties of the constituent materials, the damage mechanism and severity of exposure to F-T cycles. In general, concrete with lesser degree of hydration (high water content in large voids pores) and high w/c ratio is less frost resistant than concrete with low w/c ratios.

When water freezes, it is accompanied by a 9 percent volumetric expansion and therefore freezing water in the capillary pores of concrete causes a combination of dilation of the pore cavity and a forcing of the excess water out of the pore boundaries. Hydraulic pressure is generated in the process, the magnitude of which depends on the distance to the escape boundary, the permeability of the system that enables the flow, and the rate at which the water is freezing. These expansive forces can cause damage in fully saturated concrete, unless an escape boundary exists within three or four thousandths of an inch. In addition to the hydraulic pressure, osmotic pressure (resulting from the lowering of the freezing point due to water solubles in the pore water) can also exacerbate frost damage.

The most effective method to protect concrete from F-T damage is through the addition of a surface active agent, referred to as an air entraining agent, as an admixture to the concrete. This admixture, added generally in the order of 0.05 percent of the cement weight, serves to create a large number of closely spaced, but small-sized air bubbles in the matrix that relieve the expansive pressure built up by the freezing water. This fraction of air introduced is referred to as entrained air, which is typically 0.02 to 0.04 in (0.05 to 1 mm) in size and spaced apart in the order of 0.004 to 0.01 in (0.1 to 0.25 mm). Entrained air occupies roughly 3 to 4 percent of the volume of the concrete. Entrapped air, on the other hand, is of a larger size and spaced father apart with no benefit or contribution towards resisting frost damage. In general, it is desirable to achieve small sized entrained air closely spaced and well dispersed in the matrix.

Mix constituent properties, mix design adopted, and construction practices affect the effective quality and overall distribution of air voids in the mix. Cohesive mixes retain entrained air better than stiff, wet, or high-fine mixes. Also, inadequate mixing, over mixing, over vibration, and improper pump handling during concrete placement can reduce the air content required for F-T resistance. ACI therefore recommends performing quality control and quality assurance tests on the concrete that is placed in the structure rather than the concrete that is delivered to the project site during construction.

Determining the air content at the point of placement is the current practice at CDOT, and has been the practice historically in Colorado State projects. However, for a brief period between 1993 and 2008, the specification for determining air content for quality assurance purposes was changed from testing at the point of placement to testing at the point of delivery. While the impetus behind this change during this brief period of 15 years is not well explained today, it is of interest for CDOT to ensure that the change in specification did not result in a relatively inferior quality of concrete in bridge decks from the stand point of F-T resistance. The current study was an effort on part of CDOT to verify the quality of concrete in bridge decks built during this period relative to older structures through a series of laboratory testing of cores extracted from structures built under both specifications.

The study selected six bridges in the Denver metro area in districts 1and 4 after a review of 600 bridges in CDOT's database. NBI ratings for the selected bridges ranged from 5 to 7. Half of the structures were constructed before 1993 (using the point of placement specification), and half were constructed during 1993 to 2008 (using the point of delivery specification). Three cores from each structure were extracted and 2 cores were tested as part of the forensic evaluation plan set up for this study. The tests included petrographic analysis as per ASTM C 856, air void analyses and total air content determination (including specific surface and spacing factor) as per ASTM C 457 and chloride profile measurement at three different depths as per ASTM 1152.

Laboratory test data were analyzed to draw necessary conclusions about the quality of the mixes placed in all the six selected structure as well as to assess the impact of change in specifications. Key findings from this study are listed in the next section of this chapter.

CONCLUSIONS

In general the test results and data analyses of six selected structures suggest that the change in specifications for air content testing during 1993 to 2008 has not resulted in distinctly different quality of concrete from the standpoint of F-T resistance. The following are key findings and conclusions of this study:

- Structures selected with similar NBI ratings and comparable distresses when visually observed did not show significant difference in air void distribution, chloride ion penetrations, or durability indicators in the cement matrix.
- The air void distribution between samples within a structure appeared to be higher than the variability across structures or between the two specification types used when the whole data set was reviewed.
- Based on sample mean percent deviation from the average measured on 2 cores, the point of delivery specification has produced relatively more consistent air void characteristics.
- In general the air void distribution in almost all structures meets the conventional limit that specifies a spacing factor of less than 0.008 inch (0.2 mm) and specific surface greater than 600 in^2/in^3 (24 to 44 mm^2/mm^3) to maintain F-T durability. The entrained air content is, for a majority of the cases, between 3 to 4 percent.
- Air void parameters and distribution were fairly close across the structures and between the specifications, suggesting no evidence that the change in specification resulted in any major change in the quality of air entrainment achieved in the concrete placed.

- The chloride ion concentration levels measured in the 12 cores were found to be below the generally accepted critical levels indicating no significant difference between structures built under the two specifications.
- Likewise, the gradients calculated for the chloride concentrations at three depths—0 to 1 in (0 to 25 mm), 1 to 2 in (25 to 50 mm), and 2 to 3 in (50 to 75 mm)—showed no significantly different trends across the two specifications. In other words, all structures exhibited similar resistance to chloride ion ingress into the structure. The oldest of the selected bridges had a relatively higher chloride ion concentration in the top inch of the deck, but the levels within the next 2 inches were comparable to that of the newer structures.
- For a majority of cases, both cores within a structure follow the same trend with regard to gradients in chloride ion concentration.
- In general, the results of the chloride ion testing were consistent with the findings from the air void analysis results. These results also support the previous findings that the change in specification has not resulted in a significantly different level of durability.
- The results of the petrographic examinations do not indicate any specific trends between the structures built under the two specifications. The trends in depth of carbonation, shrinkage, and assessed resistance to F-T damage were comparable in the set of structures built under the point of placement and point of delivery specifications.
- The overall results from the laboratory testing of a limited number of structures indicate that the change in specifications during the period of 1993-2008 has no impact on the durability or the remaining service life of the bridges built in Colorado.

Recommendations

The findings reported in this study are based on laboratory test results from a very limited sample size (six bridges) that was considered to represent construction under the point of delivery and point of placement specifications. All results indicate that the bridge decks built under the point of delivery specification during the period of 1993-2008 have F-T resistance comparable to the structures built earlier under the point of placement specification. This does not suggest that the point of delivery specification is as effective as the point of placement specification. Instead it merely implies that the quality of materials used, the construction practices adopted, and the competence and workmanship of the concrete placement crew and the pump operators was good and perhaps remained consistent over the years. This does not suggest that the point of delivery specification can be adopted in future either by CDOT.

FUTURE RESEARCH

Findings from the current research and the conclusions presented are encouraging, and they indicate no alarming concerns about the structures built under the point of delivery specification. Potentially, the study could be extended to evaluate additional structures under the two specifications.

Going forward, the department has to ensure that bridge decks built in the future possess the air void distribution required for good durability. This study revealed that several other material, mix design, construction, and placement practices have a big impact on the air void distribution. One of the limitations in this study was that the data analyses were unable to capture the effect of these parameters due to lack of data and QA records for these structures. Therefore, a future effort has to look into the effective quality delivered in the as-built structures over, say, a period of five years.

To accomplish this, the CDOT panel recommends the following activities and corresponding modifications to the construction specifications for all bridge decks built over the next five years:

- Require the contractor to take three additional cores at 28 days. The contractor will also be required to provide three companion cylinders.
- Require the contractor to provide the cores to a CDOT-recommended laboratory for air void parameters testing.
- Set up a comprehensive database with results from laboratory testing as well as all details regarding the mix design, construction records, placement method, and QA data.

- Analyze data and report results on an annual basis. The effects of mix design, placement methods, and QA data should be analyzed for each construction project. Additional data from each year should be added to the database.

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RELEVANT ASTM TESTS

ASTM C143 / C143M - 08 Standard Test Method for Slump of Hydraulic-Cement Concrete.

ASTM C231 - 08c Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.

ASTM C173 / C173M - 08 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method.

ASTM C138 / C138M - 08 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.

ASTM C457 - 08c Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete.

ASTM C666 / C666M - 03 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.

ASTM C856 / C856M - 04 Standard Practice for Petrographic Examination of Hardened Concrete.

ASTM C1152 / C1152M – 04e1 Standard Test Method for Acid Soluble Chloride in Mortar and Concrete.

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16. American Association of State Highway and Transportation Officials (AASHTO) Technology Implementation Group, "*Air Void Analyzer*," American Association of State Highway and Transportation Officials, 2006.
17. Grove, J., Steffes, B., and Anderson, W. M., "*Using the Air Void Analyzer for Real-Time Quality Control Adjustment in the Field*," National Concrete Technology Center, 2006.
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APPENDIX A—CDOT AIR CONTENT SPECIFICATIONS

2005 Standard Specification for Road and Bridge Construction

601.08 Air Content Adjustment. When a batch of concrete delivered to the project does not conform to the minimum specified air content, an airentraining admixture conforming to subsection 711.02 may be added, one time only for the batch, at the Contractor's option prior to consideration for rejection or price adjustment. After the admixture is added the concrete shall be re-mixed for a minimum of 20 revolutions of the mixer drum at mixing speed. The concrete will then be re-tested and if found acceptable may be placed in accordance with the specifications. A maximum of three batches per day may be adjusted by adding air entraining admixture at the delivery site.

601.12 (d)

(d) *Chutes and Troughs*. Concrete shall be placed so as to avoid segregation of the materials and the displacement of the reinforcement.

Concrete shall not be dropped more than 5 feet, unless confined by closed chutes or pipes. Care shall be taken to fill each part of the form by depositing the concrete as near final position as possible. The coarse aggregate shall be worked back from the forms and worked around the reinforcement without displacing the bars. After initial set of the concrete, the forms shall not be jarred and strain shall not be placed on the ends of projecting reinforcement.

Where steep slopes are required, the chutes shall be equipped with baffle boards or be in short lengths that reverse the direction of movement.

Concrete shall not be pumped through aluminum alloy pipe.

All chutes, troughs and pipes shall be kept clean and free from coatings of hardened concrete.

601.12 (g)

(g) *Placement.* Concrete shall be placed in horizontal layers not more than 18 inches thick except as hereinafter provided. When less than a complete layer is placed in one operation, it shall be terminated in a vertical bulkhead. Each layer shall be placed and consolidated before the preceding batch has taken initial set. Each layer shall be so consolidated as to avoid the formation of a con-struction joint with a preceding layer which has not taken initial set. Bridge deck concrete on superelevation or grade that exceeds 2 percent, shall be placed from the low point upward.

When the placing of concrete is temporarily discontinued, the concrete, after becoming firm enough to retain its form, shall be cleaned of laitance and other objectionable material to a sufficient depth to expose sound concrete. The top surfaces of concrete adjacent to the forms shall be smoothed with a trowel to minimize visible joints upon exposed faces. Work shall not be halted within 18 inches of the top of any face, unless provision has been made for a coping less than 18 inches thick, in which case the construction joint may be made at the under side of the coping.

Immediately after the work of placing concrete is halted, all accumulations of mortar splashed upon the reinforcement and surfaces of forms shall be removed before the concrete takes its initial set. Care shall be taken when cleaning reinforcing steel to prevent damage to or breakage of the concrete-steel bond.

601.17 Acceptance and Pay Factors. These provisions apply to all concrete.

(a) *Air Content.* At any time during the placement of the concrete, when a batch deviates from the minimum or maximum percent of total air content specified, the following pro-cedure will be used to analyze the acceptability of the concrete.

1. A batch that deviates from the specified air content by more than one percent and all Class D concrete placed in bridge decks with air content exceeding eight percent will be rejected. Portions of loads incorporated into structures prior to determining test results which indicate rejection as the correct course of action shall be subject to acceptance at reduced price, no payment, or removal as determined by the Engineer.

2. A batch that deviates from the specified air content by one percent or less, may be incorporated into the project at a reduced price, calculated as follows: The first batch that deviates from the specified air content by ½ percent or less, will be accepted at full price. The first batch that deviates from the specified air content by more than ½ percent and up to 1 percent, which the Contractor elects to place, will be accepted at a reduced price. The second and third successive batches of a series that deviate from the specified air content by 1 percent or less, which the Contractor elects to place, will be accepted at a reduced price. The fourth and all other successive batches of a series that deviate from the specified air content will be rejected. The rejected batch count will stop with a batch that is within the specified air content, and deviation batch count will resume at one with the next batch that deviates from the specified air content.

April 30, 2009

REVISION OF SECTIONS 106 AND 601
CONCRETE SAMPLING AND PUMPING

601.08 Air Content Adjustment. When a batch of concrete delivered to the project does not conform to the minimum specified air content, an air entraining admixture conforming to subsection 711.02 may be added in accordance with subsection 601.17. After the admixture is added, the concrete shall be re-mixed for a minimum of 20 revolutions of the mixer drum at mixing speed. The concrete will then be re-tested by QC.

Subsection 601.12(d) shall include the following:

The Contractor shall not use pipes, chutes, troughs, spouts, or tremies that are fabricated of aluminum materials for pumping, conveying, or placing concrete.

Subsection 601.12(g) shall include the following:

When concrete is placed by pumping, the pumping equipment shall be thoroughly cleaned prior to concrete placement. Excess form release agent shall be removed from the hopper. The pump shall be primed at the Contractor's expense by pumping and discarding enough concrete to produce a uniform mix exiting the pump. At least 0.25 cubic yard of concrete shall be pumped and discarded to prime the pump. Water shall not be added directly into the concrete pump hopper after placement has commenced. If water is added to the concrete pump hopper, all concrete in the concrete pump hopper and the line shall be discarded and the pump re-primed at the Contractor's expense.

The pump operator shall have a valid operator's certification from the American Concrete Pumping Association, or approved equal. Boom pumps shall have a documented current inspection as required by ASME B30.27. Equipment added to the pump shall meet the pump manufacturer's specifications. The Contractor shall submit the specifications of the pumping equipment and the qualifications of the operator to the Engineer for review at least two weeks prior to pumping concrete. Equipment and operators rejected by the Engineer shall be replaced at the Contractor's expense.

The pump shall be operated so that a continuous stream of concrete is produced. The pump equipment shall use a minimum of one of the following to maintain concrete uniformity:

(1) A 360 degree loop immediately prior to the delivery end of the pump line.
(2) A minimum one inch reducer installed at the entry to the delivery hose.
(3) A minimum one inch reducing delivery hose.
(4) A cable attached to the pump boom creating a minimum 90 degree bend in the steel braded flexible hose. The point of discharge from the flexible hose at the end of the boom shall be at or above the lowest point of the bend.
(5) On horizontal pours a 10-foot minimum horizontal delivery system placed on the deck.
(6) Other approved methods.

Metal pump lines or couplings shall not rest directly on epoxy coated reinforcing steel.

The point of discharge of the pump shall be as close to the bridge deck elevation as possible.

Subsection 601.17 shall include the following:

The Contractor shall sample 601 pay items for both QC and QA in accordance with CP 61. The Engineer will witness the sampling and take possession of the QA samples at a mutually agreed upon location.

Delete subsection 601.17(a) and replace with the following:

(a) *Air Content*. The first three batches at the beginning of production shall be tested by QC and QA for air content. When air content is below the specified limit, it may be adjusted in accordance with subsection 601.08. Successive batches shall be tested by QC and witnessed by the Engineer until three consecutive batches are within specified limits. After the first three batches, CDOT will follow the random minimum testing schedule. Air content shall not be adjusted after a QA test.

At any time during the placement of the concrete, when a QA test on a batch deviates from the minimum or maximum percent of total air content specified, the following procedure will be used to analyze the acceptability of the concrete.

1. A batch that deviates from the specified air content by more than 1 percent and all Class D, DT, HT and H concrete placed in bridge decks with air content exceeding 8 percent will be rejected. Portions of loads incorporated into structures prior to determining test results which indicate rejection as the correct course of action shall be subject to acceptance at reduced price, no payment, or removal as determined by the Engineer.

2. A batch that deviates from the specified air content by 1 percent or less may be accepted at a reduced price using Table 601-3.

APPENDIX B—AIR VOID ANALYSIS

American Engineering Testing, Inc.

AIR VOID ANALYSIS

PROJECT:	**REPORTED TO:**
ARA Job Number 18671	Applied Research Associates, Inc.
Concrete Deck Performance Relative to Air Entrainment	100 Trade Centre Drive, Suite 200
	Champaign, IL 61820
	ATTN: Dr. Chetana Rao
AET PROJECT NO: 24-00138	**DATE:** March 30, 2009

Sample Number: C-15-AK, N

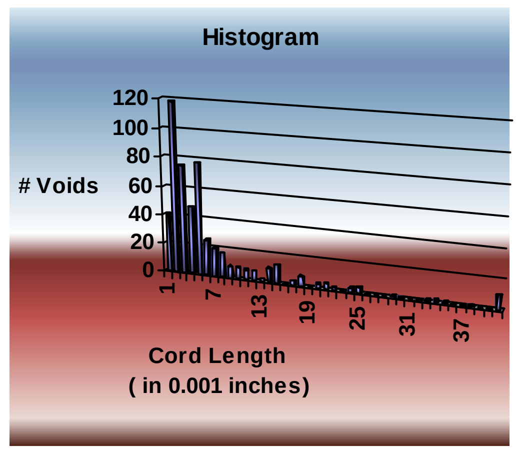
Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data

Description:	Hardened Concrete Core
Dimensions:	102mm (4”) diameter by 70mm (2 $^{3}/_{4}$”) long

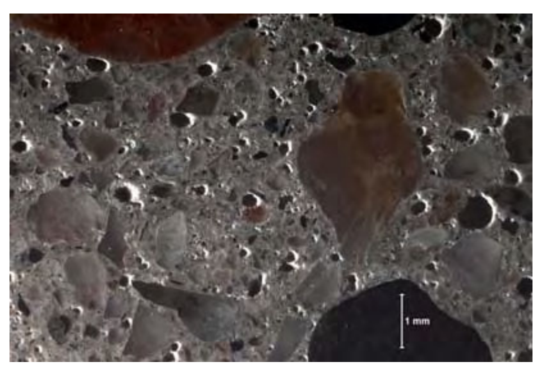
Test Data:

Air Void Content %	3.9
Entrained, % < 0.040”(1mm)	3.3
Entrapped, %> 0.040”(1mm)	0.6
Air Voids/inch	5.8
Specific Surface, in2/in3	585
Spacing Factor, inches	0.009
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	01/28/2009



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496



Magnification: 10x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao
DATE: March 30, 2009

AET PROJECT NO: 24-00138

Sample Number: C-15-AK, C

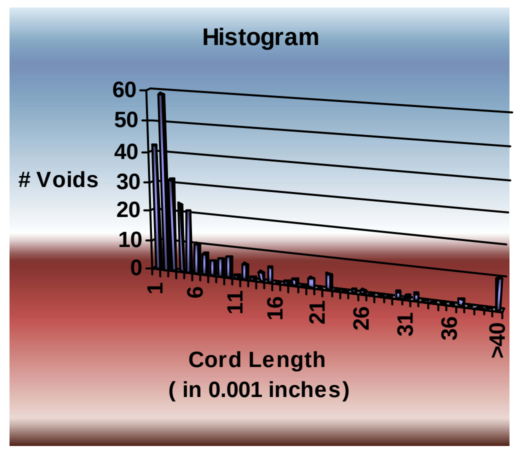
Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Core
Dimensions: 69mm (2 ¾") diameter by 69mm (2 ¾") long

Test Data:

Air Void Content %	2.2
Entrained, % < 0.040"(1mm)	1.6
Entrapped, %> 0.040"(1mm)	0.6
Air Voids/inch	2.8
Specific Surface, in2/in3	515
Spacing Factor, inches	0.013
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	03/24/2009



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 15x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao

AET PROJECT NO: 24-00138

DATE: March 30, 2009

Sample Number: D-14-I (1)

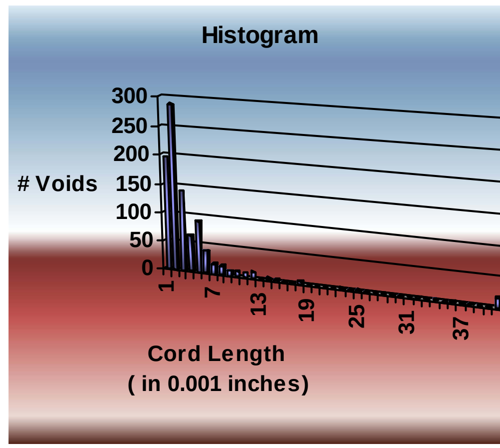
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description:	Hardened Concrete Core
Dimensions:	70mm (2 ¾”) diameter by 114mm (4 $^{1}/_{2}$”) long

Test Data:

Air Void Content %	6.1
Entrained, % < 0.040”(1mm)	3.8
Entrapped, %> 0.040”(1mm)	2.3
Air Voids/inch	10.4
Specific Surface, in2/in3	685
Spacing Factor, inches	0.006
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	01/27/2009



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao
DATE: March 30, 2009

AET PROJECT NO: 24-00138

Sample Number: D-14-I (2)

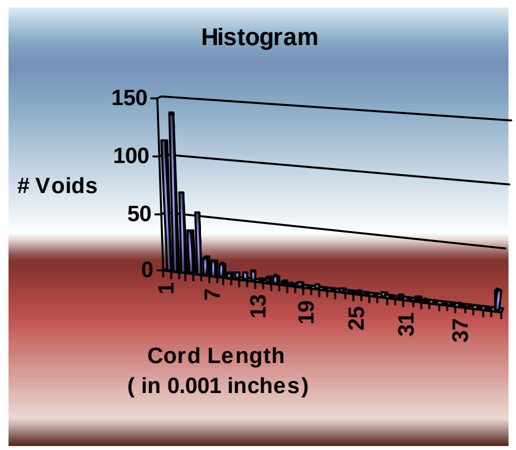
Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data

Description:	Hardened Concrete Core
Dimensions:	69mm (2 ¾”) diameter by 102mm (4”) long

Test Data:

Air Void Content %	3.9
Entrained, % < 0.040”(1mm)	2.5
Entrapped, %> 0.040”(1mm)	1.4
Air Voids/inch	5.8
Specific Surface, in2/in3	590
Spacing Factor, inches	0.009
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	03/23/2009



Magnification: 15x
Description: Hardened air void system.

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

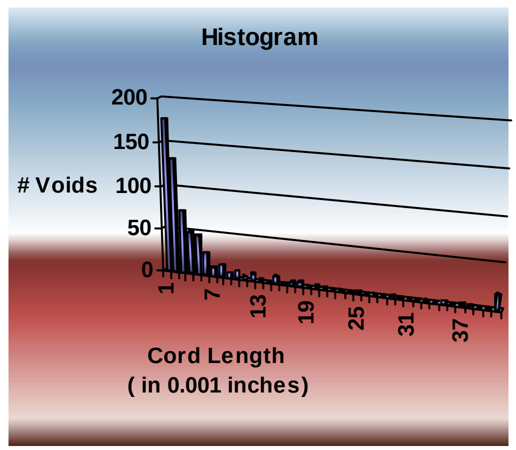
ATTN: Dr. Chetana Rao

AET PROJECT NO: 24-00138

DATE: March 30, 2009

Sample Number: F-20-BU, E

Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.



Sample Data

Description:	Hardened Concrete Core
Dimensions:	70mm (2 ¾ ") diameter by 229mm (9") long

Test Data:

Air Void Content %	6.4
Entrained, % < 0.040"(1mm)	3.0
Entrapped, %> 0.040"(1mm)	3.4
Air Voids/inch	6.8
Specific Surface, in2/in3	425
Spacing Factor, inches	0.010
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	01/26/2009

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

AET PROJECT NO: 24-00138

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao
DATE: March 30, 2009

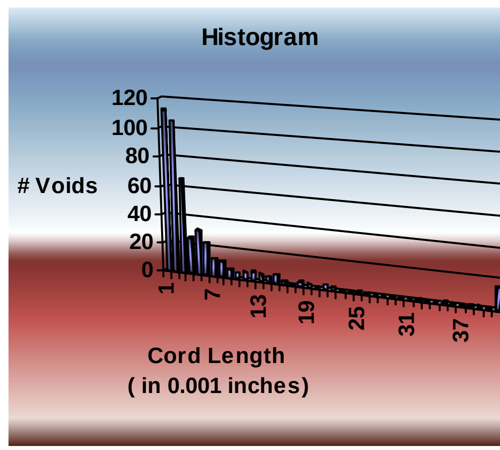
Sample Number: F-20-BU, C
Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data

Description:	Hardened Concrete Core
Dimensions:	69mm (2 ¾ ") diameter by 95mm (3 ¾ ") long

Test Data:

Air Void Content %	3.3
Entrained, % < 0.040"(1mm)	2.2
Entrapped, %> 0.040"(1mm)	1.1
Air Voids/inch	5.1
Specific Surface, in2/in3	615
Spacing Factor, inches	0.009
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	03/24/2009



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 15x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao
DATE: March 30, 2009

AET PROJECT NO: 24-00138

Sample Number: F-15-BZ (1)

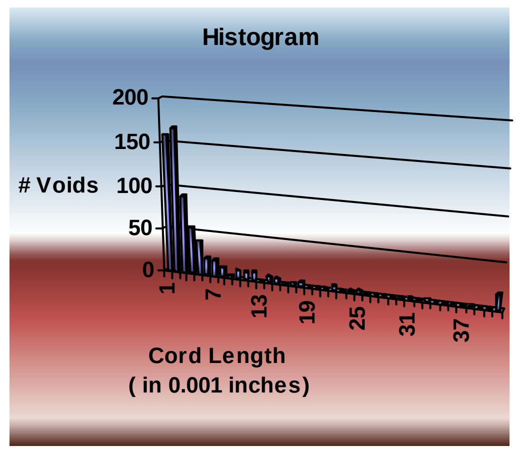
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description:	Hardened Concrete Core
Dimensions:	101mm (4”) diameter by 176mm (7”) long

Test Data:

Air Void Content %	4.7
Entrained, % < 0.040”(1mm)	3.2
Entrapped, %> 0.040”(1mm)	1.5
Air Voids/inch	7.3
Specific Surface, in2/in3	625
Spacing Factor, inches	0.008
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	01/27/2009



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

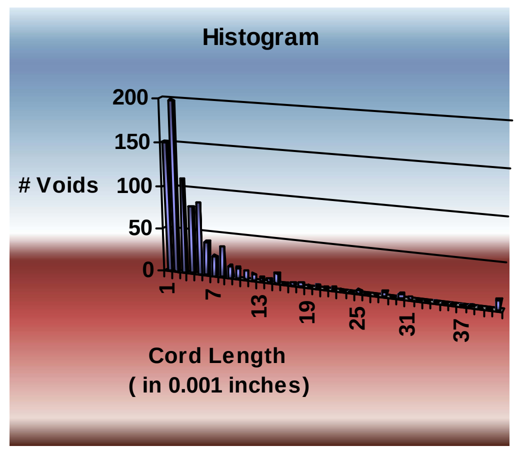
REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao
DATE: March 30, 2009

AET PROJECT NO: 24-00138

Sample Number: F-15-BZ (2)

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description:	Hardened Concrete Core
Dimensions:	101mm (4”) diameter by 145mm (5 ¾”) long

Test Data:

Air Void Content %	5.3
Entrained, % < 0.040”(1mm)	4.4
Entrapped, %> 0.040”(1mm)	0.9
Air Voids/inch	9.2
Specific Surface, in2/in3	690
Spacing Factor, inches	0.007
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	03/19/2009

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 15x
Description: Hardened air void system.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

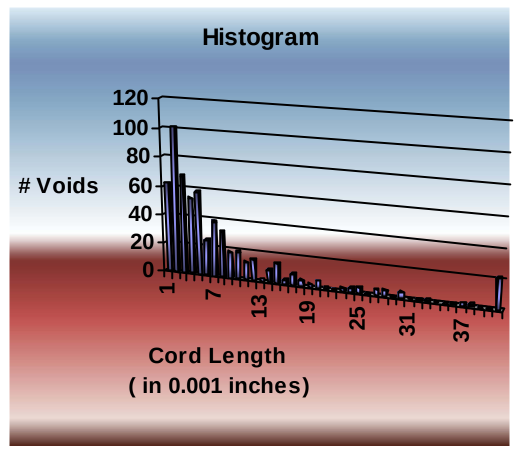
ATTN: Dr. Chetana Rao

AET PROJECT NO: 24-00138

DATE: March 30, 2009

Sample Number: G-22-BY, S

Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.



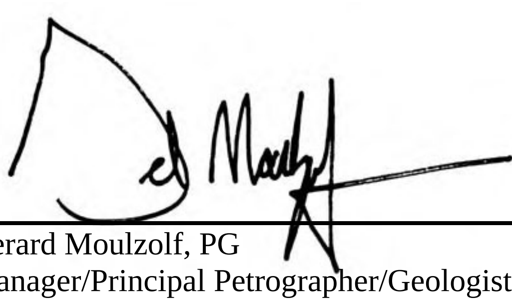
Sample Data

Description: Hardened Concrete Core
Dimensions: 102mm (4”) diameter by 115mm (4 ½”) long

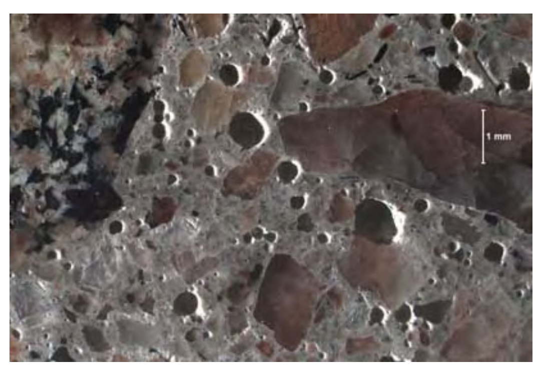
Test Data:

Air Void Content %	5.9
Entrained, % < 0.040”(1mm)	4.3
Entrapped, %> 0.040”(1mm)	1.6
Air Voids/inch	6.7
Specific Surface, in2/in3	450
Spacing Factor, inches	0.010
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	01/23/2009

Report Prepared By:



Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496



Magnification: 10x
Description: Hardened air void system.

American Engineering Testing, Inc.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao

AET PROJECT NO: 24-00138

DATE: March 30, 2009

Sample Number: G-22-BY, N

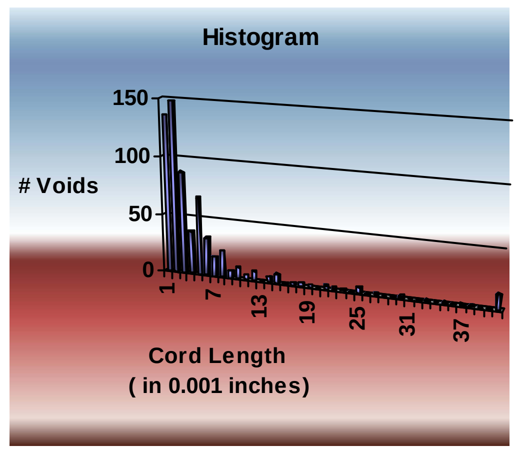
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Core
Dimensions: 102mm (4”) diameter by 102mm (4”) long

Test Data:

Air Void Content %	4.3
Entrained, % < 0.040”(1mm)	3.1
Entrapped, %> 0.040”(1mm)	1.2
Air Voids/inch	7.0
Specific Surface, in2/in3	650
Spacing Factor, inches	0.008
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	03/20/2009



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 15x
Description: Hardened air void system.

AMERICAN ENGINEERING TESTING, INC.

AIR VOID ANALYSIS

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

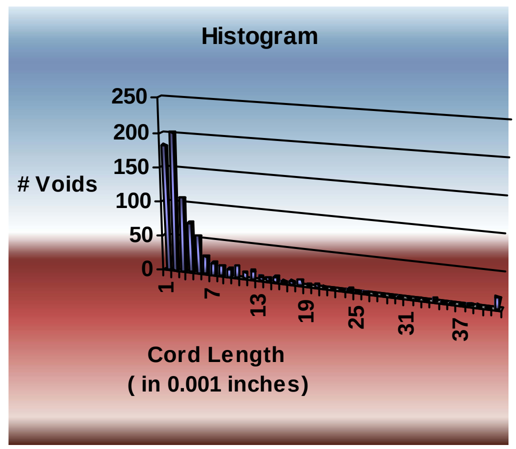
ATTN: Dr. Chetana Rao

AET PROJECT NO: 24-00138

DATE: March 30, 2009

Sample Number: G-22-BZ, S

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description:	Hardened Concrete Core
Dimensions:	102mm (4”) diameter by 105mm (4 1/8”) long

Test Data:

Air Void Content %	5.1
Entrained, % < 0.040”(1mm)	4.1
Entrapped, %> 0.040”(1mm)	1.0
Air Voids/inch	8.9
Specific Surface, in2/in3	700
Spacing Factor, inches	0.007
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	01/26/2009

Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496

Magnification: 10x
Description: Hardened air void system.

AIR VOID ANALYSIS

AMERICAN ENGINEERING TESTING, INC.

PROJECT:
ARA Job Number 18671
Concrete Deck Performance Relative to Air Entrainment

REPORTED TO:
Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

ATTN: Dr. Chetana Rao

AET PROJECT NO: 24-00138

DATE: March 30, 2009

Sample Number: G-22-BZ, N

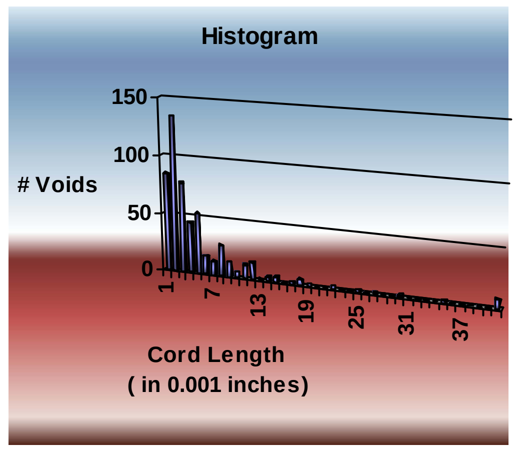
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description:	Hardened Concrete Core
Dimensions:	102mm (4”) diameter by 82mm (3 ¼”) long

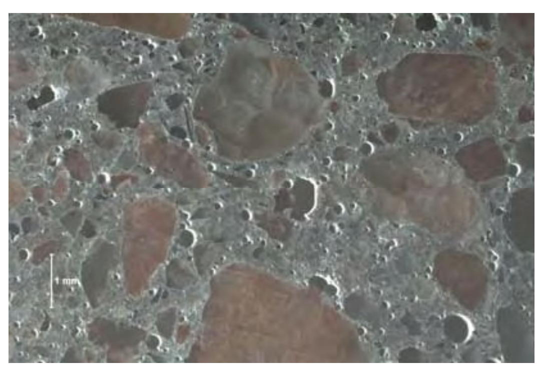
Test Data:

Air Void Content %	3.5
Entrained, % < 0.040”(1mm)	2.8
Entrapped, %> 0.040”(1mm)	0.7
Air Voids/inch	5.9
Specific Surface, in2/in3	680
Spacing Factor, inches	0.008
Paste Content, % estimated	26
Magnification	50x
Traverse Length, inches	90
Test Date	03/19/2009



Report Prepared By:

Gerard Moulzolf, PG
Manager/Principal Petrographer/Geologist
FL License #PG2496



Magnification: 15x
Description: Hardened air void system.

APPENDIX C—PETROGRAPHY RESULTS

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	February 3, 2009
Sample ID:	C-15-AK, N	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on both lapped sides of a 102mm (4”) x 70mm (2 ¾”) x 25mm (1”) thick section that was sawcut from the original 102mm (4”) diameter x 70mm (2 ¾”) long core.

2. Surface Conditions:
   Top: Rough mortar-eroded surface; with several exposed coarse aggregate surfaces.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: A rebar impression of at least 12mm diameter was present on the fractured bottom surface at 65mm (2 ½”) depth from the top surface. No evidence of corrosion was observed.

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion exposing several coarse aggregate particle surfaces. The present top up to 1mm of the paste, between exposed coarse and fine aggregate particles, was very soft, carbonated, and nearly white in coloration. It is unclear as to the origin of the compromised paste. However it is chemically altered. The core sample exhibits several drying shrinkage microcracks proceeding from the top surface up to 12mm depth. The concrete was purposefully air entrained and generally well consolidated. The current hardened air void system parameters were judged to offer only limited freeze-thaw resistance. Some of the finer sized air voidspaces (<0.002”), scattered throughout the sample below approximately 8mm depth in the core, were observed to be filled with secondary ettringite. A single reactive shale coarse aggregate article was observed in sawcut cross section of the core. The concrete exhibits no signs of material related distress.

II. Aggregate

1. Coarse: 19mm ($^3/_4$”) maximum sized natural gravel comprised chiefly of granite, gneiss, schist, quartzite, sandstone, and some shale. The coarse aggregate appeared fairly well graded and exhibited fair to good overall distribution.

2. Fine: Natural quartz, feldspar, and lithic sand. The grains were mostly sub-angular with few rounded particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 3.9% total
2. Depth of carbonation: Ranges from negligible up to 8mm depth from the mortar-eroded top surface of core.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Light tannish-gray; nearly white in the top up to 1mm of the core.
6. Paste hardness: Moderately hard; very soft in the nearly white colored top up to 1mm of the core.
7. Microcracking: Several, fine, sub-vertical, drying shrinkage microcracks were observed proceeding up to 12mm depth from the mortar eroded top surface of the core.
8. Secondary deposits: Ettringite was observed thinly lining many entrained air voidspaces and filling many of the finer (<0.002”) entrained voidspaces scattered in the sample; below approx. 8mm depth in the sample.
9. w/cm: Estimated at between 0.45 and 0.50 with approximately 3 to 5% residual portland cement clinker particles.
10. Cement hydration: Alites: fully
    Belites: fully

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	March 25, 2009
Sample ID:	C-15-AK, C	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on both lapped sides of a 69mm (2 ¾") x 69mm (2 ¾") x 19mm (¾") thick section that was sawcut from the original 69mm (2 ¾") diameter x 69mm (2 ¾") long core.

2. Surface Conditions:
   Top: Rough mortar-eroded surface; with exposed fine aggregate surfaces.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: A 16mm (5/8") diameter, moderately corroded rebar was present on the fractured bottom surface of the core at 48mm (1 7/8") depth from the top surface.

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion/traffic wear exposing fine aggregate surfaces and eradicating any tine marks. The core sample exhibits a few drying shrinkage microcracks proceeding from the top surface up to 15mm depth. The concrete was purposefully air entrained and generally well consolidated. The current hardened air void system parameters were judged to offer poor freeze-thaw resistance. Many of the finer sized air voidspaces (<0.002"), scattered throughout the sample, below approximately 10mm depth in the core, were observed to be filled with secondary ettringite. The concrete exhibits no signs of concrete material related distress. The rebar member located at 48mm depth in the core is moderately corroded and exhibits severe radiating microcracking; mostly filled with corrosion product.

II. Aggregate

1. Coarse: 19mm ($^3/_4$") maximum sized natural gravel comprised chiefly of granite, gneiss, schist, quartzite, quartz, and sandstone. The coarse aggregate appeared fairly well graded and exhibited fair to good overall distribution.

2. Fine: Natural quartz, feldspar, and lithic sand. The grains were mostly sub-angular with few rounded particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 2.2% total
2. Depth of carbonation: Ranges from negligible up to 10mm depth from the mortar-eroded top surface of the core.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Light tannish-gray; discolored light tan in the carbonated top 1mm to 10mm of the concrete core.
6. Paste hardness: Moderately hard.
7. Microcracking: A few, sub-vertical, drying shrinkage microcracks were observed proceeding up to 15mm depth from the mortar eroded top surface of the core. Severe, radiating microcracks proceed from the moderately corroded rebar member located 48mm depth from the top surface of the core.
8. Secondary deposits: Ettringite was observed partly filling many entrained air voidspaces and filling many of the finer (<0.002") entrained voidspaces scattered in the sample; generally below approx. 10mm depth in the sample. Corrosion product fills many of the microcracks radiating from the corroding rebar member.
9. w/cm: Estimated at between 0.45 and 0.50 with approximately 3 to 5% residual portland cement clinker particles.
10. Cement hydration: Alites: fully
    Belites: fully

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	February 5, 2009
Sample ID:	D-14-I (1)	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on a 70mm (2 ¾”) x 112mm (4 ½”) x 32mm (1 ¼”) thick lapped section that was sawcut from the original 70mm (2 ¾”) diameter x 112mm (4 ½”) long core.

2. Surface Conditions:
   Top: Rough mortar-eroded surface; overlain by a thin, intermittent layer of bitumen-like material.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: None observed.

4. General Physical Conditions: The top surface has undergone moderate mortar erosion exposing many fine aggregate particles. Further a thin, intermittent layer of bitumen-like material overlays the surface. Several fine shrinkage microcracks proceed to a maximum of 4mm depth from the top surface. The concrete was purposefully air entrained and fairly consolidated. The hardened air void system parameters were judged to offer freeze-thaw resistance under severe exposure conditions. Sub-vertically oriented, sinuous bleedwater voidspaces were common along paste-coarse aggregate boundaries at depth in the sample. The concrete exhibits no signs of material related distress.

II. Aggregate

1. Coarse: 24mm (1”) maximum sized crushed traprock comprised of felsite. The coarse aggregate appeared well graded and exhibited good overall distribution.

2. Fine: Quartz, feldspar, and granite sand. The grains were mostly sub-angular with a few rounded coarser particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 6.1% total
2. Depth of carbonation: Ranges from 2mm up to 15mm depth (along consolidation voidspace) from the mortar-eroded top surface of core.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Medium gray.
6. Paste hardness: Moderately hard.
7. Microcracking: Several fine drying shrinkage microcracks proceed up to a maximum of 4mm depth from the top surface.
8. Secondary deposits: Ettringite was rarely observed on the linings of entrained air voidspaces scattered in the sample.
9. w/cm: Estimated at between 0.43 and 0.48 with approximately 5 to 7% residual portland cement clinker particles.
10. Cement hydration: Alites: generally fully
    Belites: well to fully

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	March 25, 2009
Sample ID:	D-14-I (2)	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed both lapped sides of a 69mm (2 ¾”) x 102mm (4”) x 19mm (¾”) thick section that was sawcut from the original 69mm (2 ¾”) diameter x 102mm (4”) long core.

2. Surface Conditions:
   Top: Fairly rough, mortar-eroded surface, with several exposed coarse aggregate surfaces; overlain by remnants of a bitumen-like material.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: Two 19mm (¾”) diameter rebar were present on the fractured bottom surface of the core at 80mm (1 $^{7}/_{8}$”) and 95mm (3 ¾”) depth from the top surface.

4. General Physical Conditions: The top surface has undergone moderate mortar erosion exposing several coarse aggregate particles. Remnants of a bitumen-like material partly overlays the mortar eroded surface. A few, fine, sub-vertically oriented shrinkage microcracks proceed to a maximum of 16mm depth from the top surface. The concrete was purposefully air entrained and somewhat under-consolidated. The hardened air void system parameters were judged to offer only limited freeze-thaw resistance under severe exposure conditions. Little ettringite was observed on the linings of scattered voidspaces. Sub-vertically oriented, sinuous bleedwater voidspaces were common along paste-coarse aggregate boundaries at depth in the sample. The concrete exhibits no signs of material related distress.

II. Aggregate

1. Coarse: 24mm (1”) maximum sized crushed traprock comprised of felsite. The coarse aggregate appeared well graded and exhibited good overall distribution.

2. Fine: Quartz, feldspar, and granite sand. The grains were mostly sub-angular with a few rounded coarser particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 3.9% total
2. Depth of carbonation: Ranges from negligible up to 19mm depth (along consolidation voidspace and drying shrinkage microcracking) from the mortar-eroded top surface of core.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Medium gray.
6. Paste hardness: Moderately hard.
7. Microcracking: A few, fine, drying shrinkage microcracks proceed up to a maximum of 16mm depth from the top surface.
8. Secondary deposits: Ettringite was rarely observed on the linings of entrained air voidspaces scattered in the sample.
9. w/cm: Estimated at between 0.40 and 0.45 with approximately 7 to 9% residual portland cement clinker particles.
10. Cement hydration: Alites: fully
    Belites: well to fully

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	February 5, 2009
Sample ID:	F-20-BU, E	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on a 70mm (2 ¾”) x 230mm (9”) x 33mm (1 ¼”) thick lapped section that was sawcut from the original 70mm (2 ¾”) diameter x 230mm (9”) long core.

2. Surface Conditions:
   Top: Rough mortar-eroded surface; with diamond sawn transverse tining.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: None observed.

4. General Physical Conditions: The top surface has undergone moderate mortar erosion exposing many fine aggregate particles. Diamond sawn transverse tining was evident from several parallel 4mm wide sawcut grooves penetrating the surface to 2.5mm depth. A few, fine, drying shrinkage microcracks proceed to a maximum of 12mm depth from the top surface. Carbonation was generally negligible but proceeds up to 7mm depth intermittently. The concrete was purposefully air entrained and fairly consolidated. The hardened air void system parameters were judged to offer only limited freeze-thaw resistance. The concrete exhibits no signs of material related distress.

II. Aggregate

1. Coarse: 19mm (¾”) maximum sized crushed, natural, granite-rich gravel. The coarse aggregate was comprised chiefly of granite with small amounts of basalt, sandstone, and quartzite. The coarse aggregate appeared well graded and exhibited good overall distribution.

2. Fine: Quartz, feldspar, and granite sand. The grains were mostly sub-angular with a few rounded coarser particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1.	Air Content:	6.4% total
2.	Depth of carbonation:	Generally negligible but proceeds intermittently up to 7mm depth from the mortar-eroded top surface of core.
3.	Pozzolan presence:	Flyash was observed.
4.	Paste/aggregate bond:	Fair.
5.	Paste color:	Medium-dark gray.
6.	Paste hardness:	Moderately hard.
7.	Microcracking:	A few, fine, sub-vertical drying shrinkage microcracks proceed up to a maximum of 12mm depth from the top surface.
8.	Secondary deposits:	Ettringite was rarely observed on the linings of entrained air voidspaces scattered in the sample.
9.	w/cm:	Estimated at between 0.38 and 0.43 with approximately 6 to 8% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 to 20% replacement of portland cement with flyash pozzolan.
10.	Cement hydration:	Alites: well Belites: moderate to low

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	March 25, 2009
Sample ID:	F-20-BU, C	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on both lapped sides of a 69mm (2 ¾") x 95mm (3 ¾") x 19mm (¾") thick section that was sawcut from the original 69mm (2 ¾") diameter x 95mm (2 ¾") long core.

2. Surface Conditions:
   Top: Rough mortar-eroded surface; with diamond sawn transverse tining.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: A 33mm (1 ¼") diameter rebar impression was present on the fractured bottom surface of the core. No corrosion product was observed.

4. General Physical Conditions: The top surface has undergone moderate mortar erosion exposing many fine aggregate particles. Diamond sawn transverse tining was evident from several parallel 4mm wide sawcut shallow grooves, which also exhibit mortar erosion. Several, fine, drying shrinkage microcracks proceed to a maximum of 15mm depth from the top surface. Carbonation was generally negligible but proceeds up to 9mm depth, intermittently, along sub-vertical microcracking and consolidation voidspace. The concrete was purposefully air entrained and fairly consolidated. The hardened air void system parameters were judged to offer only limited freeze-thaw resistance. The concrete exhibits no signs of material related distress.

II. Aggregate

1. Coarse: 19mm (¾") maximum sized crushed, natural, granite-rich gravel. The coarse aggregate was comprised chiefly of granite with small amounts of felsite. The coarse aggregate appeared well graded and exhibited fair overall distribution.

2. Fine: Quartz, feldspar, and granite sand. The grains were mostly sub-angular with a few rounded coarser particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 3.3% total
2. Depth of carbonation: Generally negligible but proceeds intermittently up to 9mm maximum depth from the mortar-eroded top surface of core.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Medium-dark gray.
6. Paste hardness: Moderately hard.
7. Microcracking: Several, fine, sub-vertical drying shrinkage microcracks proceed up to a maximum of 15mm depth from the top surface.
8. Secondary deposits: Ettringite was rarely observed on the linings of entrained air voidspaces scattered in the sample.
9. w/cm: Estimated at between 0.37 and 0.42 with approximately 7 to 9% residual portland cement clinker particles and an amount of flyash visually consistent with a 10 to 20% replacement of portland cement with flyash pozzolan.
10. Cement hydration: Alites: well
    Belites: moderate to low

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	February 4, 2009
Sample ID:	F-15-BZ (1)	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on a 102mm (4") x 172mm (6 ¾") x 51mm (2") thick lapped section that was sawcut from the original 102mm (4") diameter x 172mm (6 ¾") long core.

2. Surface Conditions:
   Top: Rough mortar-eroded surface; with diamond sawn transverse tining.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: A rebar impression of at least 16mm ($^5/_8$") diameter was present on the fractured bottom surface at 167mm (6 $^9/_{16}$") depth from the top surface. No evidence of corrosion was observed.

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion exposing several coarse aggregate particle surfaces. Diamond sawn transverse tining was evident from several parallel 4mm wide sawcut grooves penetrating the surface to 3mm depth. The core sample exhibits a few fine drying shrinkage microcracks which proceed a minimum of 2mm to a maximum of 70mm from the top surface. The concrete was purposefully air entrained and generally well consolidated. The hardened air void system parameters were judged to offer freeze-thaw resistance under severe exposure conditions. The concrete exhibits no signs of material related distress.

II. Aggregate

1. Coarse: 19mm ($^3/_4$") maximum sized crushed natural granite-rich gravel. The coarse aggregate appeared well graded and exhibited good overall distribution.

2. Fine: Quartz, feldspar, and lithic sand. The grains were mostly sub-angular with a few rounded coarser particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 4.7% total
2. Depth of carbonation: Ranges from 2mm up to 7mm depth from the mortar-eroded top surface of core.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Somewhat mottled light tannish-gray and gray.
6. Paste hardness: Moderately hard.
7. Microcracking: A few fine drying shrinkage microcracks proceed a minimum of 2mm to a maximum of 70mm from the top surface.
8. Secondary deposits: Ettringite was observed thinly lining many entrained air voidspaces below approx. 3mm depth in the sample.
9. w/cm: Estimated at between 0.42 and 0.47 with approximately 5 to 7% residual portland cement clinker particles and an amount of flyash visually estimated to be consistent with a 5 to 15% replacement of portland cement by flyash.
10. Cement hydration: Alites: fully
    Belites: mostly fully

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	March 25, 2009
Sample ID:	F-15-BZ (2)	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on a 102mm (4") x 145mm (5 ¾") x 35mm (1 $^{5}/_{8}$") thick lapped section that was sawcut from the original 102mm (4") diameter x 145mm (5 ¾") long core.

2. Surface Conditions:
Top: Rough mortar-eroded surface; with diamond sawn transverse tining.
Bottom: Rough, irregular, fractured surface.

3. Reinforcement: A 19mm (¾") epoxy-coated rebar and a 12mm ($^{1}/_{2}$") diameter epoxy-coated rebar were observed at 70mm (2 ¾") and 90mm (5 ½") depth from the top surface. No evidence of corrosion was observed. Epoxy-coated tie-wire apparently binds the two rebar members.

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion exposing several coarse aggregate particle surfaces. Diamond sawn transverse tining was evident, from the presence of several parallel 4mm wide sawcut grooves penetrating the surface up to 4mm depth. The core sample exhibits a few fine drying shrinkage microcracks which proceed up to 9mm from the mortar eroded top surface. An apparent sub-vertical structural microcrack proceeds through 3 or 4 coarse aggregate particles to at least 65mm depth from the top surface. The concrete was purposefully air entrained and generally well consolidated. The hardened air void system parameters were judged to offer freeze-thaw resistance under severe exposure conditions. The concrete exhibits no signs of material related distress.

II. Aggregate

1. Coarse: 19mm ($^{3}/_{4}$") maximum sized crushed natural granite-rich gravel. Lithologies present include mostly granites with few gneisses and schists; with an anomalous bituminous particle. The coarse aggregate appeared well graded and exhibited good overall distribution.

2. Fine: Quartz, feldspar, and lithic sand. The grains were mostly sub-angular with a few rounded coarser particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 5.3% total
2. Depth of carbonation: Ranges from 2mm up to 8mm depth from the mortar-eroded and saw tined top surface of core.
3. Pozzolan presence: Flyash was observed.
4. Paste/aggregate bond: Fair.
5. Paste color: Somewhat mottled light tannish-gray and gray.
6. Paste hardness: Moderately hard.
7. Microcracking: A few, fine, drying shrinkage microcracks proceed up to 9mm depth from the mortar eroded top surface. An apparent sub-vertical structural microcrack proceeds through 3 or 4 coarse aggregate particles to at least 65mm depth from the top surface. A few fine shrinkage microcracks radiate from the 12mm diameter rebar.
8. Secondary deposits: Entrained air voidspaces were generally clean and free of ettringite.
9. w/cm: Estimated at between 0.42 and 0.47 with approximately 5 to 7% residual portland cement clinker particles and an amount of flyash visually estimated to be consistent with a 10 to 20% replacement of portland cement by flyash.
10. Cement hydration: Alites: mostly fully
Belites: well to fully

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	January 30, 2009
Sample ID:	G-22-BY, S	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on a 115mm (4 ½”) x 102mm (4”) x 50mm (2”) thick lapped section that was sawcut from the original 102mm (4”) diameter x 115mm (4 ½”) long core.

2. Surface Conditions:
Top: Fairly rough mortar-eroded/traffic-worn surface with diamond sawn transverse tining.
Bottom: Rough, irregular, fractured surface.

3. Reinforcement: No evidence of reinforcement was observed.

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion and/or traffic wear exposing many fine aggregate particles. Diamond sawn transverse tining was evident from several parallel 4mm wide sawcut grooves penetrating the surface to 3mm depth. The core sample exhibits a plastic shrinkage macrocrack proceeding from the top surface. The cracking thins below 30mm depth and exhibits drying shrinkage characteristics to 85mm depth. The concrete was purposefully air entrained and generally well consolidated. However, the hardened air void system parameters were judged to offer only limited freeze-thaw resistance. Some of the finest sized air voidspaces were observed to be filled with secondary ettringite. The concrete currently exhibits no signs of materials related distress.

II. Aggregate

1. Coarse: 19mm ($^{3}/_{4}$”) maximum sized crushed granite. The coarse aggregate appeared fairly well graded and exhibited fair to good overall distribution. Quartz within the granite exhibits a moderate to low degree of strain.

2. Fine: Crushed granitic sand; comprised chiefly of quartz and feldspar. The grains were mostly sub-angular with many smaller angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1.	Air Content:	5.9% total
2.	Depth of carbonation:	Ranges from 1mm up to 8mm depth intermittently from the top surface of the core.
3.	Pozzolan presence:	None observed.
4.	Paste/aggregate bond:	Good.
5.	Paste color:	Medium tannish-gray.
6.	Paste hardness:	Moderately hard.
7.	Microcracking:	Several, very fine, sub-vertical drying shrinkage microcracks were observed proceeding up to 8mm depth from the top surface of the core. A sub-vertical plastic shrinkage macrocrack proceeds to approximately 30mm depth before becoming a drying shrinkage microcrack proceeding to 85mm depth.
8.	Secondary deposits:	Ettringite was observed thinly lining some finer (<0.003”) entrained air voidspaces and filling some of the finest (<0.001”) voidspaces scattered in the sample.
9.	w/cm:	Estimated at between 0.40 and 0.45 with approximately 7 to 9% residual portland cement clinker particles.
10.	Cement hydration:	Alites: generally fully Belites: very well

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	March 25, 2009
Sample ID:	G-22-BY, N	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on both lapped sides of a 102mm (4”) x 102mm (4”) x 26mm (1”) thick section that was sawcut from the original 102mm (4”) diameter x 102mm (4”) long core.

2. Surface Conditions:
   Top: Fairly rough mortar-eroded/traffic-worn surface with diamond sawn transverse tining.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: A 19mm diameter rebar impression and an approximately 10mm diameter rebar impression were observed on the fractured bottom surface of the core at approximately 98mm and 100mm depth, respectively, from the top surface of the core. No corrosion product was observed

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion and/or traffic wear exposing many fine aggregate particles. Diamond sawn transverse tining was evident from several parallel 4mm wide, shallow sawcut grooves; which also exhibit mortar erosion. The core sample exhibits a sub-vertical macro/microcrack proceeding from the top surface the entire length of the core to the 19mm diameter rebar impression. The cracking thins dramatically below 35mm depth and proceeds through a few coarse aggregate as opposed to around them. The concrete was purposefully air entrained and generally well consolidated. The hardened air void system parameters were judged to offer freeze-thaw resistance under severe exposure conditions. The air void system was relatively free of secondary ettringite fillings. The concrete exhibits no signs of materials related distress.

II. Aggregate

1. Coarse: 19mm ($^3/_4$”) maximum sized crushed granite. The coarse aggregate appeared fairly well graded and exhibited good overall distribution. Quartz within the granite exhibits a moderate to low degree of strain.

2. Fine: Crushed granitic sand; comprised chiefly of quartz and feldspar. The grains were mostly sub-angular with many smaller angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 4.3% total
2. Depth of carbonation: Ranges from 1mm up to 19mm depth intermittently from the top surface of the core along the sub-vertical macrocracking.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Good.
5. Paste color: Medium tannish-gray.
6. Paste hardness: Moderately hard.
7. Microcracking: Several, fine, sub-vertical drying shrinkage microcracks were observed proceeding up to 12mm depth from the top surface of the core. A sub-vertical macrocrack proceeds to approximately 35mm depth before becoming a microcrack; proceeding the entire depth of the core, through a few coarse aggregate particles, and terminating at the 19mm diameter rebar impression.
8. Secondary deposits: Small amounts of ettringite were observed on some void linings.
9. w/cm: Estimated at between 0.39 and 0.44 with approximately 8 to 10% residual portland cement clinker particles.
10. Cement hydration: Alites: fully
    Belites: well to fully

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	February 3, 2009
Sample ID:	G-22-BZ, S	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on a 102mm (4") x 102mm (4") x 50mm (2") thick lapped section that was sawcut from the original 102mm (4") diameter x 102mm (4") long core.

2. Surface Conditions:
   Top: Fairly rough mortar-eroded/traffic-worn surface with diamond sawn transverse tining.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: No evidence of reinforcement was observed.

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion and/or traffic wear exposing many fine aggregate particles. Diamond sawn transverse tining was evident from several parallel 4mm wide sawcut grooves penetrating the surface to 4mm depth. The core sample exhibits two significantly deep drying shrinkage microcracks proceeding from the top surface up to 70mm (2 ¾") depth. The concrete was purposefully air entrained and generally well consolidated. The hardened air void system parameters were judged to offer freeze-thaw resistance under severe exposure conditions. Some of the finest sized air voidspaces were observed to be filled with secondary ettringite. The concrete currently exhibits no signs of materials related distress.

II. Aggregate

1. Coarse: 19mm ($^3/_4$") maximum sized crushed granite. The coarse aggregate appeared fairly well graded and exhibited fair to good overall distribution. Quartz within the granite exhibits a moderate to low degree of strain.

2. Fine: Crushed granitic sand; comprised chiefly of quartz and feldspar. The grains were mostly sub-angular with many smaller angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 5.1% total
2. Depth of carbonation: Ranges from 3mm up to 7mm depth from the mortar eroded top surface of the core.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Good.
5. Paste color: Medium tannish-gray.
6. Paste hardness: Moderately hard.
7. Microcracking: Several, very fine, sub-vertical drying shrinkage microcracks were observed proceeding up to 6mm depth from the top surface of the core. Two significantly deeper sub-vertical drying shrinkage microcracks proceed up to approximately 70mm depth.
8. Secondary deposits: Ettringite was observed thinly lining some finer (<0.003") entrained air voidspaces and filling some of the finest (<0.001") voidspaces scattered in the sample.
9. w/cm: Estimated at between 0.40 and 0.45 with approximately 7 to 9% residual portland cement clinker particles.
10. Cement hydration: Alites: generally fully
    Belites: very well

00 LAB 001 Petrographic Examination of Hardened Concrete
ASTM: C-856

Project No.	24-00138	Date:	March 26, 2009
Sample ID:	G-22-BZ, N	Performed by:	G. Moulzolf

I. General Observations

1. Sample Dimensions: Our analysis was performed on both lapped sides of a 102mm (4”) x 82mm (3 ¼”) x 25mm (1”) thick section that was sawcut from the original 102mm (4”) diameter x 82mm (3 ¼”) long core.

2. Surface Conditions:
   Top: Fairly rough mortar-eroded/traffic-worn surface with diamond sawn transverse tining.
   Bottom: Rough, irregular, fractured surface.

3. Reinforcement: An approximately 12mm (1/2”) diameter rebar impression was observed on the fractured bottom surface of the core; at 69mm (2 ¾”) depth from the top surface of the core. No evidence of corrosion product was observed.

4. General Physical Conditions: The top surface appears to have undergone moderate mortar erosion and/or traffic wear exposing several coarse aggregate surfaces. Diamond sawn transverse tining was evident from several parallel 4mm wide sawcut grooves penetrating the surface to 2mm depth. The sawcuts also exhibit significant mortar erosion. The core sample exhibits several drying shrinkage microcracks proceeding from the top surface up to 25mm (1”) depth. The concrete was purposefully air entrained and generally well consolidated. The hardened air void system parameters were judged to offer freeze-thaw resistance under severe exposure conditions. The concrete exhibits no signs of materials related distress.

II. Aggregate

1. Coarse: 19mm ($^3/_4$”) maximum sized crushed granite. The coarse aggregate appeared fairly well graded and exhibited fair to good overall distribution. Quartz within the granite exhibits a moderate to low degree of strain.

2. Fine: Crushed granitic sand; comprised chiefly of quartz and feldspar. The grains were mostly sub-angular with many smaller angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. Air Content: 3.5% total
2. Depth of carbonation: Ranges from 1mm up to 7mm depth from the mortar eroded top surface of the core.
3. Pozzolan presence: None observed.
4. Paste/aggregate bond: Fair to good.
5. Paste color: Medium tannish-gray.
6. Paste hardness: Moderately hard.
7. Microcracking: Several, fine, sub-vertical drying shrinkage microcracks were observed proceeding up to 25mm (1”) depth from the top surface of the core.
8. Secondary deposits: Ettringite was observed on the linings of scattered air voidspaces; and rarely filling or partly filling some of the finest voids.
9. w/cm: Estimated at between 0.39 and 0.44 with approximately 8 to 10% residual portland cement clinker particles.
10. Cement hydration: Alites: fully
    Belites: well to fully