CONSTRUCTION MATERIALS CONSULTANTS, INC.

Investigation of Concrete Driveway Distress by Laboratory Examinations of A Concrete Core

ABC Drive
Franklinton, North Carolina

Prepared for:
ABC Engineers, Inc.

Date
CMC Project#

Construction Materials Consultants, Inc.

Berkshire Center, Suite 104
4727 Route 30
Greensburg, PA 15601 USA
Phone: 724-834-3551
Fax: 724-834-3556
www.cmc-concrete.com

Date

ABC
ABC Engineers, Inc.

RE: ABC Drive, Franklinton, North Carolina

Dear ABC:

Construction Materials Consultants, Inc. (CMC) is pleased to provide the enclosed comprehensive report on 'Investigation of Concrete Driveway Distress by Laboratory Examinations of A Concrete Core' that was, reportedly, retrieved from ABC Drive located in Franklinton, North Carolina.

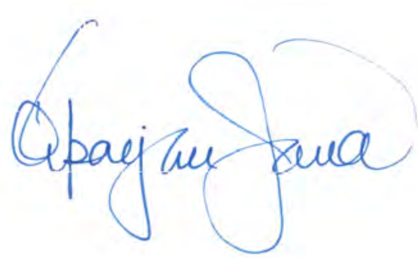
Results, opinions, and conclusions presented herein are based on the information and sample provided at the time of this investigation. We reserve the right to modify the report as additional information becomes available. Neither CMC nor its employees assume any obligation or liability for damages, including, but not limited to, consequential damages arising out of, or in conjunction with the use, or inability to use this resulting information.

Sample will be returned after submission of the report as requested. All reports are the confidential property of clients, and information contained herein may not be published or reproduced pending our written approval.

Please feel free to contact us with any additional questions. We look forward to providing our service again for your future projects.

Sincerely Yours,

CONSTRUCTION MATERIALS CONSULTANTS, INC.



Dipayan Jana, PG
President, Petrographer

DJ:jlh

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Suggested Reading:

Jana, D., "Concrete, Construction or Salt – Which Causes Scaling? Part I: Importance of air-void system in concrete", *Concrete International*, American Concrete Institute, November 2004, pp. 31-38.

Jana, D., "Concrete, Construction or Salt – Which Causes Scaling? Part II: Importance of finishing practices", *Concrete International*, American Concrete Institute, December 2004, pp. 51-56.

EXECUTIVE SUMMARY

Scaling of a residential single-family concrete driveway slab located at ABC Drive in Franklinton, North Carolina has prompted this investigation. Scaling has occurred at isolated locations on the slab surface, as loss of the original finished surface. The slab was reportedly placed on December 28, 2015, developed surface pitting from dripping of water from over garage immediately after the placement, and, scaling within a year of placement.

A partially scaled concrete core, C-1 (where approximately 50 percent of the top surface is scaled) was received from a distressed location of the slab to investigate this scaling, and evaluate relative roles of concrete quality, construction practices followed, and possible exposures to deicing salts in causing or aggravating the distress.

The core was examined by detailed petrographic examinations *a la* ASTM C 856 to evaluate the concrete quality (e.g., aggregates, water-cement ratio, air content, air-void system) and the potentially deleterious effects of construction practices followed (e.g., placement, consolidation, finishing, and curing). Additionally detailed air-void analysis of concrete was done on the core *a la* ASTM C 457 to determine the air-void parameters. Furthermore, chloride content of concrete was determined both at the scaled surface region as well as in the interior to determine if the scaled surface was exposed to a chloride-containing deicing chemical, and if the concrete mix contained a chloride-containing set-accelerating admixture for the reported winter weather placement.

Based on petrographic examinations the concrete is determined to contain: (a) crushed granite coarse aggregate having a nominal maximum size of $^3/_4$ in. (19 mm) which are well-graded, well-distributed, and have been sound during their service with no effect on the scaling; (b) natural siliceous (quartz-quartzite) sand fine aggregate having a nominal maximum size of $^3/_8$ in. (9.5 mm) which too is well-graded, well-distributed, and sound with no effect on scaling; (c) a hardened Portland cement paste having an estimated Portland cement content of 6 to $6^1/_2$ bags per cubic yard (without any other pozzolan or cementitious materials) and a water-cement ratio (*w/c*) that is noticeably higher at the scaled surface region in top 1 to 2 mm than the body i.e. 0.50 to 0.55 at the surface compared to 0.40 to 0.45 in the body with consequent soft, porous, dusty paste at the scaled surface than the interior, and (d) excessive air entrainment, having an air content estimated from petrographic examinations to be at least 10 percent, semi-quantitatively determined by the flatbed scanner method to be as high as 16 percent, and actually determined *a la* ASTM C 457 to be 11.5 percent., which are all well in excess of the common industry-recommended maximum limits of $7^1/_2$ percent; the overall air-void system, however, has a specific surface well in excess of the industry-recommended minimum value of 600 in^2/in^3 and a void spacing factor noticeably less than the industry-recommended maximum limit of 0.008 in.

Excessive air entrainment is judged to be more due to excessive dosage of air entraining admixture in the mix than from subsequent placement, consolidation, finishing, water addition during finishing practices since all these construction effects are unlikely to increase the air to as high as 12 to 16 percent if the concrete delivered from the batch plant was within the maximum allowable air of $7^1/_2$ percent. Excessive air has detrimental effects in reducing compressive strength of concrete – both by having high air and by clustering of air-voids along aggregate-paste interfaces that weaken the interfaces, and, thereby, reducing the strength (unless strength loss from high air is not adjusted by concomitant reduction in *w/c* of concrete). Another side effect of having too much air is the “sticky” nature of concrete that increases difficulty in finishing and achieving an acceptable finish, often requiring addition of excess water during finishing. Such water addition to improve finishability of a sticky high-air concrete can introduce scaling if water addition becomes too excessive affecting the scaling resistance of surface.

Two clear evidence of increased difficulty in finishing a “sticky” high-air concrete noticed in the core are: (1) higher *w/c* at the very top than the body to indicate possible water addition during finishing to increase workability of the high-air sticky concrete, and (2) soft, porous, earthy-textured, severely carbonated, and dusty paste at the surface and within the top few millimeters that have formed due to water addition to the sticky concrete. These artifacts of finishing are not unexpected considering air content as high as 12 to 16 percent. Both these artifacts can reduce the durability of surface concrete, especially in the presence of moisture, freezing, salts, and snow in areas that received uncontrolled water addition.

Despite excessive air entrainment, the overall air-void system i.e. mainly the fineness and closeness of air bubbles as measured from specific surface and void spacing factor are found excellent for providing the necessary freeze-thaw durability of the interior concrete as long as it is protected from freezing, salts, and snow.

The observed high *w/c* at the finished surface region and subsequent soft, porous, dusty, earthy-textured less durable paste at the scaled surface region are, therefore, judged to be the artifacts of finishing a high-air concrete that required to add excess water to improve finishability of a ‘sticky’ high-air concrete. Excess water at the finished surface is judged to be more from the water added during finishing than from mixing of bleed water on the surface, since high air probably reduced the rate of bleeding significantly (and that too may have promoted water addition at the surface during finishing). Areas that received too much water during finishing have softened significantly and lost the scaling resistance than the other areas having relatively lesser amount of water addition. Such water addition during finishing may have also caused the reported pitting on the finished surface immediately after placement at areas that received water drippings from over the garage door.

Acid-soluble chloride contents of concrete were determined from: (a) the top scaled surface region, as well as (b) from the interior body from near the bottom end of core to determine (a) if the concrete surface was exposed to any chloride-containing deicing chemicals, and, (b) if a chloride-containing set accelerating admixture was added in the concrete let alone for the reported winter-weather concrete placement, which may have provided chloride to the concrete, respectively. Results showed noticeably lower chloride at the scaled surface region (i.e. 0.008 percent by mass of concrete) compared to 0.033 percent chloride in the interior (near the bottom end). Absence of high chloride at the scaled surface region compared to that in the interior is indicative of the absence of any chloride-containing deicing chemicals at the surface. Absolute value of chloride at the surface is indicative of chloride from concrete-making ingredients and possible washing away of concrete's own chloride, e.g., from water addition during finishing. Higher chloride in the interior is indicative of possible addition of a chloride containing set accelerating admixture in the mix, which is consistent with the reported winter-weather placement of slab in the month of December. Therefore, comparison of chloride contents at the scaled surface region and in the interior removes any possibility of exposure of a chloride-containing deicing salt at the surface to cause the surface scaling.

The maturity of concrete is defined as a period of air drying and a compressive strength of at least 4000 psi both prior to the first exposure of salts and snow so that the concrete does not contain any 'freezable' water in its capillary pores to freeze, expand, and thus cause distress (hence the importance of at least a period of air drying), and is strong enough to resist freezing-related stresses (hence the importance of adequate strength of at least 4500 psi) both prior to the first exposure of snow and salt. A concrete should be 'matured' prior to the first exposure of freezing, especially during the winter weather constructions. Due to the reported placement of driveway on December 28, 2015, and reported numerous subfreezing temperature minimums at the project location during the month of January (ranging from 18 to 29°F as per the report of National Weather Service), the concrete may not have attained the necessary maturity prior to the first exposure of freezing (unless a chloride containing set accelerating admixture, as suspected from the chloride result, accelerated the strength development). Within a week after placement i.e. prior to the attainment of a minimum 4000-psi strength, the slab was probably exposed to the subfreezing temperatures (e.g., subfreezing temperatures occurred during January 4 to 6, 11 to 14, and 17 to 25 of 2016).

The observed surface scaling could be alleged due to the failure to protect the surface from the environment, e.g., by a surface sealer. However, it is the concrete itself, i.e. an adequately air-entrained concrete made using optimum air content and good air-void system, sound aggregates, good paste, placed, finished, and cured properly, and has been matured prior to the first exposure to freezing, salts, and snow, which should provide the necessary adequate durability. When all these basic factors are fulfilled from concrete materials to construction practices, having an additional surface sealer is not needed for protection. A surface sealer, however, does provide an additional protection, particularly when the inherent concrete quality and/or construction practices is/are questionable such as in this present case. There are, however, many incidences of surface scaling in many outdoor slabs that did receive surface sealers, simply because sealer did not provide a long-term protection, and needed repeated applications. On the other hand, there are many incidences of perfectly sound outdoor slabs without any sealer that were exposed to freezing, salts, and snow but no distress at all simply because the concretes were made using sound durable materials and were constructed and matured properly. Therefore, having or not having a sealer is not the paramount for providing the first hand protection against the environment. Sealer becomes more important when the inherent quality of concrete is questionable as here when concrete surface has poor scaling resistance.

Based on detailed laboratory investigations, the observed and reported surface scaling of concrete driveway is judged to be due to one or a combination of the following factors:

a. Excessive air entrainment of concrete that has made the concrete sticky and has, thereby, increased difficulty in finishing, with the consequence of -

b. Addition of excess water during finishing, higher water-cement ratio having soft, dusty, and porous paste at the exposed surface from such water addition that has reduced the overall freeze-thaw durability and scaling resistance of finished surface, especially during -

c. The early exposures to freezing prior to the attainment of concrete maturity, particularly -

d. In the areas that have received more (uncontrolled) water addition during finishing that developed preferential scaling than elsewhere.

e. Finally, there is no evidence of exposure of a chloride containing deicing salt to cause the scaling.

Beneath the scaled surface, however, the interior concrete is sound, it has an excellent air-void system (though excessively air-entrained), and the concrete delivered was made using sound aggregates, and reasonable water-cement ratio. Therefore, the slab can still be serviceable if the scaled surfaces can be repaired and the overall exposed surface of the slab is protected by an appropriate durable, scaling-resistant protective coating that is properly placed and well-bonded to the interior concrete.

INTRODUCTION

Reported herein are the results of detailed laboratory examinations of a hardened concrete core (C-1) received from ABC Engineers, Inc. The concrete core was, reportedly, taken from a single-family residential driveway for the Project: ABC Drive, Franklinton, North Carolina, where the concrete driveway is, reportedly, exhibiting surface distress.

BACKGROUND INFORMATION

The following background information was received with the sample in a letter from ABC Engineers, Inc.:

"The concrete is a driveway for a single-family home near Franklinton, North Carolina which appears to be experiencing **scaling and dusting**. The driveway slopes upwards from the road to the end of the driveway at the back yard.

The concrete was placed on December 28 and 29, 2015. The problems observed appear to be confined to the **December 28 placement**. Some light dusting was observed on December 29 placement.

Pitting of the surface where water had dripped from the eaves over the garage was noticed by the homeowner soon after construction. Scaling/dusting was not noticed by the homeowner until about January 2017.

Weather stations from the surrounding area indicated between 0.08 and 0.20 inches of rain on December 28, and between 0.05 to 0.16 inches of rain on December 29. Average wind speeds ranged from 5 to 9 mph on December 28 and 2 to 4 mph on December 29. Temperatures ranged from low 50's to mid 70's Fahrenheit on both days.

The builder has accused the homeowner of placing mulch, yard fertilizer, de-icing salts on the driveway and tracking road brine onto the driveway.

- The homeowner indicated that mulch delivered by the landscaper was dumped in a natural area off of the driveway, not on the driveway.
- Fertilizer was placed on the yard during initial establishment of grass. The yard does not appear to drain to the driveway except at the back. A small swale is present above the back end of the driveway and appears to divert surface water away from the driveway.
- The homeowner indicated that they have not used de-icing salts or any other chemicals to address snow/ice.
- The home is approximately 6 miles from the nearest highway, which would have likely received brine before severe winter weather. A secondary highway which may received brine is approximately 2 miles from the home.

A mix design is not available.

It is not known if testing and sampling of the concrete was performed during placement.

- A representative from the concrete supplier performed testing with a rebound hammer soon after the scaling distress was reported. Specifics not available.
- No cores have been sampled from the driveway except the cores obtained by GeoTechnologies for the purpose of petrographic analysis.

Visual inspection performed by GeoTechnologies on March 8, 2017; report attached dated March 15, 2017 (see Appendix A1) documenting our observations and opinions, and photographs. Cores (3) obtained June 6, 2017. Additional photographs obtained on June 6 are attached as well.

All 3 cores obtained from December 28 placement. Cores C-1 and C-2 obtained from areas of scaling. Core C-3 obtained from an area with less obvious surface deterioration. Some loss of material from surface has occurred at C-3, and surface can be easily rubbed away with bare hand. Request that 1 core be selected for petrographic analysis, preferably C-1 or C-2 where the distress was most significant, unless Petrographer feels otherwise."

Figure 1: Map of the reported driveway showing the location of the core C-1 received (left), and locations of two additional cores, C-2 and C-3, which were not received.

FIELD PHOTOGRAPHS

Figure 2 shows condition of concrete driveway at the locations of Cores C-1 and C-2. As seen in both photos, isolated areas on the driveway show loss of the original broom-finished surface of concrete as ***surface scaling***, and exposures of underlying paste and aggregates.

A close examination of distress in these field photos in Figure 2 shows *loss of the original finished concrete as eroding or washing away at isolated locations* (circled in the photos), as opposed *to thin sheet-like separation of the finished surface from the body*. The former type of scaling is common when the finished surface is soft, porous, and earthy-textured preferentially at the locations where water was accumulated at the finished surface during finishing (e.g., from the bleed water on the surface) and/or from excess water present during finishing (either water added during finishing and/or mixing of bleed water at the surface during finishing). The latter type of scaling is common where bleed water accumulates beneath the finished surface usually from premature finishing operations prior to the cessation of bleeding thus creates a plane of weakness immediately beneath the finished surface causing eventual loss of bond of the top finished surface from the body and subsequent separation of the top finished surface as thin sheets (sheet-like scaling).

Although both types of scaling, as described above are the consequences of improper finishing operations, either of these two types, however can also occur from cyclic freezing and thawing of a poor quality concrete at critically saturated conditions, e.g., a concrete having improper air-void system and/or inadequate amount of entrained air that is needed for protection of concrete in a moist outdoor environment exposed to freezing, salts, and snow.

The former type of scaling can also occur from premature application of salt on a concrete surface that has: (a) not been matured, or (b) a concrete that has inadequate air and/or improper air-void system at the surface or (c) has a soft, porous surface that is not resistant to the potentially deleterious actions of salts. A chemically corrosive salt (magnesium sulfate, ammonia based salt) can also cause chemical erosion of paste from the surface apparently creating a distress similar to local loss of the original finished surface as seen in the field photos.

Therefore, a detailed petrographic examination is needed to investigate all these possible factors, from: (a) concrete quality (e.g., soundness of aggregates, paste, and air content and air void system) to (b) workmanship (finishing and curing procedures and their effect on the durability of the finished surface) to (c) potentially deleterious actions of deicing chemicals and determine which of these factors either independently or in combination may have caused the observed surface scaling.

Figure 3 shows additional field photos of surface scaling as well as dusting of the finished surface, which is also another indication of a soft, dusty paste at the surface commonly occur when finishing is done with excess water at the surface to soften the paste.

Figure 2: Conditions of concrete surface at the locations of two cores C-1 and C-2. At both core locations the driveway surface shows isolated areas of scaling as loss of the original finished surface of the slab.

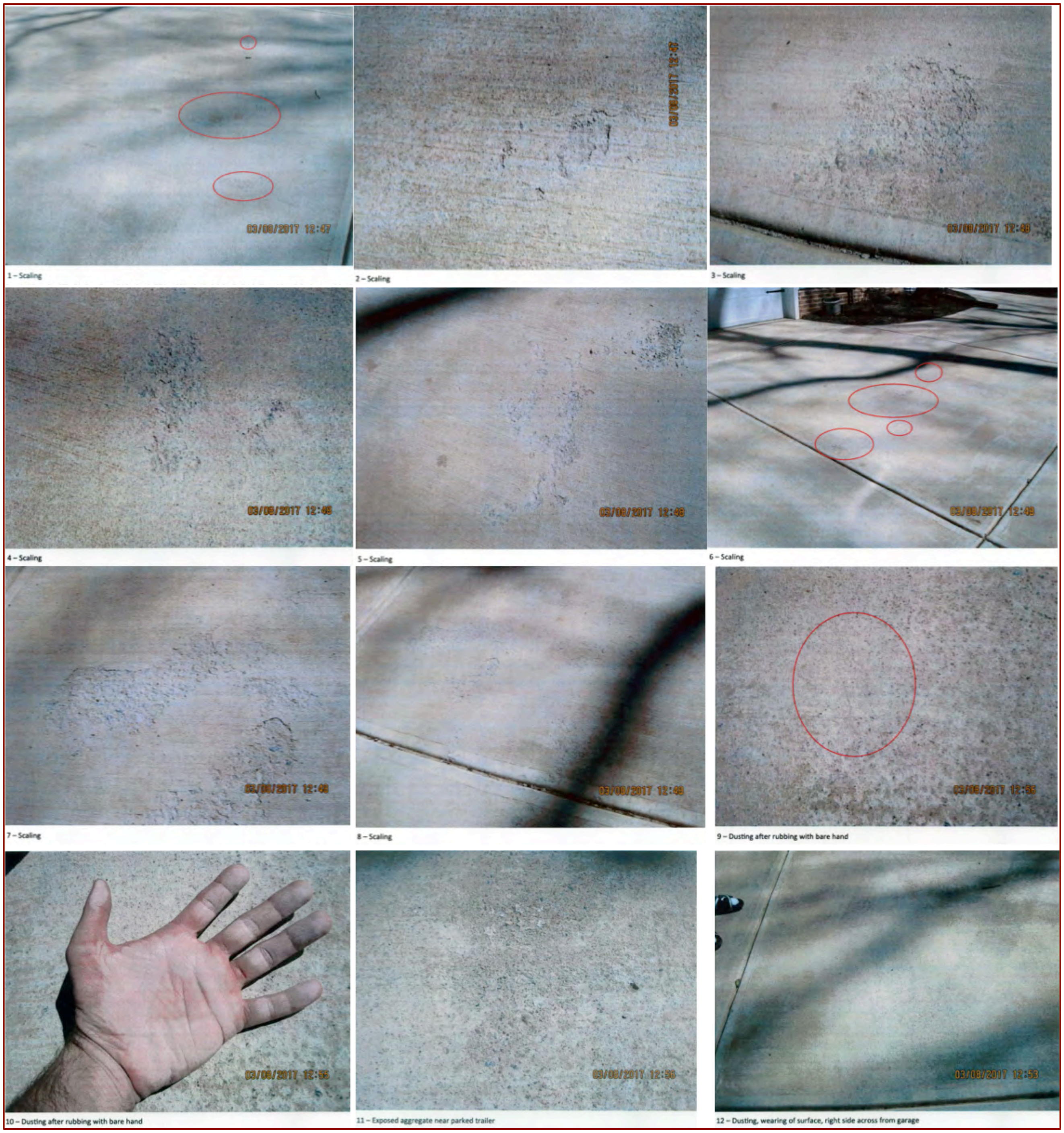

Figure 3: Additional field photographs showing surface scaling and dusting of the concrete driveway slab at various locations.

PURPOSE OF PRESENT INVESTIGATION

Based on the background information provided, and observations of concrete surface scaling in field photographs, the purposes of the present investigation, therefore, are to determine:

i. The composition, quality, and overall condition of concrete in the core;
ii. Evidence of any physical or chemical deterioration of concrete in the core; and,
iii. Based on detailed laboratory investigation, investigation of all possible reasons to explain the observed and reported surface distress (scaling/dusting) of concrete.

METHODOLOGIES

The concrete core C-1 was tested and examined by using the following ASTM standardized Test Methods and Standard Practices:

a. Petrographic examinations by following the methods of ASTM C 856 "Standard Practice for Petrographic Examination of Hardened Concrete." Details of petrographic examinations and sample preparation are described in Jana (1997a, b, 2001, 2004a, b, 2005a, b, 2006, 2007).

   The steps of petrographic examinations include (Jana 2006):

   i. Visual examinations of sample, as received;
   ii. Low-power stereomicroscopical examinations of as-received, saw-cut and freshly fractured sections, and lapped cross sections of core for evaluation of textures, and composition;
   iii. Low-power stereomicroscopical examinations of air content and air-void system of concrete in the core;
   iv. Examinations of oil immersion mounts in a petrographic microscope for mineralogical compositions of specific areas of interest;
   v. Examinations of blue dye-mixed (to highlight open spaces, cracks, etc.) epoxy-impregnated large area (50 mm × 75 mm) thin section of concrete in a petrographic microscope for detailed compositional and microstructural analyses;
   vi. Photographing sample, as received and at various stages of preparation with a digital camera and a flatbed scanner;
   vii. Photomicrographs of lapped section and thin section of sample taken from stereomicroscope and petrographic microscope, respectively to provide detailed compositional and mineralogical information of concrete.

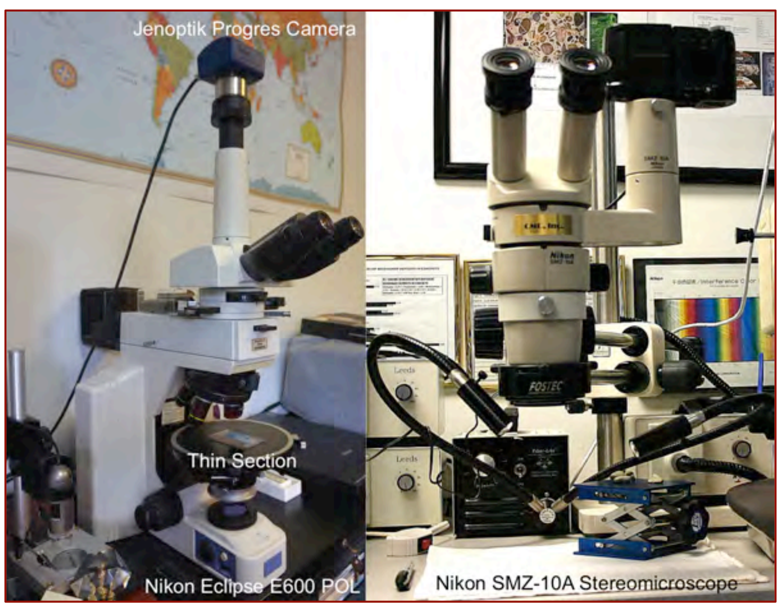

Figure 4: Nikon Eclipse E600POL Petrographic Microscope with Jenoptik Gryphax Camera and Nikon SMZ-10A Stereo-microscope used for petrographic examinations.

viii. A Nikon Eclipse 600 POL petrographic microscope attached to a Jenoptik Progres GRYPHAX high-resolution digital camera were used for petrographic examinations and collecting photomicrographs of thin sections of concretes (Figure 3). A Nikon SMZ-10A stereomicroscope (Figure 3) and an Olympus SZH stereomicroscope were used for examinations of fresh fractured and lapped sections and transmitted-light examinations of thin section, respectively.

ix. Additionally, air-void analyses of the lapped cross section of core was done by using the flatbed scanner method (Peterson et al. 2016), where air voids are highlighted in white against everything else in the black background in a black-and-white binary image of the lapped section. The lapped cross sections were first darkened with a black Sharpie permanent marker pen, and then all voids were filled with a white zinc oxide paste; then scanned at a high resolution on a flatbed office scanner. The scanned images were then used for calculation of air-void parameters according to the procedures described in Peterson et al., 2002, 2016, and Jana 2007.

b. Acid-soluble chloride content analyses from the top scaled surface region as well as at the bottom end of Core C-1 were done by using the methods of ASTM C 1152: "Standard Test Method for Acid-Soluble Chloride In Mortar and Concrete." The purpose of this test is to determine whether or not the scaled surface was exposed to any chloride-containing deicing chemicals.

Steps followed in chloride analysis include:

i. Sample Selection and Sectioning – A representative portion of core at the top and interior location selected for chloride analysis was sectioned for approximately 0.25 in. thick slices for chloride analysis. Chloride contents were then determined by crushing and pulverizing the sectioned slices in a tungsten carbide ring & puck within a vibratory mixer/mill (shatterbox) for a few seconds to pulverize the mass down to pass US No. 20 sieve.

ii. Acid Digestion – About 10±0.01 g of powdered sample was measured and dispersed with 75-mL water in a 250-mL beaker; immediately 25 mL dilute (1+1) nitric acid (HNO_3) was slowly added, stirring and breaking up any lumps with a glass rod. In case of hydrogen sulfide smell, a 3 mL of H_2O_2 (30%) was added. Then 3 drops of methyl orange indicator was added to the beaker and stirred.

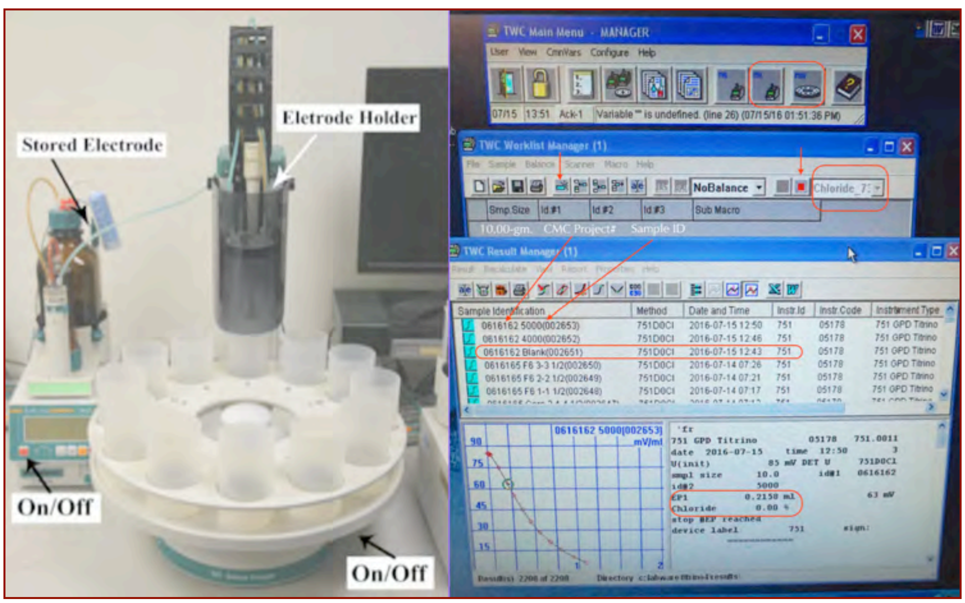

Figure 5: Determination of chloride contents by automated titration with Metrohm DMS 751 Titrino and attached Titrino 730 auto-sample changer (left). Results are displayed in Brinkmann Metrohm Titrino Workshell software (right).

iii. Further Digestion in Boiling Acid – Covered the beaker from previous step with a watch glass, allowed to stand for 1-2 min. Then a few drops of HNO_3 (1+1) were added until a faint pink or red color persisted in the solution above the settled solid. Then 10 additional drops of nitric acid was added and stirred. Then the covered mixture in the beaker was heated rapidly to boiling, but not more then a few seconds. Removed from hot plate.

iv. Filtration – Filtered the sample solution, under suction, through a washed No. 41 coarse-textured filter paper fitted to a Buchner funnel in a 500-mL filtration flask. Transferred the filtrate from the flask to the original beaker, which was already rinsed twice with water, along with the flask. Cooled the filtrate to room temperature. The volume was < 175-mL.

v. Preparation for Titration – To the cooled filtrate, carefully pipetted 2-mL standard 0.05N NaCl. The solution was transferred from the beaker to the sample cup for automated titration. Each sample cup either contained a magnetic stirring rod for stirring, or, received a stirrer from the auto-sample-changer/holder during titration. A Metrohm DMS 751 Titrino Automated Titrator equipped with a Titrino 730 Auto-sample-changer was used for simultaneous titration of three sections of core. The chloride combination electrode was immersed into the sample solution, along with the stirrer, and delivery tip of the $AgNO_3$ disperser (to dispense 0.05N standard $AgNO_3$ solution) all from the 730 auto-sampler to each sample solution.

vi. Automatic titration was monitored by Brinkman Metrohm Titrino Workshell software running in Windows PC attached to the DMS 751 Titrino to accurately record the equivalent point of titration. Blank samples having known chloride contents were run before and after running the concrete samples.

vii. Percent chloride by mass of concrete to the nearest 0.001% is determined from CL, % = 3.545 [(V1-V2) N]/W, where V1 = milliliters of 0.05 N $AgNO_3$ solution used for sample titration (equivalent point), V2 = Milliliters of 0.05N $AgNO_3$ solution used for blank titration (equivalent point); N = exact normality of 0.05 N $AgNO_3$ solution, and W = mass of sample in grams. This equation is equivalent to % chloride = (equivalent point from titration times 0.177) divided by sample weight in grams.

c. The core was tested and examined by using the ASTM Standard Practice of air-void analysis by following the modified point count method, as mentioned in ASTM C 457 "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete," where the steps followed during air-void analysis are given below. Details of sample preparation for air-void analysis are given in Jana 2007.

i. The Velmex point-count device used in the analysis (see Figure 6) comprised a platform connected to E-W and N-S lead screws and designed in such a way that a lapped concrete sample placed on the stage can be moved smoothly and uniformly through equal distances by turning of the screws. It was ensured that the total possible translation of the stage was at least 100 mm (4.0 in.) in each direction. Lead screws were fitted with notched wheels and stopping devices, such that with each rotation of the screws the operator can detect a click when a stop position was reached. It was ensured that the intervals between the stops correspond to a translation of the stage a distance of 0.025 to 0.64 to 5.0 mm (0.025 to 0.200 in.). The magnitude of the average translation of the stage between stops was determined to the nearest 0.03 mm (0.001 in.). A total of six digital counters were used for calculating aggregates, paste, entrained and entrapped voids, and total voids intercepted during the traverse.

ii. A high-resolution Olympus SZH stereomicroscope attached to a high-resolution digital microscope camera was used to capture live image of the lapped concrete surface on the PC screen.

iii. A lapped section of concrete was place on the stage of the point-count device. Using the spirit level, the prepared surface was leveled with the leveling device so that the surface may be traversed and microscopically examined with a minimum of refocusing. Lamp was adjusted so the beam evenly illuminated the field of view of the microscope and was incident upon the surface at a low angle, so the air voids were demarked by a shadow. Superimposed in the computer screen was the index point of the cross hairs to pinpoint the area to be counted. A magnification not less than 50X was used and wasn't changed during the course of the analysis. For a rectangular lapped section, the index was placed near an upper corner (for a circular section, it is usually placed near the top) and at one end of the initial traverse. The stopping device was positioned at a stop or click position at the beginning of the traverse. The initial stops for each traverse line were not included in the total number of stops or in the number of stops for any component. Zeroed all counters. By operation of the E-W lead screw, caused movement of the stage and specimen while simultaneously scrutinizing the surface. At each click stop, except not at the beginning of any traverse line, paused and examined the field of view, and recorded on the appropriate counter the material or phase on which the index point was superimposed. Normally used one counter for air voids, one for paste, and one for all other phases (or a totaling counter). Other components (fine and coarse aggregate, for example—if they are lithologically distinguishable) of the concrete was determined with the use of additional counters. Continued in this way along the line until a last stop is reached just within the prepared area, but close to its edge. When the end of the line is reached, turned off the totaling counter. Reversed the E-W lead screw and proceeded back along the same line, recording on another counter each air void intersected, whether or not a stop has occurred within the air void. Terminated the void counting just before the initial stop. Took extreme care to determine whether a section of an air void was intersected by the movement of the index when the line of traverse is nearly tangent to the void section. The results can be affected significantly by consistent error in this respect. If the periphery of an air void was crumbled or rounded, estimated the position of the true periphery in the plane of the surface by extrapolation of the surface contour of the air void. If the examination was being made to determine only the air content of the concrete, the number of air voids intersected by the line of traverse need not be determined. By means of the N-S lead screw, shifted the concrete specimen at right angles to the direction of traverse an appropriate distance. Spaced the segments of the traverse so as to cover the whole prepared surface and achieved at least the minimum length of traverse and the minimum number of points specified in C 457. Proceeded along the new line of traverse as before, and so on, for all segments of the total traverse and for all sections prepared from a sample of concrete so as to comply with the requirements of this test method.

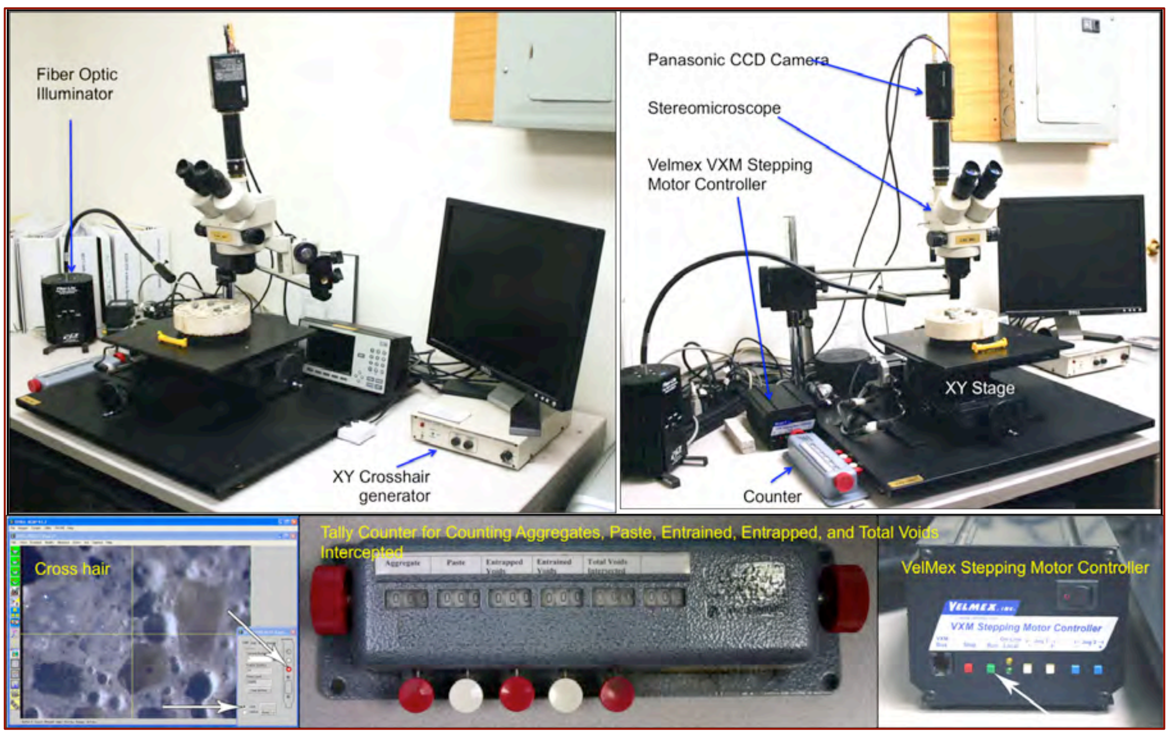

Figure 6: Set-up in the CMC laboratory for air-void analysis in hardened concrete by the modified point count method of ASTM C 457.

iv. Minimum length of traverse and minimum number of points for the modified point count method were: (a) 2540 mm (100 in.) and 1500 points for $1\frac{1}{2}$-in. nominal size aggregate, (b) 2413 mm (95 in.) and 1425 points for 1-in. nominal size aggregate, (c) 2286 mm (90 in.) and 1350 points for $\frac{3}{4}$-in. nominal size aggregate, (d) 2032 mm (80 in.) and 1200 points for $\frac{1}{2}$-in. nominal size aggregate, and (e) 1905 mm (75 in.) and 1125 points for $\frac{3}{8}$-in. nominal size aggregate.

v. Air-void parameters were calculated by using the equations provided in C 457.

SAMPLE

PHOTOGRAPHS, IDENTIFICATION, INTEGRITY, AND DIMENSIONS

Figure 7 shows the core, C-1, as received. The core is 3.5 in. (90 mm) in nominal diameter, and has a nominal length of 4 in. (100 mm). The core was received in intact condition with scaling of 50 percent area of the top surface. The following photographs show the top, bottom, and side views of the concrete core, as received.

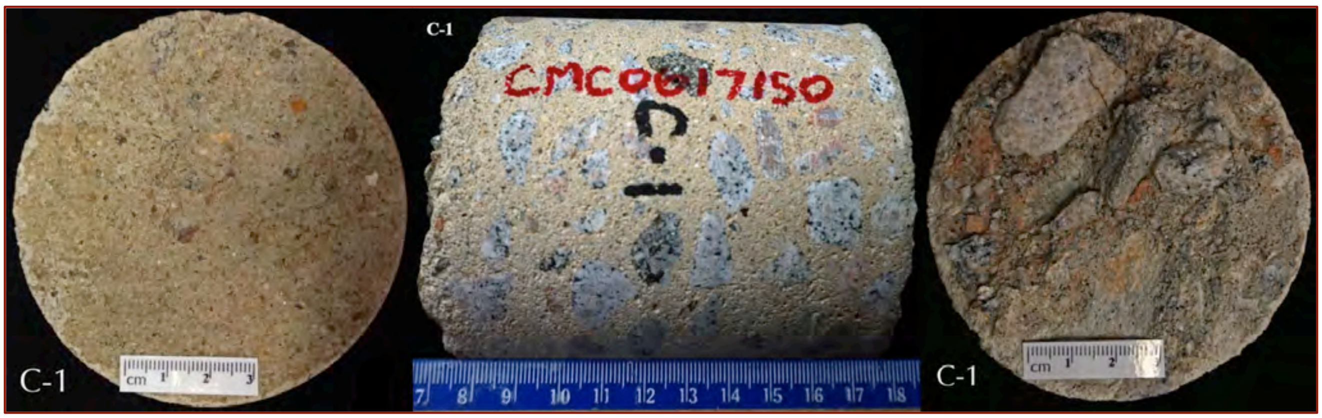

Figure 7: Top surface with scaling of 50 percent area where aggregate particles are exposed (left photo), cylindrical side view of the core with identification (middle photo), and bottom surface with adhered materials from subbase (right photo), as received.

END SURFACES

Figure 8 shows the top surface of core C-1 where approximately 50 percent of the surface is scaling as loss of the original finished surface and exposures of underlying paste and aggregate. According to the terminologies of ACI Committee 116 the scaling is termed as 'light' since the underlying coarse aggregate particles are not exposed.

The right photo in Figure 7 shows the bottom surface end of the core where subbase materials are adhered to the concrete. The core, thus, represents the full thickness of the driveway slab at its location, which is 4 in.

CRACKING & OTHER VISIBLE DISTRESS, IF ANY

No visible cracking was observed in the core.

EMBEDDED ITEMS

No reinforcing steel, wire mesh, fibers, or other embedded items are present in the core.

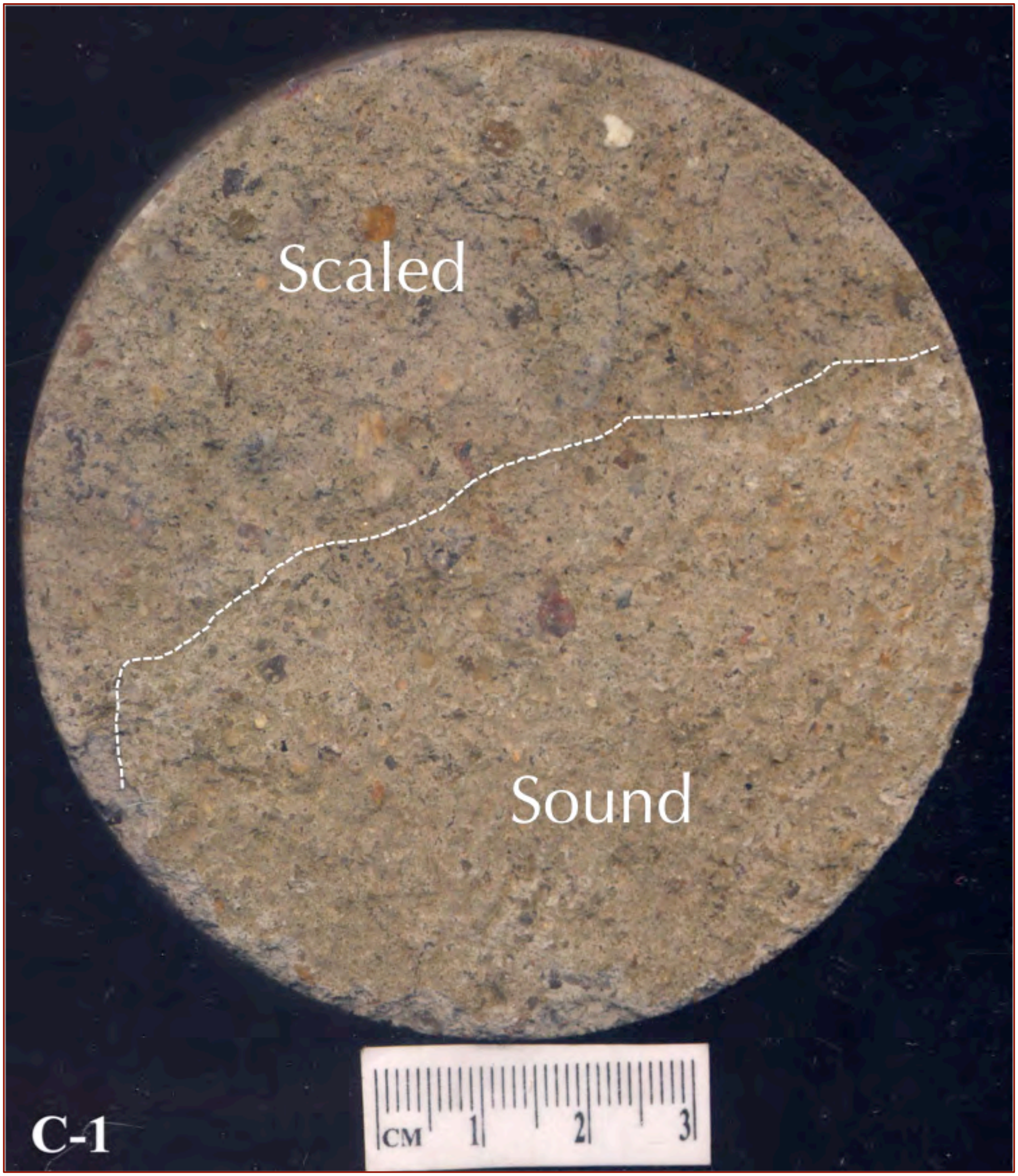

Figure 8: Shown is the moderately scaled top surface, as received, with exposed aggregate particles.

RESONANCE

The core has a ringing resonance, when hammered.

PETROGRAPHIC EXAMINATIONS

LAPPED CROSS SECTION OF CORE

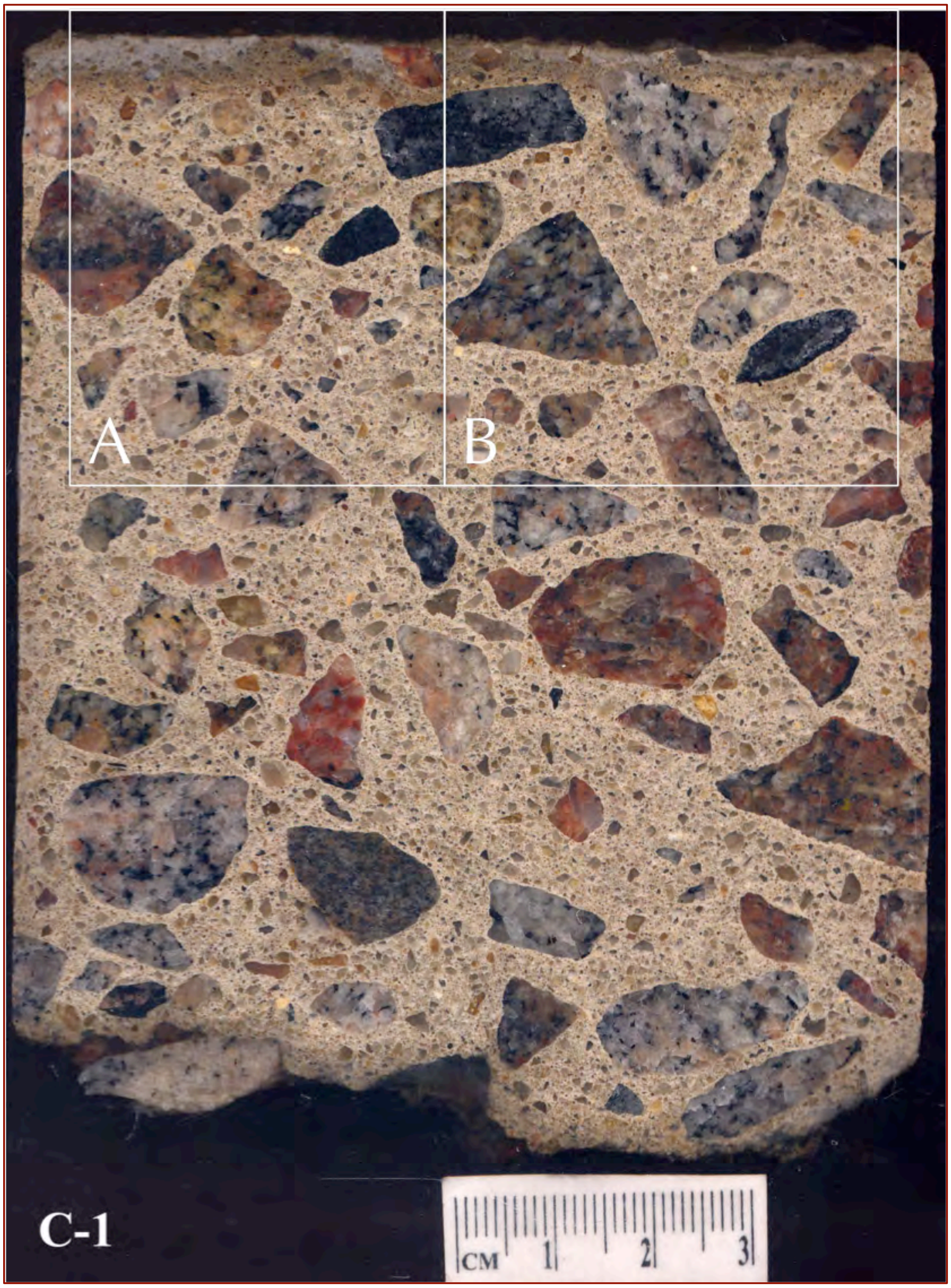

Figure 9: Lapped cross section of the core showing light gray discoloration of the scaled top surface region, the good grading and well-distribution of crushed granite coarse aggregate and sand fine aggregate particles, and the overall sound, dense, well-consolidated nature of the concrete in the body. Boxed areas A and B are enlarged in Figure 10.

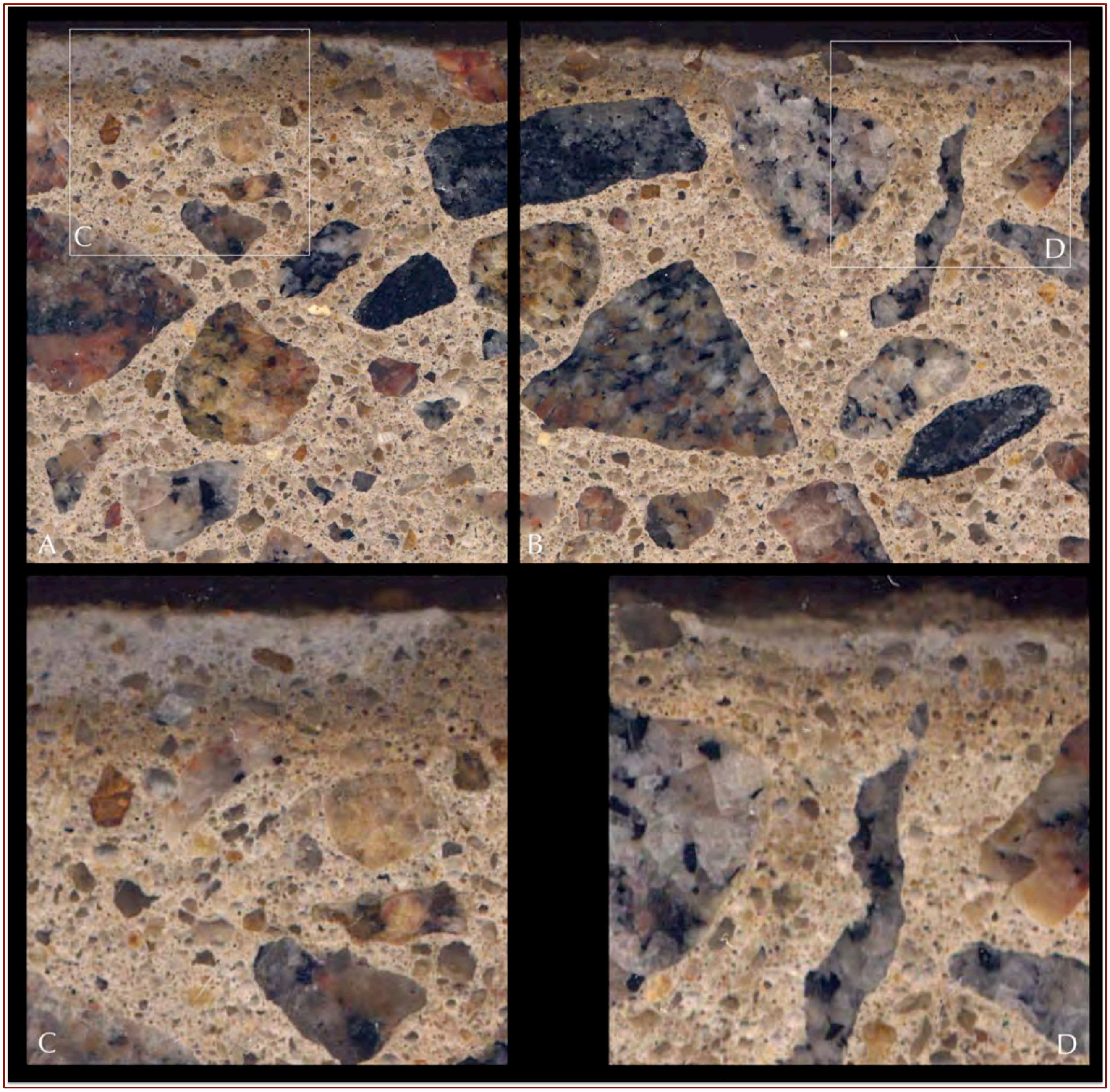

Figure 10: Enlarged views of the boxed areas A and B in Figure 9 showing discoloration of the scaled surface region. Boxed areas C and D in the top row are further enlarged in the bottom row to show the discoloration.

Figure 9 shows lapped cross section of the core where beneath the scaled surface and associated discoloration of paste at the scaled surface region, concrete in the interior body of the core is found to be present in dense, well-consolidated and sound condition without any cracking or other distress. Aggregate particles are well-graded and well-distributed. Surface scaling and associated discoloration are further enlarged in boxed areas A and B from Figure 9 to Figure 10.

COARSE AGGREGATE

Coarse aggregate is crushed granite, having a nominal maximum size of $^3/_4$ in. (19 mm). Particles are angular, dense, hard, light to dark gray, massive textured, equidimensional to elongated, unaltered, uncoated, and uncracked. Coarse aggregate particles are well-graded and well-distributed (Figures 9, 11). There is no evidence of alkali-aggregate reactions of coarse aggregate particles in the core. Coarse aggregate particles have been sound during their service in the concrete, and are judged not to have contributed to the observed surface distress.

FINE AGGREGATE

Fine aggregate is natural siliceous sand having a nominal maximum size of $^3/_8$ in. (9.5 mm). Particles contain major amounts of quartz and quartzite, and subordinate amounts of feldspar, granite, sandstone, and ferruginous rock. Particles are variably colored, rounded to subangular, dense, hard, equidimensional to elongated, unaltered, uncoated, and uncracked. Fine aggregate particles are well-graded and well-distributed (Figures 10, 11). There is no evidence of alkali-aggregate reaction of fine aggregate particles. Fine aggregate particles have been sound during their service in the concrete. The following Table summarizes properties of coarse and fine aggregates.

Properties and Compositions of Paste	C-1
Coarse Aggregates	
Types	Crushed Stone
Nominal maximum size (in.)	$^3/_4$ in. (19 mm)
Rock Types	Granite
Angularity, Density, Hardness, Color, Texture, Sphericity	Angular, dense, hard, light to dark gray, massive textured, equidimensional to elongated
Cracking, Alteration, Coating	Unaltered, Uncoated, and Uncracked
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None
Fine Aggregates	
Types	Natural siliceous sand
Nominal maximum size (in.)	$^3/_8$ in. (9.5 mm)
Rock Types	Major amounts of quartz and quartzite, and subordinate amounts of feldspar, granite, sandstone, and ferruginous rock
Cracking, Alteration, Coating	Variably colored, rounded to subangular, dense, hard, equidimensional to elongated
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None

Table 1: Properties of coarse and fine aggregates of concrete.

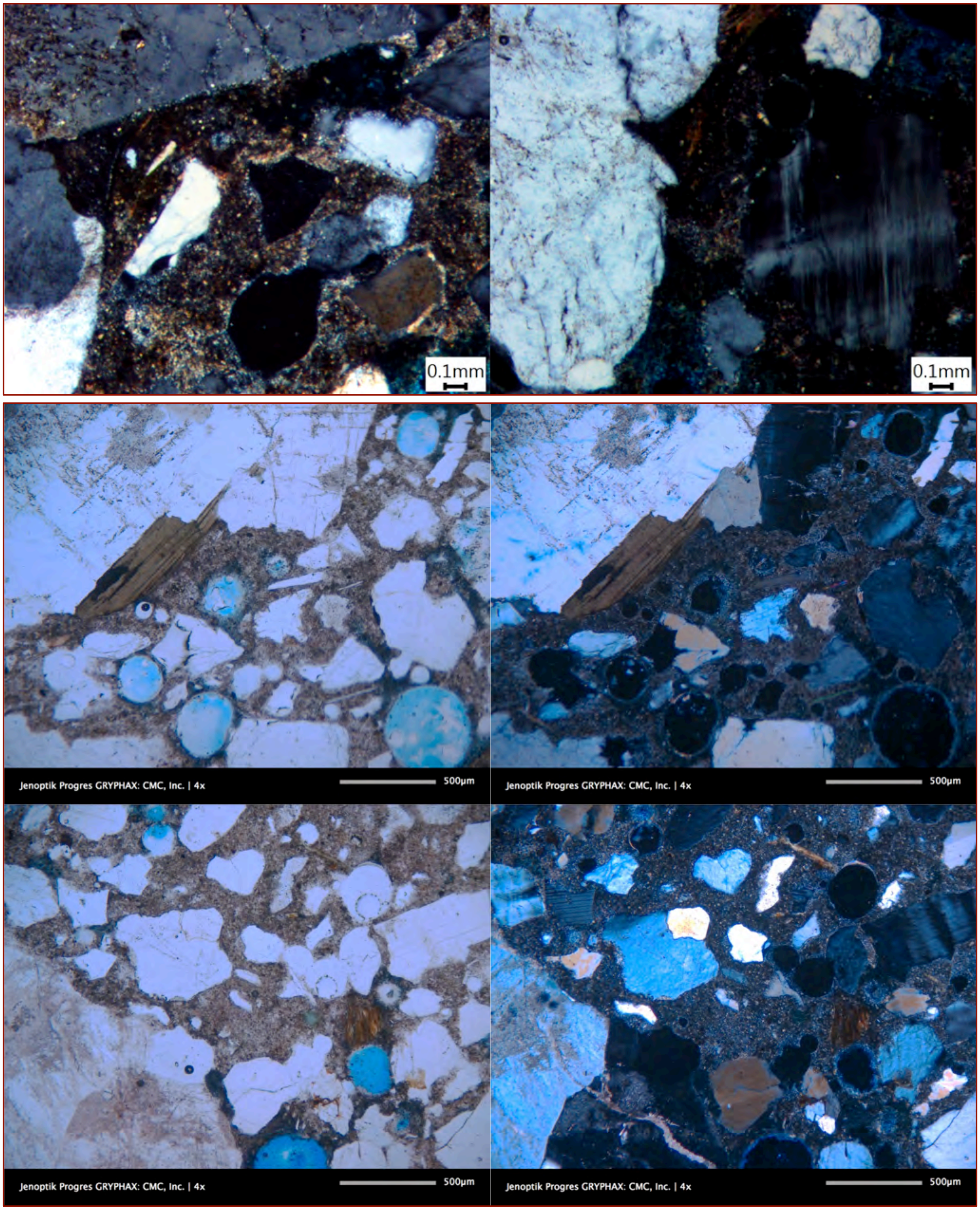

Figure 11: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of the core showing crushed granite coarse aggregate and natural siliceous (quartz-quartzite) sand fine aggregate particles.

PASTE

Properties and compositions of hardened cement paste are summarized in Table 2. Paste is discolored light gray, soft, porous, earthy-textured, fragile, dusty at the top 1 to 2 mm of the scaled surface region but denser, harder, more darker beige or tan-toned in the interior; freshly fractured surfaces of interior paste have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 6 to 8 percent of the paste volumes. Hydration of Portland cement is normal.

Properties and Compositions of Paste	C-1
Color, Hardness, Porosity, Luster	Discolored light gray, soft, porous, earthy-textured, fragile, dusty at the top 1 to 2 mm of the scaled surface region but denser, harder, more darker beige or tan-toned in the interior; freshly fractured surfaces of interior paste have subvitreous lusters and subconchoidal textures.
Residual Portland Cement Particles	Normal, 6 to 8 percent by paste volume
Calcium hydroxide from cement hydration	Normal, 10 to 14 percent by paste volume
Pozzolans, Slag, etc.	None
Water-cementitious materials ratio (*w/cm*), estimated	0.40 to 0.45 in the body but higher (0.50 to 0.55) within the top $^1/_{16}$ in. (1 to 2 mm)
Cementitious materials contents, estimated (equivalent to bags of portland cement per cubic yard)	6 to 6$^1/_2$
Secondary Deposits	None
Depth of Carbonation, mm	2 to 3 mm
Microcracking	Very fine shrinkage cracking at the top surface; Microcracking parallel to the top surface at a depth of 1 mm from the top surface
Aggregate-paste Bond	Moderately Tight (at areas of void clustering) to Tight
Bleeding, Tempering	None
Chemical deterioration	None

Table 2: Proportions and composition of hardened cement paste.

The textural and compositional features of the paste are indicative of a Portland cement content estimated to be equivalent to 6 to 6$^1/_2$ bags per cubic yard, and a water-cement ratio estimated to be 0.40 to 0.45 in the body but higher (0.50 to 0.55) within the top $^1/_{16}$ in. (1 to 2 mm).

The following photomicrographs of the top surface region of the core show the higher *w/c* within the top scaled surface to a depth of 1 to 2 mm, as indicated by the softer and earthy-textured nature of paste at the top above the white dashed lines compared to the denser and harder paste in the interior beneath the dashed lines.

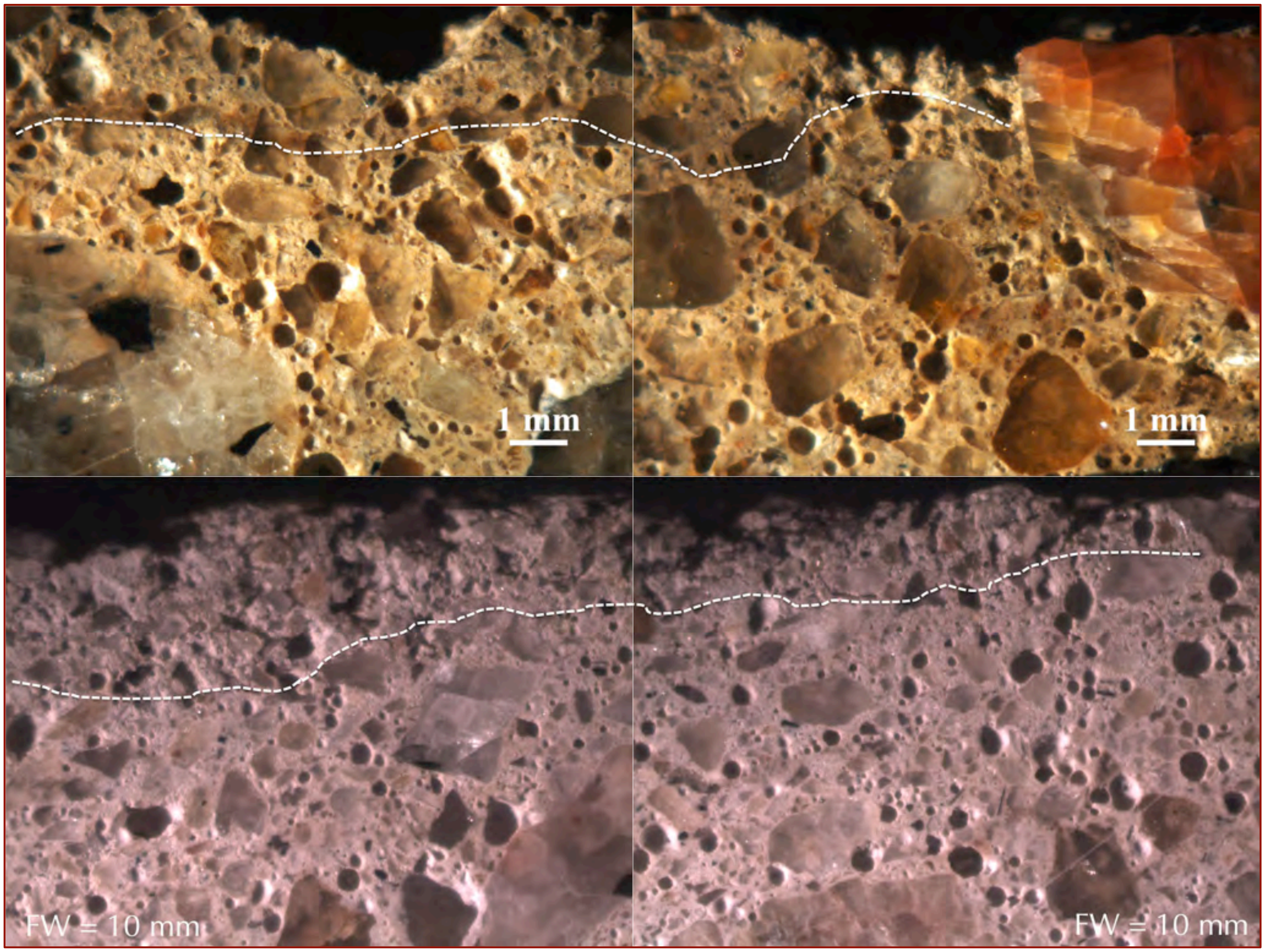

Figure 12: Soft, earthy-textured paste at the scaled surface region within the top 1 to 2 mm above the dashed lines compared to denser paste in the interior beneath the dashed lines.

There is no evidence of any deleterious secondary deposits found in the core. Carbonation extended to a depth of 2 to 3 mm from the top surface. Bonds between the coarse and fine aggregate particles and paste are moderately tight to tight. There is no evidence of microcracking due to deleterious reactions except some freezing-related microcracks at the top scaled surface region.

The overall quality and condition of the concrete in the interior body of the core i.e. beneath the scaled surface is judged to be reasonable and sound with no evidence of any physical or chemical deterioration.

The following photomicrographs of blue dye-mixed epoxy-impregnated thin sections of the core show the soft, porous, severely carbonated paste at the top scaled surface region to a depth of 1 to 2 mm in Figure 13, but denser and less carbonated to non-carbonated paste in the interior in Figures 14 (right photo) and 15.

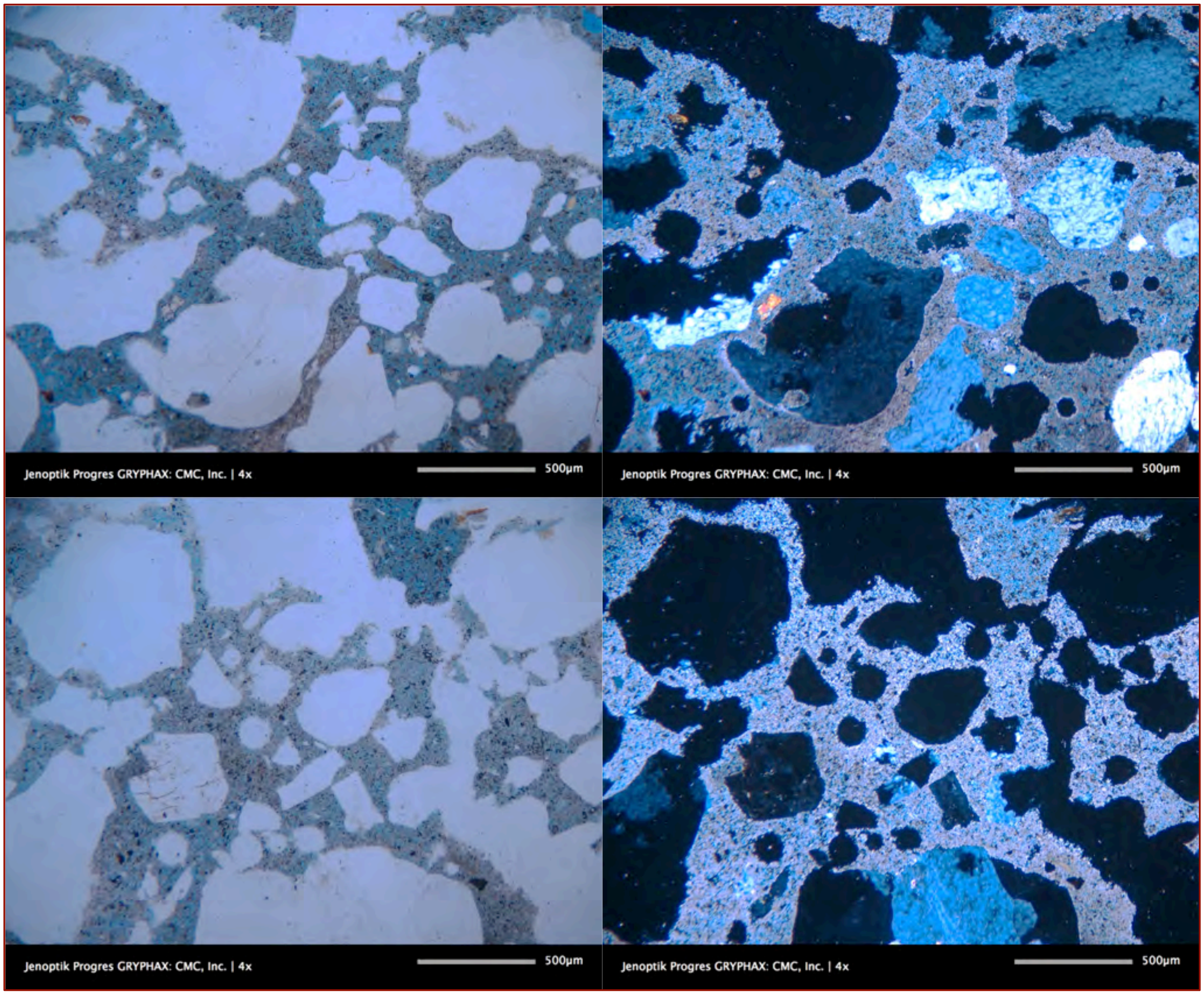

Figure 13: Blue dye-mixed epoxy-impregnated thin seciton of concrete showing soft, porous, and carbonated paste at the scaled surface region to a depth of 1 to 2 mm.

Figures 13 through 15 show thin section photomicrographs of paste, particularly the contrasting compositions and properties of pastes between the scaled surface region (within the top 1 to 2 mm) and the interior sound concrete. Figures 13 and 14 show the soft, porous, and severely carbonated paste at the scaled surface region, which is indicative of the higher water-cement ratio of paste at the scaled surface. The interior paste, by contrast shows non-carbonated and dense nature (Figure 14 right photo, and Figure 15), which is continuous all throughout the depth of the core from beneath the scaled surface. Therefore, the soft, porous, high water-cement ratio paste is found to be confined to within 1 to 2 mm of the scaled surface and did not extend beyond that depth.

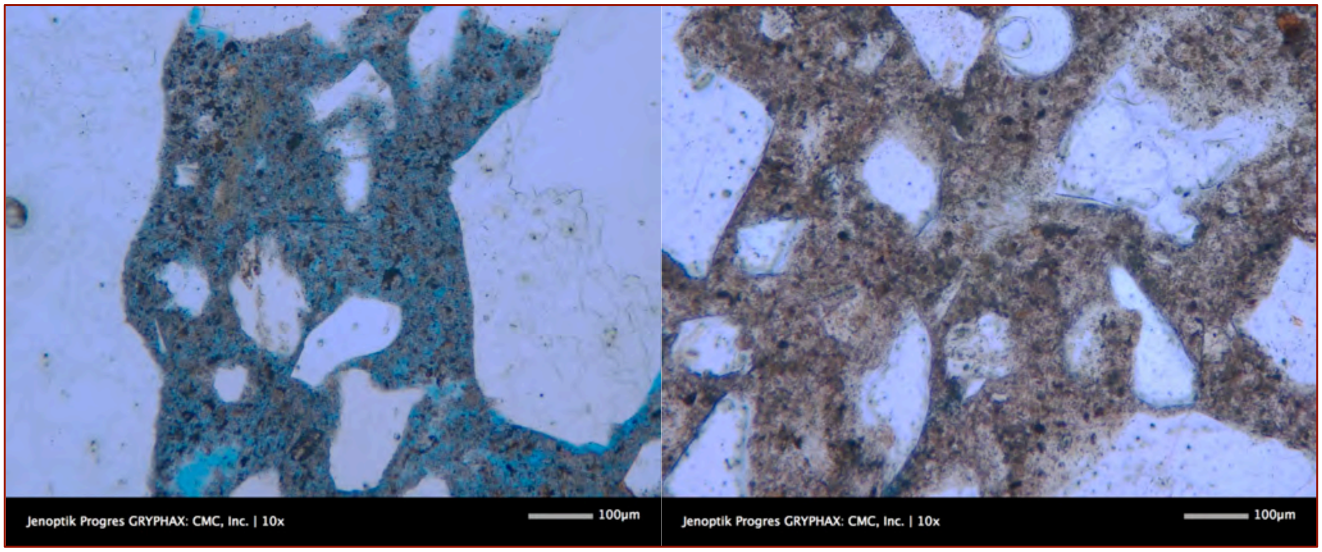

Figure 14: Blue dye-mixed epoxy-impregnated thin seciton of concrete showing soft, porous, and carbonated paste at the scaled surface region to a depth of 1 to 2 mm in the left photo, but dense, non-carbonated paste in the interior concrete in the right photo.

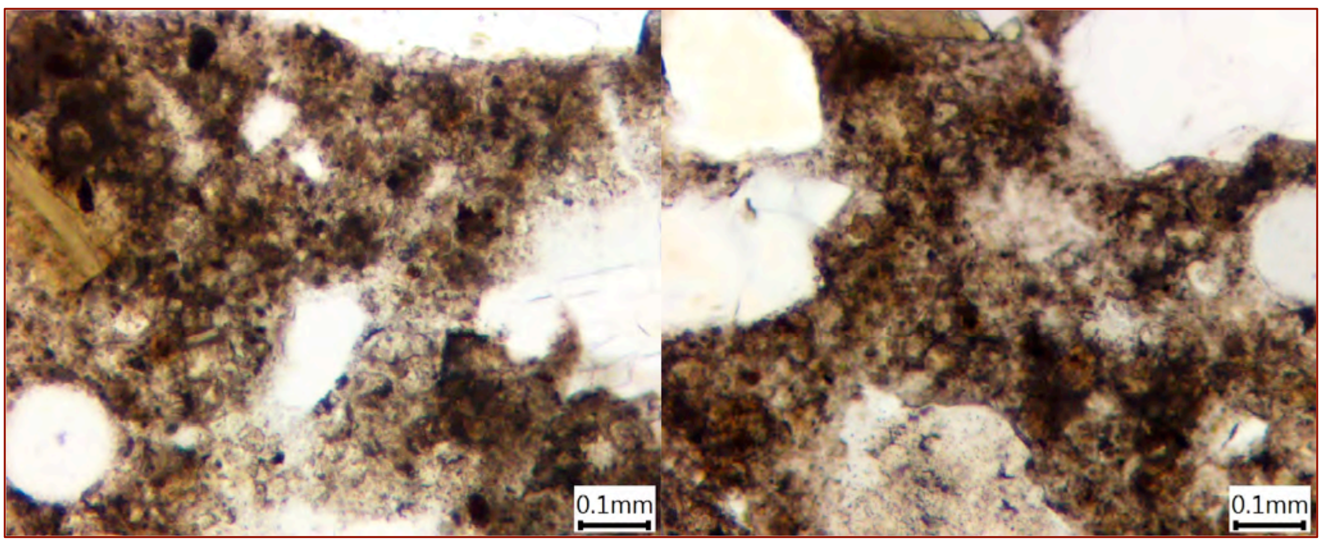

Figure 15: Blue dye-mixed epoxy-impregnated thin seciton of concrete showing dense, non-carbonated paste in the interior concrete in the right photo. Notice the absence of any pozzolanic or cementitious materials besides Portland cement.

AIR

Air occurs as: (i) numerous fine discrete, spherical and near-spherical voids having sizes of up to 1 mm, and (ii) a few coarse, near-spherical and irregularly shaped voids of sizes coarser than 1 mm. The former voids are characteristic of entrained air and the latter ones are entrapped air. Air-void system of concrete in Core C-1 is suggestive of intentional addition of an air-entraining agent in the mix. Air content is estimated from petrographic examinations to be at least 10 percent (Figure 16), semi-quantitatively determined by the flatbed scanner method of Peterson et al. (2016) to be as high as 16 percent, and actually determined *a la* ASTM C 457 to be 11.5 percent.

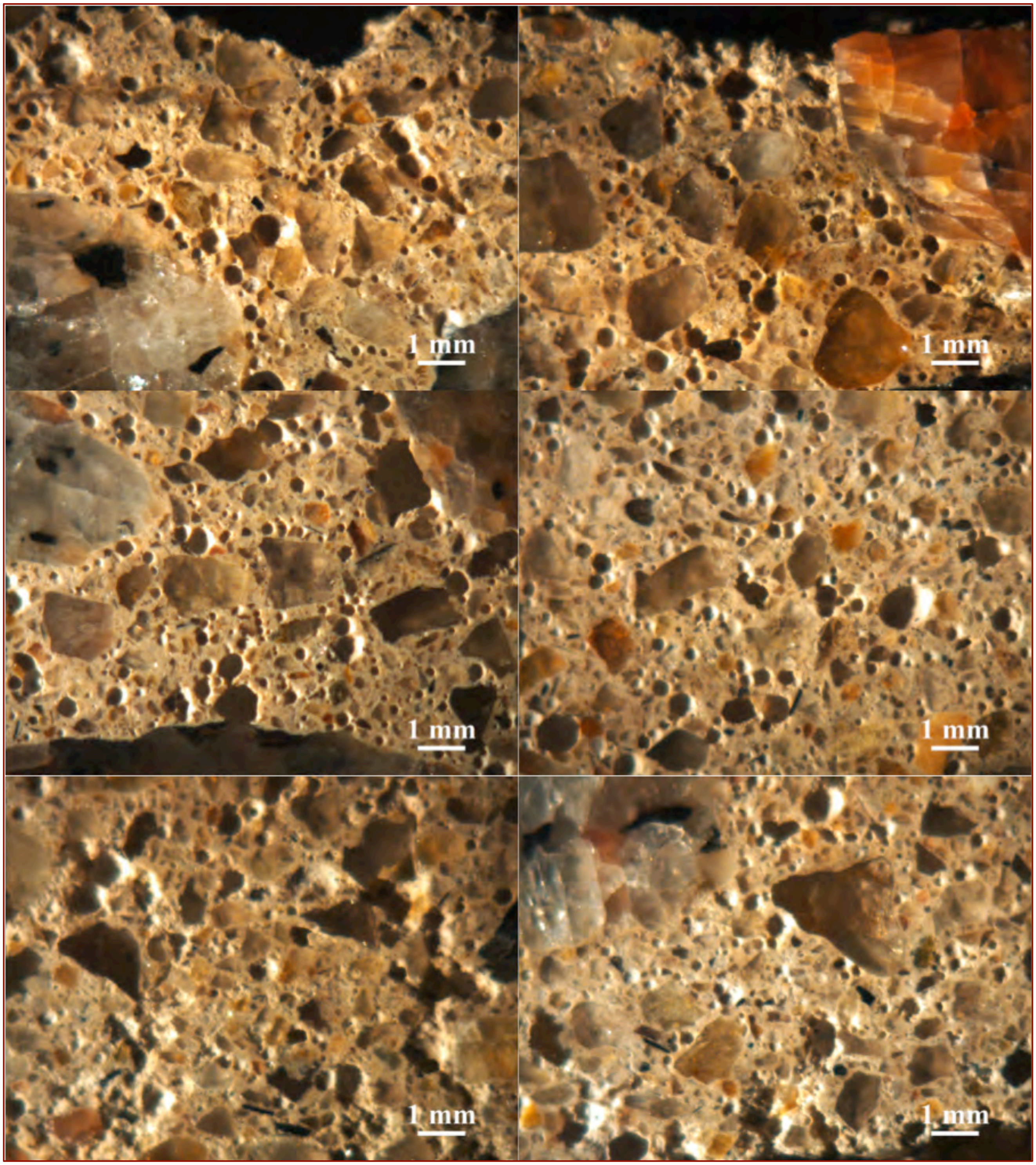

Figure 16: Photomicrographs of lapped cross section of the core showing the excessively air entrained nature of the concrete, the distribution of entrained and entrapped air-voids, the soft, porous paste at the top 1 to 2 mm of the scaled surface, and more or less uniform air content and air-void system beneath the scaled surface and throughout the depth of the core.

Figure 17 shows more photomicrographs of air-void system taken from a different stereomicroscope-camera system than that used in Figure 16.

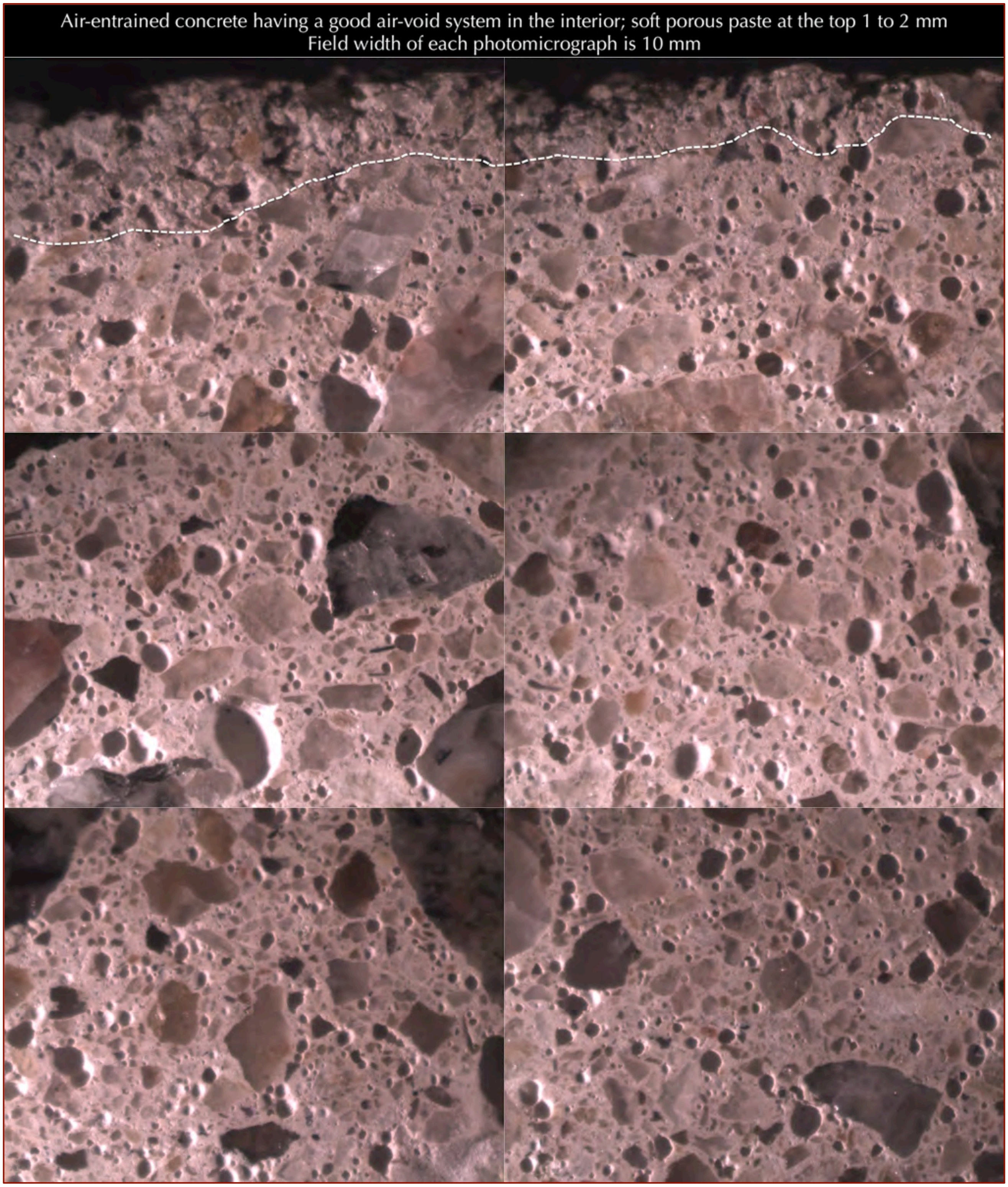

Figure 17: Further photomicrographs of lapped cross section of the core showing the air-entrained nature of the concrete, the distribution of entrained and entrapped air-voids, the soft, porous paste at the top 1 to 2 mm of the scaled surface, and more or less uniform air content and air-void system beneath the scaled surface and throughout the depth of the core.

Air-void analysis of Core C-1 *a la* modified point count method of ASTM C 457 determined the concrete to be excessively air-entrained. The following table provides the determined air-void parameters of concrete in the core:

Air Void System and Parameters	C-1
Air-Void System	Excessively Air-Entrained
Total Air Content, %, Determined	11.5
Entrained Air Content, %, Determined	6.8
Paste Content, %, Determined	32.0
Paste-Air Ratio	2.8
Specific Surface, in.^{2}/in.^{3}	1107
Air-Void Spacing Factor, in.	0.0025

Table 3: Properties and parameters of air void system of concrete in Core C-1. Entrained air voids are defined as discrete spherical or near-spherical voids of sizes 1 mm or less. Common industry (e.g., ACI, ASTM) requirements for a concrete containing $^3/_4$ in. nominal maximum size coarse aggregate and exposed to a moist outdoor environment of cyclic freezing and thawing are an air content of $6\pm1^1/_2$ percent, a minimum specific surface of 600 in.^{2}/in.^{3} and a maximum void-spacing factor of 0.008 in.

Air-void parameters determined from the modified point count method of ASTM C 457 show excessive air entrainment and an air content of 11.5 percent, a fine air-void system with a specific surface in excess of the industry-recommended minimum value of 600 in^2/in^3, and a void spacing factor less than the industry-recommended maximum limit of 0.008 in.

The following black-and-white photograph of lapped cross section of core (the same lapped section shown in Figure 10 but after contrast enhancements) show the air (and other stringy voids, separation) voids in white against everything else in black, which was prepared to scan in a flatbed office scanner and do actual air measurements by using the flatbed scanner method for determining air-void parameters according to Peterson et al. (2002, 2009, 2016). Air-void parameters obtained from flatbed scanner method have usually shown good to excellent correlations with that obtained from conventional ASTM C 457 methods of hardened air measurements (Jana et al., 2007; Peterson et al., 2009, 2016). The flatbed scanner method showed a total air content as high as 16 percent, which is certainly higher than the air content estimated from petrography or determined from ASTM C 457 modified point count method but is consistent with the initial estimation from petrography to have an air content of at least 10 percent. Air content from all three independent methods, therefore, showed a high air in the concrete i.e. higher than the common industry (e.g., ACI, ASTM)-recommended maximum air content of $7^1/_2$ percent.

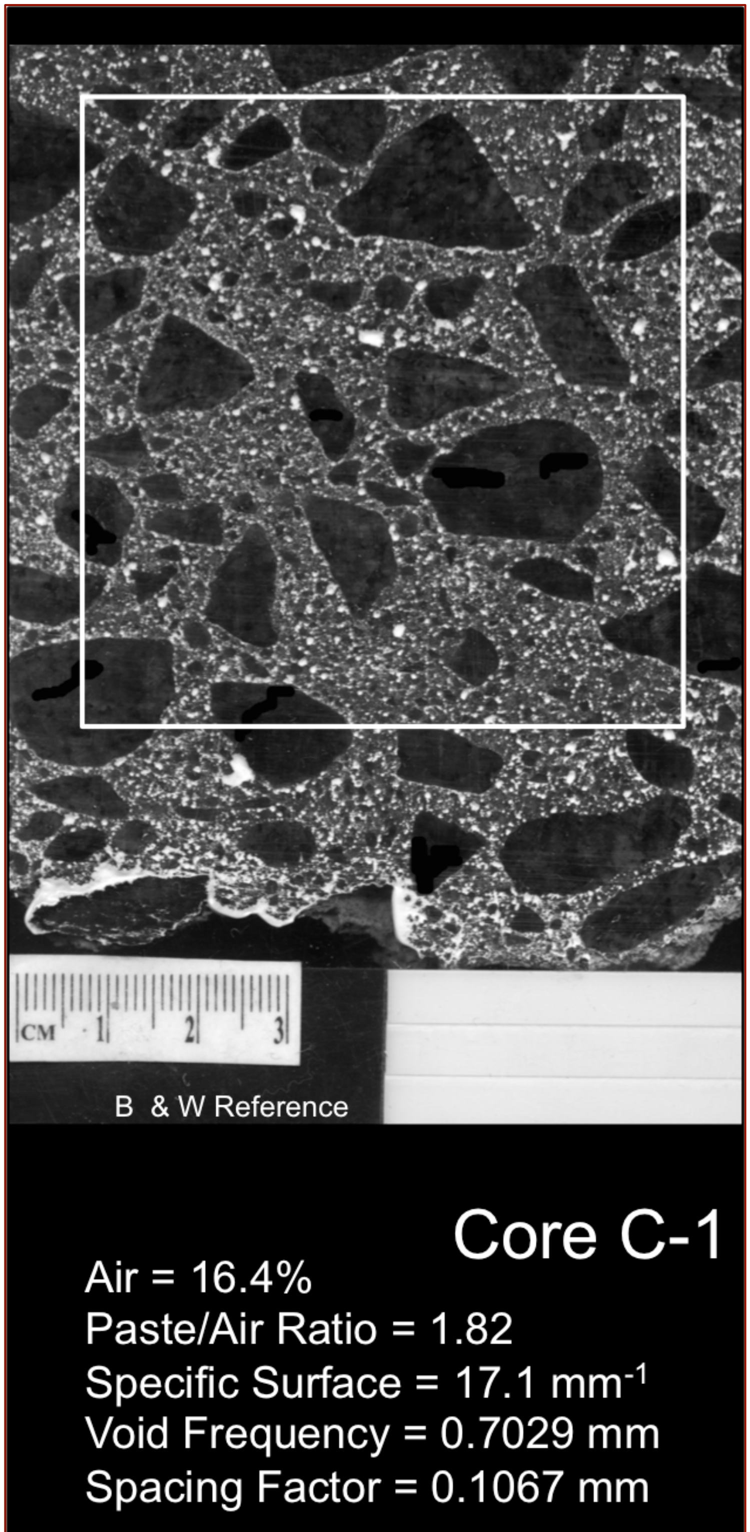

Figure 18: Determination of air-void parameters of concrete in Core C-1 by using the flatbed scanner method of Peterson et al. (2002, 2009, 2016). Boxed area is where air measurements were taken. Calculated air content is at the maximum for possible inclusion of some non-air-voids. The air-void specific surface is less than the industry recommended minimum value of 25 mm^{-1} (due to the presence of some coarse air-voids), and void spacing factor is within the common industry-recommended range of 0.1 to 0.2 mm.

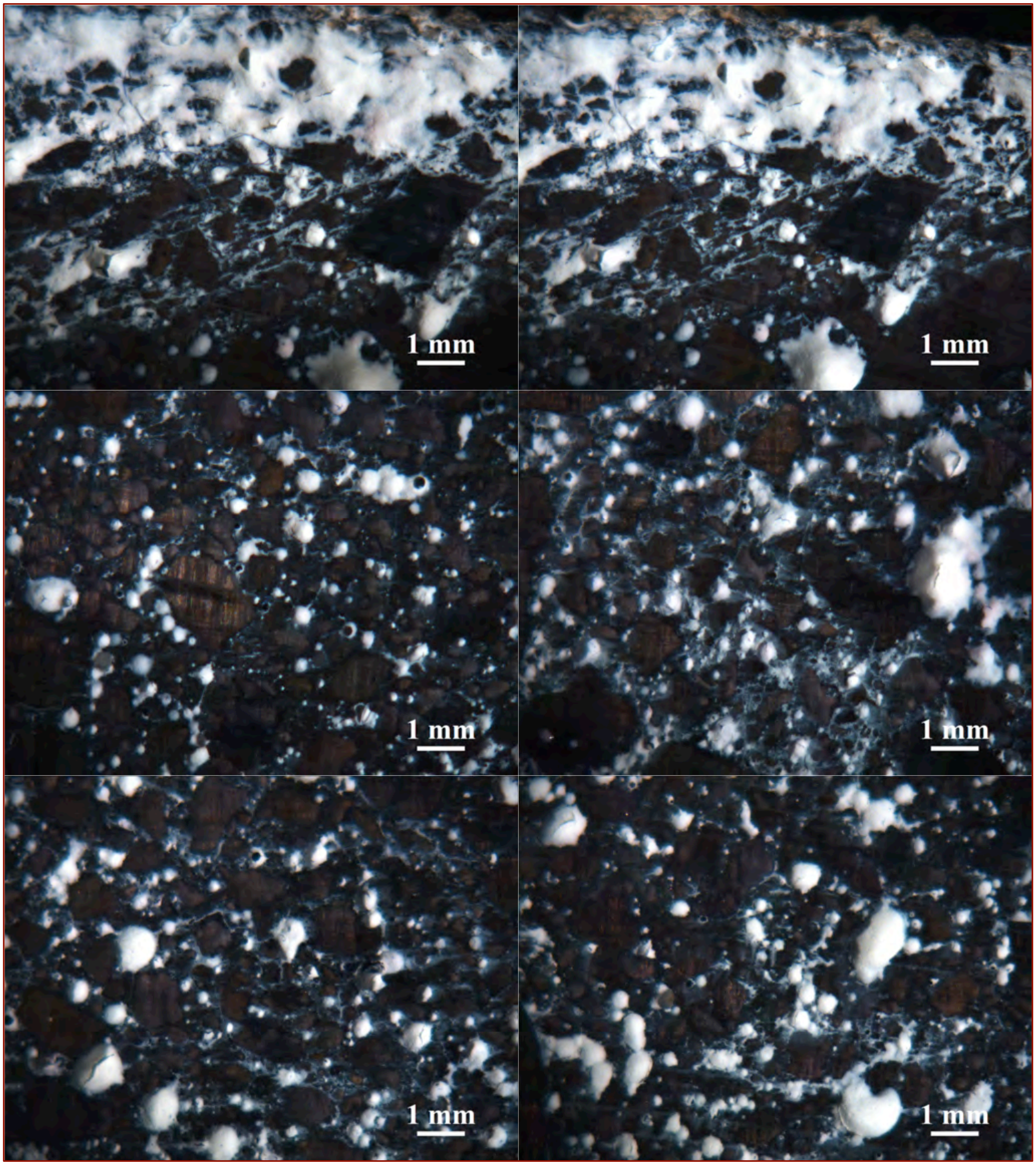

Figure 19: Photomicrographs of lapped cross section of core after treatment with black and white contrast enhancement showing porous areas of concrete at the scaled surface region from excessive white areas as well as some fine hair-like microcracks immediately beneath the porous paste due to freezing-related distress at the scaled surface, but more or less unfiorm and excessive air in the interior seen in middle and bottom rows.

TOO MUCH AIR

All three independent methods from estimation from petrographic examinations to semi-qualitative determination from flatbed scanner method to actual determination by the modified point count method of ASTMC 457 showed excessive air in the concrete, i.e. air contents higher than the common industry (e.g., ACI, ASTM)-recommended maximum air content of $7^1/_2$ percent for an outdoor concrete intended to be exposed to cyclic freezing and thawing and deicing chemicals at critically saturated conditions (ACI Committee Report 201). High air can adversely affect the overall compressive strength of concrete. For every percent point increase in air content above the design limit, for a given workability can reduce the compressive strength of concrete by 3 to 5 percent points.

Another detrimental side effect of having too much air is clustering of air-voids giving a frothy texture to the paste, and especially along aggregate-paste interfaces, which can weaken the interfacial bonds, and, thereby further reduce the compressive strength. Strength of concrete depends strongly on the strength of interfacial bonds (since concrete is weak in tension). The lapped surface of the examined core does show such clustering (see Figure 20), especially along coarse aggregate-paste interfaces, having the potential for strength loss from such weakening of aggregate-paste bonds.

Another potential downfall of having too much air is the increased stickiness and unworkability of concrete, which often requires addition of water during finishing to improve the workability (finishability) of sticky high air concrete. Such water addition during finishing, if not controlled, can end up creating a soft, porous paste at the surface that is less resistant to freezing-related stresses.

FINENESS AND CLOSENESS OF AIR BUBBLES

Besides total air, the other air-void parameters that are more crucial for freeze-thaw durability of concrete are the air-void specific surface, which measures the 'fineness' of air-voids, and, air-void spacing factor, which measures the 'closeness' of voids. The air-void specific surface in the flatbed scanner method is slightly less than the industry-recommended minimum value of 25 mm^2/mm^3, indicating a coarse air-void system of concrete, which is determined to be due to clustering and coalescence of many finer air-voids that have generated coarser voids. The ASTM C 457 method, however, showed higher specific surface, which is more representative of the air-void system, and shows an overall finer air-void system in between the coarse voids. The void spacing factor is below the maximum limit of 0.2 mm, which is beneficial for overall freeze-thaw durability since this parameter plays the most important role for freeze-thaw durability (Jana et al., 2005).

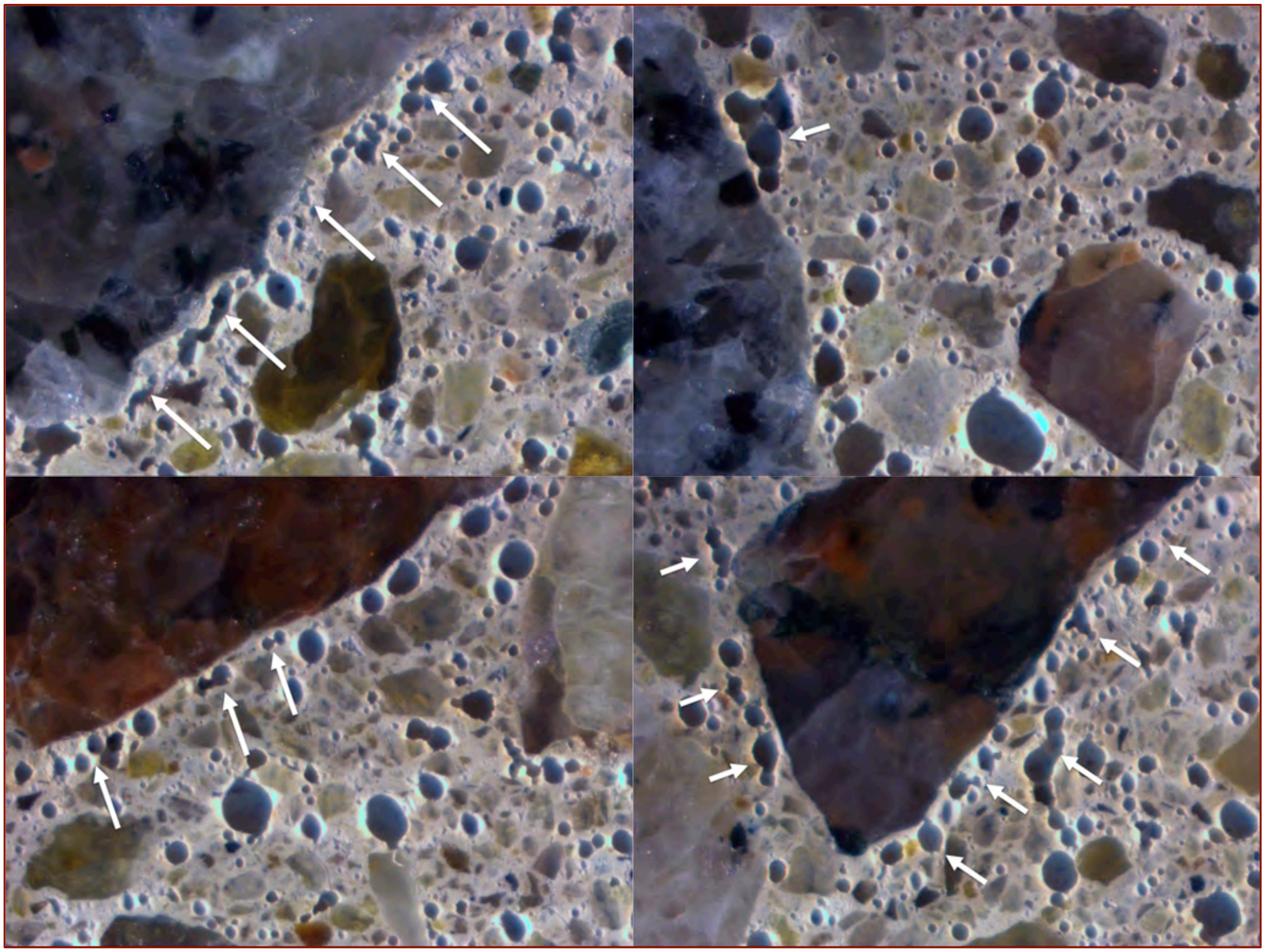

Figure 20: Photomicrographs of lapped cross section of core C-1 showing clustering of air voids along aggregate-paste interfaces due to excessive air entrainment. Field width of each photomicrograph is 15 mm.

STRENGTH VS. DURABILITY

Therefore, for this concrete, there is a trade-off between strength and freeze-thaw durability – which factor will win in the field during service depends on: (a) whether or not concrete will be exposed to freezing at critically saturated conditions for an extended period of time, (b) how early will it be exposed to freezing, as well as (c) if the potential loss of strength from having too much air can be counter-balanced by a concomitant reduction in overall water-cementitious materials ratio of concrete without affecting the workability so that any strength loss of high air can be adjusted by reducing the *w/c* so that concrete still has the necessary strength to resist the freezing-related stresses.

CHLORIDE CONTENTS

Acid-soluble chloride contents were determined from: (a) the top scaled surface region, as well as (b) from the interior body from near the bottom end of Core C-1 to determine (a) if the concrete surface was exposed to any chloride-containing deicing chemicals, and, (b) if a chloride-containing set accelerating admixture was added in the concrete let alone for the reported winter-weather concrete placement, which may have provided any chloride to the concrete, respectively. Table 4 and Figure 21 show results of chloride analyses, which show:

a. Noticeably lower chloride at the scaled surface region (0.008 percent by mass of concrete) compared to 0.033 percent chloride in the interior (near the bottom end).
b. Absence of high chloride at the scaled surface region compared to that in the interior is indicative of the absence of any chloride-containing deicing chemicals at the surface. Absolute value of chloride at the surface is indicative of chloride from concrete-making ingredients.
c. Higher chloride in the interior compared to that at the scaled surface is indicative of possible addition of a chloride containing set accelerating admixture in the mix, which is consistent with the reported winter-weather placement of slab in the month of December.
d. Comparison of chloride contents at the scaled surface region and in the interior removes any possibility of exposure of a chloride-containing deicing salt at the surface to cause the surface scaling.

The first column in Table 4 represents Core ID. The second column shows the location from where section for chloride content was taken. The third column shows the raw chloride content data of percent chloride in the concrete by mass of the concrete sample. The forth column represents percent chloride content in the sample by mass of cement by assuming 15 percent Portland cement content in the concrete and normal-weight concrete (i.e. by dividing the raw chloride contents by mass of 'concrete' by 0.15 to obtain chloride contents by mass of 'cement'). The fifth column converts the raw chloride content in concrete from weight percent to ppm by multiplying the second column data by 10,000. The last column is only applicable if the chloride found in concrete is obtained not from the external environment but from the use of flake (anhydrous) calcium chloride as a set-accelerating admixture in solution, in which case the data in the last column represents equivalent flake calcium chloride added to the mix as an accelerating admixture.

Sample ID	Location (centimeters from top)	Percent Chloride by Mass of Sample	Percent Chloride by Mass of Cement[1] (% Chloride by Mass of Sample/0.15)	% Chloride PPM (% Chloride by Mass of Sample x 10000)	Equivalent Flake Calcium Chloride (% Chloride by Mass of Cement x 2.07)
Core No. C-1	Top	0.008	0.051	77	0.02
	Bottom	0.033	0.222	333	0.07

Table 4: Acid-soluble chloride contents of core at various depths. [1]Assuming a cementitious materials content of 15 percent by mass of a normal-weight concrete.

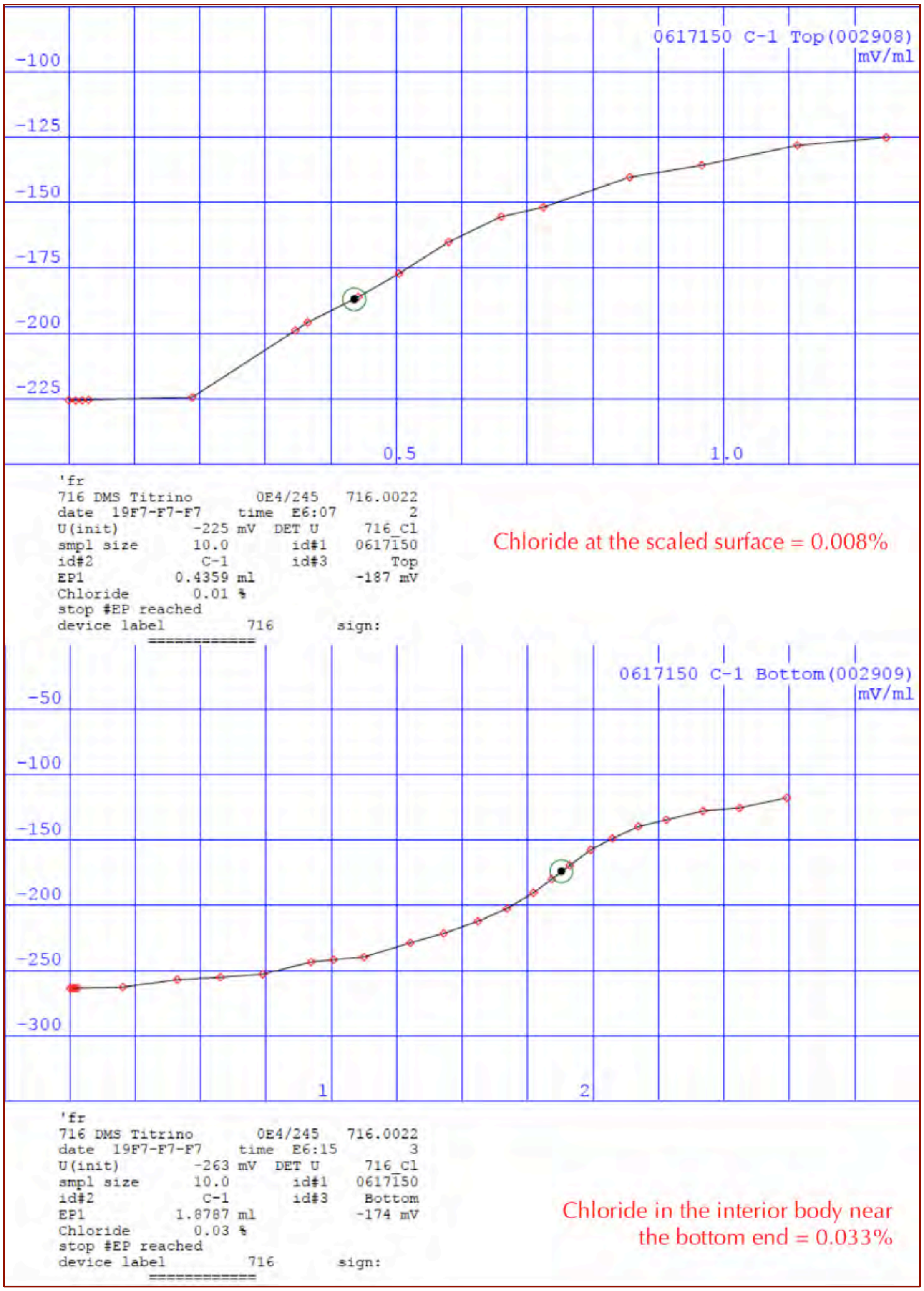

Figure 21: Potentiometric titration graphs of millivolts versus milliliters of silver nitrate solutions formed during titration in Metrohm DMS Titrino 716 and the equivalent point of titration (circled on the plot) at the steepest slopes that were used in calculations of chloride contents of concretes [% chloride = (Equivalent point times 0.177) divided by sample weight in grams]. Top graph is for chloride from scaled surface region, whereas bottom graph is for chloride from the interior concrete.

DISCUSSIONS

The following paragraphs discuss various factors that are important for investigation of concrete surface distress in the subject driveway slab:

AIR CONTENTS AND AIR-VOID SYSTEMS

Concrete in the examined core shows evidence of addition of an air-entraining agent, however, in an excessive amount or enough to stabilize more than 10 percent total air and more importantly to generate an air-void system consisting of many fine, discrete spherical and near-spherical entrained air bubbles of 1 mm of less in size, and spaced closed enough for water to escape during freezing. Air content is estimated from petrographic examinations to be at least 10 percent, semi-quantitatively determined by the flatbed scanner method to be as high as 16 percent, and actually determined *a la* ASTM C 457 to be 11.5 percent.

Concrete is, therefore, *excessively air-entrained* for having an air content *not* in conformance to the common industry requirements for concretes from an outdoor environment exposed to freezing, thawing, and deicing chemicals in a moist environment, where the concrete should have a total air content in the range of 4.5 to maximum 7.5 percent.

The other air-void parameters that are more crucial for freeze-thaw durability of concrete than the total air are the air-void specific surface, which measures the 'fineness' of air-voids, and, air-void spacing factor, which measures the 'closeness' of voids. The air-void specific surface in the flatbed scanner method is slightly less than the industry-recommended minimum value of 25 mm^2/mm^3, indicating a coarse air void system of concrete, which is determined to be due to clustering and coalescence of many finer air-voids that have generated coarser voids. The ASTM C 457 method, however, showed higher specific surface, which is more representative of the air-void system, and shows an overall finer air-void system in between the coarse voids. The void spacing factor is below the maximum limit of 0.2 mm, which is beneficial for overall freeze-thaw durability since this parameter plays the most important role for freeze-thaw durability (Jana et al., 2005).

Entrained air-voids are necessary for the protection of a concrete in a moist outdoor environment against distress due to cyclic freezing and thawing at critically saturated conditions, especially in the presence of deicing salts (Jana 1997, 2004, 2007, Jana and Cole 1997, Jana and Erlin 2001). Entrained air provides the necessary room for the water to escape during freezing, thus relieving the freezing-related stresses to not exceed the tensile strength of concrete for it not to crack or spall. Having a very fine network of numerous discrete spherical air bubbles at a very close-spaced distance for ready escape of water (i.e. fulfilling the specific surface and void-spacing factor requirements) are far more important for an outdoor concrete in a moist environment than having a lot of air-voids but not fine enough and close enough for water to escape. The absolute total air content of concrete, therefore, has little significance on freeze-thaw durability (Jana et al. 2005, except possible strength loss from high air) than the fineness of air-void system (i.e. the specific surface) and its closeness (i.e. the void-spacing factor).

Other than the possible strength reduction from void clustering as discussed before, too much air also makes a concrete sticky and increases difficulty of finishing to achieve an acceptable finish. Air contents as high as 12 to 16 percent would make concrete sticky enough to impose difficulty in finishing such a high-air concrete, with some obvious effects of finishing and unworkable concrete, e.g., tendency to add water during finishing to increase workability of sticky, high-air concrete, and subsequent loss of freeze-thaw durability of the surface if water addition reduces the scaling-resistance of surface.

AGGREGATES

The crushed granite coarse aggregate and natural siliceous (quartz-quartzite) sand fine aggregate are present in sound conditions and did not contribute to the observed scaling. These coarse and fine aggregate should not cause any popout from unsoundness. Therefore, any distress that resembles popouts i.e. having fractured remains of underlying near-surface aggregate should be a mortar lift-off than a popout, where the original finished surface was lifted off from the flat topside of underlying aggregate due to the weak bond between the finished surface and the underlying aggregate than any expansion or unsoundness of the aggregate itself. Aggregates, therefore, are not responsible for the distress.

PLACEMENT, FINISHING, AND CURING

The interior concrete is dense and well consolidated without any coarse voids or honeycombing, indicating adequate consolidation of concrete during placement. There is also no evidence of any segregation of aggregates during placement. There is, therefore, no evidence of any improper consolidation practice of slab at the location of this core.

Based on the determined excessive air entrainment, the observed high *w/c* at the very top finished surface region and subsequent soft, porous, dusty, earthy-textured less durable paste at the scaled surface region are judged to be due to the artifact of finishing a high-air concrete where it is not uncommon to add water to improve workability of a 'sticky' high-air concrete. Excess water during finishing is judged to be more from the water added during finishing than from mixing of bleeding water at the surface during finishing, since high air probably reduced the rate of bleeding significantly (and that too may have promoted water addition at the surface during finishing). Areas that have received too much water during finishing have softened significantly and lost the scaling resistance than the other areas having relatively lesser amount of water addition.

There is no evidence of premature finishing in the core, i.e. finishing prior to the cessation of bleeding, which causes accumulation of bleed water beneath the finished surface, which eventually causes separation of the top thin sheet of finished surface from the main body of concrete. As mentioned due to the presence of high air, however, such possibility is not unlikely. A common evidence of premature finishing and accumulation of bleed water beneath the finished surface is sheet-like scaling of the finished surface in the field (due to the presence of a weak bond immediately beneath the scaled sheets by the accumulated bleed water).

Curing is essential for adequate cement hydration at the surface, and, thereby, development of the necessary strength of concrete at the surface by providing enough moisture and optimum temperature for cement hydration. The core shows no evidence of inadequate curing of concrete, e.g., no evidence of restricted cement hydration at the surfaces at least to cause the reported surface scaling.

COMPRESSIVE STRENGTH & CONCRETE MATURITY

The maturity of concrete is defined as: (i) a period of air drying and (ii) a compressive strength of at least 4000 psi – both prior to the first exposure of salts and snow so that the concrete does not contain any ‘freezable’ water in its capillary pores to freeze, expand, and thus cause distress (hence the importance of at least a period of air drying), and is strong enough to resist freezing-related stresses (hence the importance of adequate strength of at least 4500 psi) both prior to the first exposure of snow and salt (Jana 2004, Jana 2007). A concrete is, therefore, needed to be ‘matured’ prior to the first exposure of freezing, especially during the winter weather constructions.

Due to the reported winter weather placement of the driveway slab on December 28, 2015, and reported numerous subfreezing temperature minimums at the project location during the month of January (ranging from 18 to 29°F as per the report of National Weather Service), the concrete may not have attained the necessary maturity prior to the first exposure of freezing. Within a week after placement i.e. prior to the attainment of a minimum 4000-psi strength, the slab was probably exposed to the subfreezing temperatures (e.g., subfreezing temperatures have occurred during January 4 to 6, 11 to 14, and 17 to 25 of 2016).

DEICING SALTS

Deicing salts, usually, do not cause surface scaling in a properly air-entrained concrete having a good air-void system that is made using sound aggregates, and has been placed, finished, cured, and was matured properly (Jana 2004, 2007), *unless*: (i) salt is applied prior to the attainment of maturity of concrete, and/or (ii) a chemically aggressive (e.g., magnesium or ammonium sulphate or urea-based) salt is applied that can chemically decompose the paste (calcium silicate hydrate, the heart of concrete).

Due to the higher *w/c* of paste at the top than the interior, exposures to common sodium or calcium chloride-based deicing salts could have aggravated surface scaling. Due to the hygroscopic character of common road salts, having adequate entrained air-voids is essential for resistance to salt-related scaling. Exposures to corrosive salts, such as magnesium-based salts, however, could cause scaling even in a good concrete by chemical decomposition of calcium silicate hydrate, the main component of paste that is responsible for development of strength in a concrete to magnesium silicate hydrate that has no cementitious property.

Results of chloride profile analyses from the top scaled surface region and the interior body from near the bottom end, however, showed no evidence of exposure to a chloride-containing salt at the surface, and rather chloride is higher in the body than the surface probably due to addition of a chloride-containing set-accelerating admixture in the mix, where chloride was washed away from the surface probably from finishing with excess water.

Therefore, the driveway surface is judged not to have been exposed to an external chloride from a deicing salt, at least at the location of this examined Core C-1.

BENEFICIAL ASPECT OF A SURFACE SEALER

It is the concrete itself, i.e. an adequately air-entrained concrete made using optimum air content and good air void system, sound aggregates, good paste, placed, finished, and cured properly, and has been matured prior to the first exposure to freezing, salts, and snow, which should provide the necessary adequate durability. When all these basic factors are fulfilled from concrete materials to construction practices, having an additional surface sealer is not needed for protection. A surface sealer, however, does provide an additional protection, particularly when the inherent concrete quality and/or construction practices is/are questionable such as in this present case. There are, however, many incidences of surface scaling in many outdoor slabs that did receive surface sealers, simply because sealer did not provide a long-term protection, and needed repeated applications. On the other hand, there are many incidences of perfectly sound outdoor slabs without any sealer that were exposed to freezing, slats, and snow but no distress at all simply because the concretes were made using sound durable materials and were constructed and matured properly. Therefore, having or not having a sealer is not the paramount for providing the first hand protection against the environment. Sealer becomes more important when the inherent quality of concrete is questionable as here when concrete surface has poor scaling resistance.

CONCLUSIONS

Based on detailed laboratory investigations, the observed and reported surface scaling of concrete driveway is judged to be due to one or a combination of the following factors:

a. Excessive air entrainment of concrete that has made the concrete sticky and has, thereby, increased difficulty in finishing with the consequence of addition of excess water during finishing, higher water-cement ratio having soft, dusty, and porous paste at the exposed surface from such addition that has reduced the overall freeze-thaw durability and scaling resistance of finished surface, especially during the early exposures to freezing prior to the attainment of concrete maturity, particularly in the areas that have received more water addition during finishing than elsewhere.

b. Possible early exposure to freezing during the month of January prior to the attainment of concrete maturity, e.g., a compressive strength of at least 4000-psi.

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APPENDIX

END OF REPORT[1]

[1] The CMC logo is made using a lapped polished section of a 1930's concrete from an underground tunnel in the U.S. Capitol.