

## Chloride and Carbonation-Induced Corrosion of Reinforcing Steel In A Concrete Column – A Case Study



North Carolina State University  
Mann Hall Column Testing



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## EXECUTIVE SUMMARY

**Background** - Exposed perimeter reinforced concrete columns at 4-story Mann Hall (constructed in 1963) in North Carolina State University has experienced corrosion of reinforcing steel in columns resulting in various levels of distress from vertical and horizontal cracking, delamination and spalls. Previous tests have determined the presence of elevated chlorides in some columns and deep carbonation, hence potential chloride-induced and/or carbonation-induced corrosion of steel in concrete to cause the distress. A repair attempt in 1993 was taken to reduce chloride and carbonation ingress by patching many deteriorated concrete covers over corroded rebars with adequate concrete cover of 1 to 4 in. thicknesses. However, continued deterioration over the past couple of decades has led to other engineering firms evaluate these columns in 2017. Recently, field evaluation of these columns were done in August of 2019 from visual surveying to audible sounding, excavations, chloride powder sampling, and removal of cores for present petrographic examinations. Recent field evaluation confirmed prior assessment of distress consistent with corrosion of steel in concrete.

**Cores** - Four cores were provided for examinations, which are marked as PC-1, PC-3, PC-4, and PC-5.

- a. Core PC-1 was taken through the 2<sup>1</sup>/<sub>2</sub> in. thick overlay from a north column face (column line E/8, Level 2) that was cracked and moderately delaminated on all sides.
- b. Core PC-3 was taken from low roof column (column line E/5, Level 2) exposed on all sides that has experienced severe spalling on all sides with a reported chloride content determined to be 942 ppm within 2" of column face.
- c. Core PC-4 was taken through a map cracked overlay from Column line A/7, Level 3.
- d. Core PC-5 was taken from Column Line K/4, Level 1 where no overlay or coating was reportedly visible, surface is cracked but doesn't appear severe, the core was accidentally taken through a cold-joint between column and beam where beam concrete was evidently placed over the column.

**Methodologies** - The cores were examined by detailed petrographic examinations from optical microscopy to SEM-EDS according to the procedures of ASTM C 856 and ASTM C 1723, respectively. The study evaluated:

- a. Qualities and conditions of coarse and fine aggregates used in the concrete, including assessment of any potential internal sulfate attack in concrete from sulfates that may have released from oxidation of sulfide-inclusions in aggregates, if any,
- b. Composition and properties of paste, including depths of carbonation by conventional phenolphthalein treatment and optical microscopy of thin sections of concrete, and sulfate content of paste by SEM-EDS,
- c. Air content and air-void systems in concrete, and
- d. Indication of any physical or chemical deterioration of concretes, materials imperfection, workmanship or improper mix proportions, etc., if any, or other factors that may have affected performance of concrete.

Additionally, chloride and sulfate contents of column concretes across various depths of cores were determined by various methods from potentiometric titration *a la* ASTM C 1218 for water-soluble chloride to ion chromatography *a la* ASTM D 4327 for water-soluble chloride, sulfate and other anions to X-ray fluorescence for water-soluble chloride and sulfate ions. Finally, protective paint applied over repair overlay in a core was tested by FT-IR for the composition of the paint. All these studies have evaluated the previous conclusions of chloride and carbonation-induced corrosion of reinforcing steel in concrete to cause spalling and delamination as well as investigated any potential internal sulfate attack in the concrete.

**Cementitious Repair Overlay** - The repair overlay applied over deteriorated concrete is found in all four cores that has varied in thicknesses from:

- a. A uniform 1<sup>1</sup>/<sub>4</sub> in. (35 mm) thickness overlay, which is completely debonded from concrete in Core PC-1; concrete has a nominal recovery length of 6 in. (150 mm). The overlay consists of crushed silica sand containing major amount of quartz of nominal sizes from 0.5 mm up to 1 mm that are well-graded, well-distributed and sound, and dense Portland cement paste of water-cement ratio estimated to be 0.35 to 0.40. The overlay is marginally air-entrained to air-entrained having an estimated air content of 6 to 8 percent. A skim coat is found at the base of repair overlay that is nominal 0.5 mm in thickness, consisted of crushed silica sand and Portland cement paste as the main overlay and bonded to the concrete beneath.
- b. A tapered 1<sup>1</sup>/<sub>8</sub> in. (4 mm) to maximum 2 in. (50 mm) thickness overlay, which is separated from concrete by a diagonal crack in Core PC-3; concrete has a nominal recovery length of 5<sup>1</sup>/<sub>2</sub> in. (140 mm) to maximum 7 in. (180 mm). The overlay is compositionally similar to that found in Core PC-1 and consists of crushed silica sand containing major amount of quartz of nominal sizes from 0.5 mm up to 1 mm that are well-graded, well-distributed and sound, and



dense Portland cement paste of water-cement ratio estimated to be 0.35 to 0.40. The overlay is non air-entrained having an estimated air content of 2 to 3 percent.

- c. A uniform 2 in. (50 mm) thickness overlay, which is completely debonded from concrete in Core PC-4; concrete has a nominal recovery length of 5 in. (120 mm). The overlay consists of crushed silica sand containing major amount of quartz of nominal sizes from 0.5 mm up to 1 mm that are well-graded, well-distributed and sound, and dense Portland cement paste of water-cement ratio estimated to be 0.35 to 0.40. Multiple applications of overlay of slightly different water-cement ratios are found in this core that are detected by slight difference in densities of pastes. The base of overlay is completely de-bonded from concrete and shows the presence of a separate thin repair coat of 2 to 3 mm thickness at the base of the main overlay of 2 in. (50 mm). The main overlay is well-bonded to the thin coat at the base but the latter shows clean debonding from the concrete. The overlay is marginally air-entrained to non-air-entrained having an estimated air content of 4 to 5 percent.
- d. A thin ( $1/8$  in., 4 mm) dark gray repair coat well-bonded to concretes from beam and column in Core PC-5; concretes contain portions of beam concrete, which is a lightweight concrete and column concrete, which is a normal-weight concrete of maximum recovered length of 6 in. (150 mm). Two repair overlays are found in PC-5 - one top porous overlay of 0.5 mm to 1 mm thickness that contains crushed fine silica sand plus Portland cement paste but with many coarse irregular-shaped voids, and another underling dense overlay of 0.5 mm thickness that also contains crushed fine silica sand and dense Portland cement paste but no major voids.
- e. In all four cores examined, overlays are dense dark gray repair mortars (lack coarse aggregate) applied over light grey to beige column concretes (that contain crushed stone coarse aggregates for column and lightweight aggregate for portion of beam concrete in Core PC-5).
- f. Thin section microcopy and SEM-EDS studies show typical Portland cement composition of paste in the overlay, high sulfate in paste from high cement content, and lack of any chemical or physical deterioration.
- g. Lack of adequate air entrainment in the overlays is counterbalanced by very dense, well-consolidated, low w/c, high cement content paste to provide the necessary freeze-thaw durability, which, however, is not of concern for the columns with minimal water saturation from standing water during freezing. There is no evidence of any freezing-related deterioration found in the overlays.

Protective Coatings Over Overlay - The exposed faces of columns represented by the Cores PC-1, 3, and 4 show multiple applications of protective coats over the main repair overlay, which are determined to be as follows:

- a. An exposed shiny cream-colored paint coat in Core PC-1, which is determined by SEM-EDS to have a titanium oxide pigment based polymer coat at the very top, followed by a titanium oxide pigment and china clay filler based PVC binder coat – both of which constitute the Coat #1 of two coat system, and an underlying cementitious coat (Coat #2) lacking titanium oxide pigment. The binder in Coat #1 is determined from FT-IR to be a PVC-based paint. The top coat (Coat #1) is approximately 0.25 mm in thickness, applied over an interior cementitious coat of another 0.25 mm thickness; the latter was applied directly over the overlay;
- b. An exposed titanium oxide pigment and perlite filler based PVC polymer exterior coat of approx. 0.3 mm thickness in Core PC-3, which was applied over a thin calcitic coat of 0.1 mm thickness, which, in turn, was applied over a cementitious coat of approx. 0.2 mm thickness, the latter was applied and well-bonded to the repair overlay;
- c. A textured matte-finished cream coat in Core PC-4 of approx. 0.1 to 0.4 mm variable thicknesses which is titanium oxide pigment and china clay filler based polymer coat, applied over a relatively uniform 0.3 mm thick cementitious coat, the latter was applied directly over and well-bonded to the concrete.
- d. Protective coats over overlays in all three cores have denser interior cementitious coats applied over the overlay compared to relatively porous titanium oxide pigment and clay or perlite filler based polymer outer coats.

Column Concrete - The column concretes in Cores PC-1, 3, and 4, and portion of Core PC-5 are compositionally similar and made using:

- a. Crushed granite and granite gneiss coarse aggregates having nominal maximum size of 1 in. (25 mm), particles are angular, dense and hard, variably colored from white (plagioclase feldspar, quartz) with black specs of mica to brown (alkali feldspar, quartz) with black specs of mica, equigranular for granite to gneissose textured for granite gneiss, equidimensional to elongated, unaltered, uncoated, uncracked, well-graded, well-distributed, and sound with no evidence of any deleterious alkali-aggregate reactions;
- b. Natural siliceous sand fine aggregate having major amount of quartz and quartzite and subordinate amounts of feldspar that have nominal maximum sizes of  $1/4$  in. (6.4 mm), particles contain crushed silica (quartz and feldspar-based) sands having nominal maximum sizes of  $3/8$  in. (9.5 mm), containing major amounts of quartz and quartzite, and subordinate amounts of feldspar, sandstone, schist, mafic minerals, etc.; particles are variably colored, rounded



- to subrounded to subangular, variably dense and hard, equidimensional to elongated, unaltered, uncoated, uncracked, well-graded, well-distributed, and sound with no evidence of alkali-aggregate reactions;
- c. Hardened Portland cement pastes having cement contents estimated to be 6 to 6<sup>1</sup>/<sub>2</sub> bags per cubic yard, and water-cement ratios (w/c) similar throughout the depths and between the cores and estimated to be in the range of 0.40 to 0.45, and,
  - d. The column concrete in all cores show lack of adequate air entrainment to the point to question addition of an air entraining chemical. In all cores, air in the column concrete occurs as a few discrete spherical and near-spherical voids of sizes less than 1 mm that are similar to entrained air but their abundance is less than that expected from intentional addition of an air entraining agent, and some coarse spherical, near-spherical and irregular-shaped voids that are characteristic of entrapped air. Air contents are estimated to be: (i) 1-2% in Core PC-1 where concrete is non-air-entrained, (ii) 2<sup>1</sup>/<sub>2</sub>-3<sup>1</sup>/<sub>2</sub> % in Core PC-3 where concrete is non-air-entrained to marginally air-entrained, (iii) 4-5 % in Core PC-4 with non-uniform distribution and local clustering of voids where concrete is marginally air-entrained, (iv) 3<sup>1</sup>/<sub>2</sub>-4<sup>1</sup>/<sub>2</sub> percent in the column concrete portion of Core PC-5 with non-uniform distribution and local clustering of voids where concrete is marginally air-entrained.

Beam Concrete - Beam concrete present in Core PC-5 (which was reportedly drilled through a cold-joint between column and beam where beam concrete was evidently placed over the column) is lightweight concrete (LWC), which contains (a) expanded clay and shale lightweight coarse aggregate of <sup>3</sup>/<sub>4</sub> in. (19 mm) nominal size, (b) natural siliceous sand fine aggregate, (c) Portland cement paste (estimated w/c 0.45 to 0.50), and (d) characteristic but marginal air entrainment (estimated 3 to 4 percent air content).

Carbonation of Column Concrete Prior to the Application of Repair Overlay/Coating Systems - The overlay showed minimal carbonation of 3 to 5 mm across all cores where not only the dense, low w/c, near-impermeable nature of the overlay but further protection from multi-layered coatings placed over the overlay provided additional protections against migration of atmospheric carbon dioxide.

The concrete beneath, however, has a different condition, which showed deep carbonation due to prolonged interaction between atmospheric carbon dioxide and column concrete prior to the installation of overlay. Carbonation depths are measured to be greater than 1 in. (30 mm) in Cores PC-1 and PC-3, variable from 15 to 25 mm in Core PC-4, and the deepest in Core PC-5 where the entire lightweight aggregate beam concrete is carbonated as well as the column concrete beneath the beam to a depth of 25 to 30 mm. Presence of reinforcing steel within the 1 to 1<sup>1</sup>/<sub>2</sub> in. of exposed faces of the column are thus susceptible to depassivation and carbonation-induced corrosion in the presence of oxygen and moisture.

Water-Soluble Chloride Contents - Chloride contents in the interior column concretes in Cores PC-1, PC-3, and PC-4 are higher than the common industry-recommended threshold chloride content of 0.2 percent by mass of cement for chloride-induced corrosion of reinforcing steel to occur in concrete in the presence of oxygen and moisture. Column concretes in Cores PC-1, PC-3, and PC-4 are thus susceptible to chloride-induced corrosion of steel in the presence of oxygen and moisture. Deep carbonation of concrete in the column at the locations of these cores measured to be 30 mm in PC-1 and PC-3 and 15 to 25 mm in PC-4 can further reduce the threshold chloride needed for steel corrosion (along with depassivation of gamma-lepidocrocite protective oxide film over the steel situated within the carbonated zone to cause carbonation-induced corrosion of steel). For PC-5, chloride content in interior depths of column concrete are lower than threshold chloride limits to cause corrosion. High chloride contents within the columns are judged to have been introduced most plausibly from the mix water used in the column concretes than any chloride-containing admixtures or aggregates. Crushed granite coarse aggregate and crushed silica sand fine aggregate in the column concretes are dense and free of any chloride salts. Admixtures added in the concrete are judged to be chloride-free or else higher than the observed chloride contents would have consistently been found across all sections in all cores rather than some isolated depths in three out of four cores. The dense, near-impermeable cementitious repair overlays showed negligible chloride compared to the interior column concretes.

Water-Soluble Sulfate Contents – Unlike chloride, however, water-soluble sulfate content in the cementitious repair overlays are noticeably higher than the column concretes, which is due to the higher cement contents in the overlays than in the underlying concrete. Sulfate contents of column concretes are indicative of sulfides from cement only within no additional internal or external source.

Chloride and Carbonation-Induced Corrosion of Reinforcing Steel in Columns - The reported cracking, delamination and spalling of columns in Mann Hall in North Carolina State University is found to be due to dual actions of chloride-induced corrosion of reinforcing steel in concrete and carbonation-induced corrosion of steel, where the former was initiated by



the presence of chloride within the column concrete in the presence of oxygen and moisture, whereas the latter mechanism was initiated by deep penetration of atmospheric carbon dioxide into the reinforcing steels of inadequate concrete covers. Both mechanisms caused corrosion of steel and associated expansion, cracking, delamination and spalling of concrete exposing corroded rebars in the columns. Other than steel corrosion, no other distress is found in the concrete. Evidences in favor of these dual actions of corrosion are: (a) deep atmospheric carbonation of concrete from around 30 mm in Cores PC-1 and PC-4 to 15 to 25 mm in Core PC-4 prior to the applications of repair systems of protective coatings and cementitious repair overlays, and, (b) higher than the common industry-recommended threshold chloride content of 0.2 percent chloride by mass of cement within the column as found in the Cores PC-1, PC-3, and PC-4.

No Internal Sulfate Attack in Column Concrete - Evidence of secondary ettringite lining air voids is a common cause of a Portland cement concrete exposed to moisture for prolonged periods. Such evidence does not indicate any sulfate attack. Column concrete in the cores examined showed such secondary ettringite lining some air voids, which are mere results of the presence of moisture in the concrete for prolonged periods. There is no evidence of any internal sulfate attack in the concrete, e.g., from oxidation of sulfide inclusions in aggregates or from any other source. SEM-EDS studies on sulfate contents of paste showed very low sulfate, which is typical of a Portland cement concrete and does not indicate any elevated sulfate in the paste, which commonly results from sulfate attacks. Microstructural examinations of concrete showed no evidence of any sulfate attack, e.g., there is no evidence of any microcracking, or ettringite-filled cracks or ettringite-lined aggregate-paste interfaces that are commonly found in concrete distressed by internal sulfate attacks.

Lack of Freezing-Related Distress in Column Concrete - Despite lack of air entrainment or mere marginal air entrainment found in the column concrete cores, there is, however, no freezing-related distress (e.g., surface-parallel cracking, spalling, etc.) found in the concrete beneath the repair overlay (or in the overlay itself). The vertical orientation of concrete in the columns with minimal potential for reaching critical saturation during freezing, along with dense, very low water-cement ratio of repair overlay prevented any freezing-related distress to occur in the concrete or in the overlay.

De-bonding of Repair Systems - The repair strategy on the spalled and delaminated columns have constituted (a) placement of a dense, near-impermeable very low water-cement ratio Portland cement and fine crushed silica sand based repair overlay of variable thicknesses (maximum 50 mm found in Cores PC-1 and PC-4), and (b) further protection of the repair overlay with multiple applications of protective coatings, starting with a cementitious coating directly applied over the repair overlay, followed by further application of exterior polymer based paints (titanium oxide pigment and china clay or perlite filler based PVC paint). Such multi-layer overlay and protective coating should have provided the needed protection of the interior column concrete.

However, in Cores PC-1, PC-3, and PC-4 the repair overlay is de-bonded from the column concrete where the purpose of application of such doubly protective systems was lost, e.g., (a) either complete debonding of overlay from concrete with minor remains of column concrete present at the underside of overlay in Core PC-1, or (b) clean separation of the overlay from concrete with no trace of column concrete adhered to the debonded overlay in Core PC-4, or (c) detachment of overlay from concrete by visible cracking in Core PC-3. Such overlay-concrete separations allow continued access of external deleterious agents from chloride and atmospheric carbon dioxide to other agents into the columns to continue the distress. This could be the reason for failure of prior repair applications in 1993 and continued distress to initiate present investigation. Any repair strategy must develop an intimate bond to the existing concrete system (after removing all distressed concrete) to protect the columns from further deteriorations.



## INTRODUCTION

### BACKGROUND

Reported herein are the results of detailed laboratory studies of four hardened concrete-composite cores from exposed perimeter concrete columns within Mann Hall at North Carolina State University that were studied to investigate, cracking, delamination, and spalling of concrete columns exposing near-surface corroded reinforcing steels .

The following background information was received with the samples including core locations provided in Table 1 below:

Sample ID	Sample Type	Level	Column Line	Description
PC-1*	4" Core	2	E/8	Column face cracked and moderately delaminated on all sides; MIRA testing indicated deeper delaminations; 2 1/2" overlay applied on north face (core taken through overlay)
PC-2	4" Core	3	G/8	Overlay map cracked; overlay 2 1/2" thick; parent concrete inside core hole appeared in good condition; rebar cover approximately 1 1/2" past parent concrete face.
PC-3*	4" Core	2	E/5	Core taken from low roof column; column exposed on all sides; distress severe – concrete cover mostly spalling on all sides; chloride sample taken from column yielded 942 ppm within 2" of column face
PC-4*	4" Core	3	A/7	Overlay map cracked; core taken through overlay
PC-5*	4" Core	1	K/4	No overlay or coating on surface; surface cracked but doesn't appear severe; core accidentally taken through cold-joint between column and beam where beam concrete was evidently placed over the column
PC-6	4" Core	2	H/2	Column appeared in good condition from ground level; no overlay

Table 1: Concrete cores collected from various locations across Mall Hall in North Carolina State University. Cores with asterisks were requested for examinations.

**Subject Building Description:** Mann Hall is an existing 4-story building constructed in 1963 with 79,722 gross square feet. It consists of a basement laboratory and 3 above ground floors that contain faculty and administrative office space, classrooms, student computer labs and study rooms. The structure is constructed of concrete cast-in-place columns with a cast-in-place beam-joint system.

**Subject Building Element:** Exposed perimeter concrete. There are 30 exterior columns. Columns are generally reinforced with at least four (4) #18 bars enclosed within #4 stirrups specified at 16" o.c.



**Reason for Testing:** Exposed perimeter concrete columns are exhibiting variable levels of distress around the building. Distress includes **vertical and horizontal cracking, delamination and spalls**. In 1993, deteriorating concrete cover from rebar corrosion was patched and an overlay of variable thickness between 1 to 4 inches was applied to provide adequate concrete cover over reinforcement and reduce carbonation induced rebar passivation. Further deterioration over the past couple of decades led to another engineering firm evaluating these columns in November 2017. Prior testing determined the presence of elevated chlorides in some columns, deep carbonation, and one core displayed ettringite that a previous petrographic report from a different laboratory indicated was a possible result of internal sulfate attack from iron inclusions in aggregates.

Detailed field evaluation of these columns were done in the week of August 12, 2019. The evaluation included visual surveying, audible soundings, excavations, chloride powder sampling and petrographic core sampling. The evaluation discovered distress and conditions consistent with rebar corrosion. It is unknown how much of this corrosion is attributable to chlorides. The client was also concerned about possible sulfate attack.

Results of eight (8) chloride tests were provided by the client, which were conducted on powers extracted from various locations. Table 2 provides the result:

Sample ID	Sample Type	Chloride Content (ppm)	Col	Level	Minimum Stirrup Cover	Minimum #18 Cover	Sample Depth	Proximate Distress
CL-1-1	Powder	122	K/6	1	7/8"	1 1/2"	1"-1 1/2"	None
CL-2-1	Bulk	942	E/5	2	1 1/4"	2"	Taken from face	Severe deterioration; concrete cover spalled off from corrosion of steel
CL-2-2	Powder	70	K/6	2	1 1/8"-1 5/8"	2"	1 1/4" to 1 3/4"	No Distress
CL-3-1	Powder	96	E/5	3	2"	2 1/2"	1" to 1 1/2"	No Distress
CL-3-2	Powder	101	K/3	3	1" to 1 1/2"	2 1/4"	1 1/4" to 1 3/4"	Yes; outer face delaminated
CL-3-3	Powder	259	H/2	3	1 7/8"	3/4"	From exposed interior concrete 1/2" deep	Yes; exposed bar at interior column within classroom
CL-4-1	Powder	84	A/4	4	1"	1 3/4"	1" to 1 1/2"	No Distress
CL-4-2	Powder	84	E/5	4	1 1/4"	2 1/8"	1 1/4" to 1 3/4"	Light cracking at outer face

Table 2: Results of chloride contents of concrete provided by the client.

**PURPOSE**

The purposes of the investigation are to determine: (a) the compositions, qualities, and overall conditions of concretes in the cores; and (b) based on detailed laboratory examinations, evidence of physical or chemical deterioration of concretes, if any, including evaluation of previously assessed chloride and carbonation-induced corrosion of reinforcing steel in concrete, or other factors (e.g., internal sulfate attack), which may have caused cracking, delamination, and spalling of concrete in the distressed columns.

**FIELD PHOTOGRAPHS**

Figure 1 shows overall views of Mann Hall at North Carolina State University. Figure 2 shows locations of cores extracted for present laboratory testing. The column at the location of Core PC-3 shows severe delamination and exposure of corroded rebar.



Figure 1: Field photos showing an overview of Mann Hall.

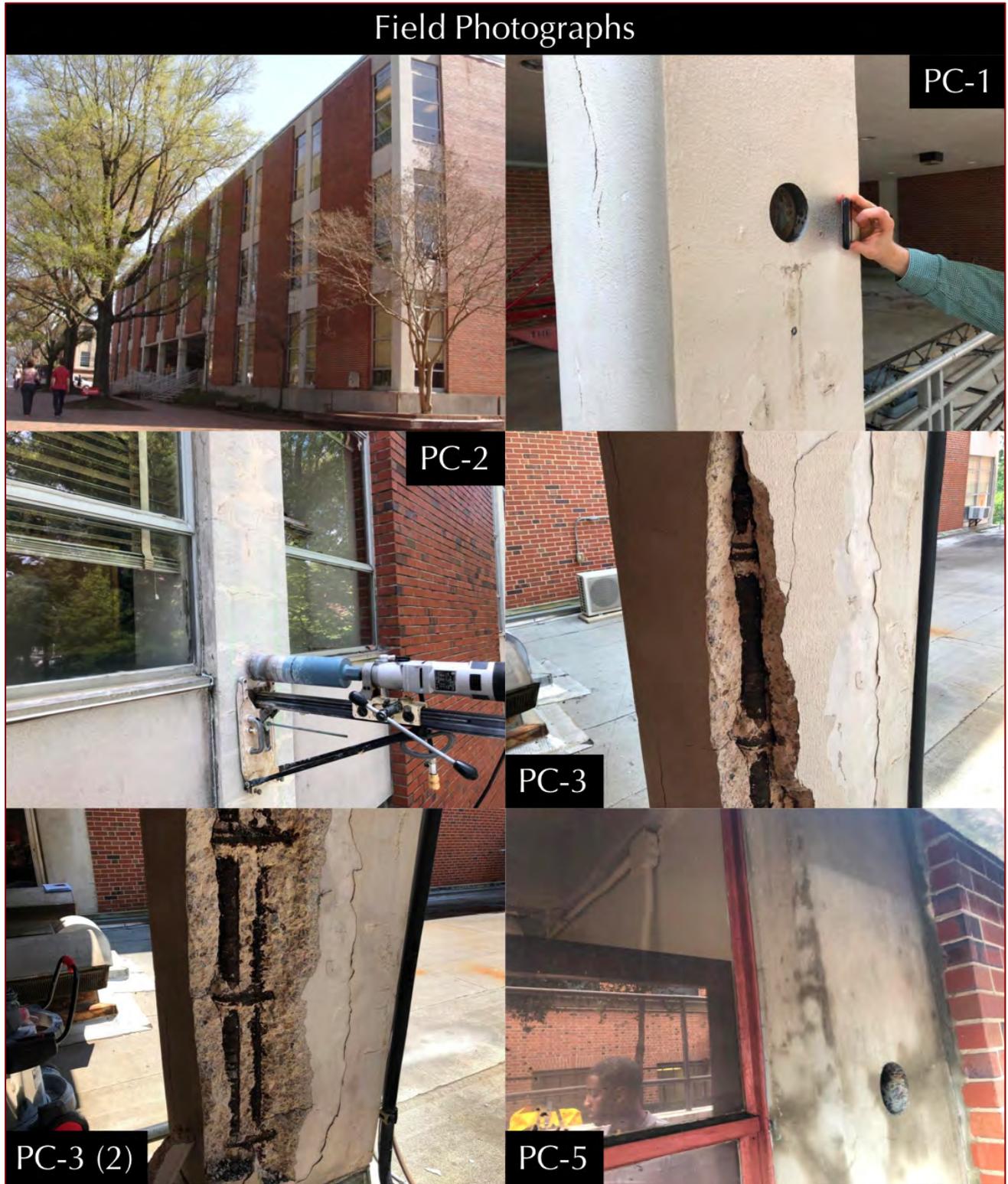


Figure 2: Field photos showing the locations at which core samples were taken for the present laboratory investigation.

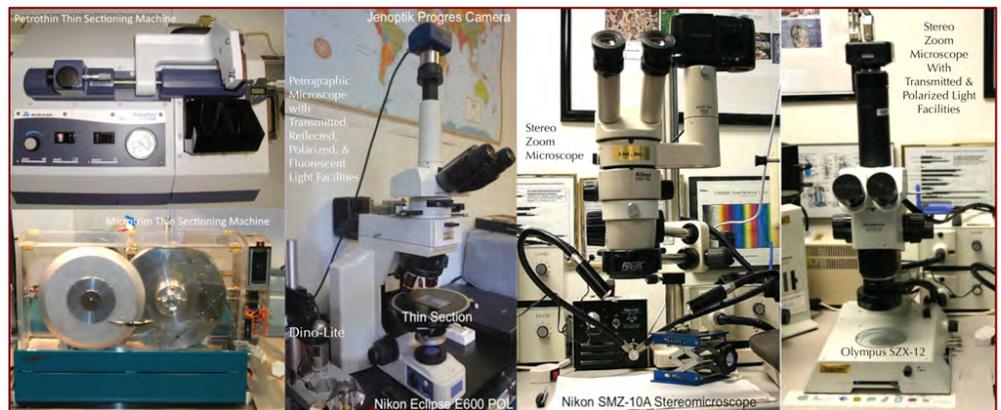
## METHODOLOGIES

### PETROGRAPHIC EXAMINATIONS

The cores were examined by using petrographic examinations by following the methods of ASTM C 856 “Standard Practice for Petrographic Examination of Hardened Concrete.” Details of concrete petrography, and sample preparation techniques for petrographic examination of concrete are provided in Jana (2006). Briefly, the steps followed during petrographic examinations of the samples include:

- i. Visual examinations of cores, as received, including documentation of dimensions, measurements, condition, exposed surface condition, distress (e.g., cracking), physical properties, integrity, etc.;
- ii. Low-power stereomicroscopical examinations of as-received, saw-cut, freshly fractured surfaces, and lapped cross sections of cores for evaluation of texture, air-void system through depth, and composition;

- iii. Examinations of oil immersion mounts in a petrographic microscope for mineralogical compositions of specific areas of interest;



- iv. Examinations of colored dye-mixed (to highlight open spaces, cracks, etc.)

Figure 3: Thin sectioning machines (left column) used for preparation of thin sections, petrographic microscope (2<sup>nd</sup> column from left), Stereozoom microscope (3<sup>rd</sup> from left), and transmitted-light Stereozoom microscope with polarized-light facilities (right) used for petrographic examinations.

low-viscosity epoxy-impregnated large area (50 mm × 75 mm) thin sections of concretes in a petrographic microscope for detailed compositional and microstructural analyses;

- v. Photographing samples, as received and at various stages of preparation with a digital camera and a flatbed scanner. Photomicrographs of lapped sections and thin sections of samples taken from stereomicroscope and petrographic microscope, respectively to provide detailed compositional and mineralogical information of concretes;
- vi. A Jenoptik Progres GRYPHAX camera attached to a Nikon Eclipse 600 POL petrographic microscope (equipped with reflected, transmitted, polarized and fluorescent-light facilities), a Jenoptik Progres C14 camera attached to an Olympus SZH reflected and transmitted-light stereomicroscope, and an OMAX digital camera attached to a Nikon SMZ-10A low-power stereomicroscope were used together for detailed optical microscopical examinations and associated digital photomicrography.

SEM-EDS



Figure 4: CamScan Series 2 scanning electron microscope used for examination of samples.

Thin section examination was further carried out in a CamScan Series 2 scanning electron microscope (Figure 4) equipped with a high-resolution column 40Å tungsten, 40 kV electron optics zoom condenser 75° focusing lens operating at 20 kV, equipped with a variable geometry secondary electron detector, backscatter electron detector, EDS detector for observations of microstructures at high-resolution, compositional analysis, and quantitative determinations of major element oxides from various areas of interest, respectively. Revolution 4Pi software is used for digital storage of secondary electron and backscatter electron images, elemental mapping, and analysis along a line, a point or an area of interest. A 50 mm × 75 mm thin section of Core PC-1 was polished with gold-palladium coat and used with a custom-made aluminum sample holder in the large multiported chamber with the eucentric 50 × 100 mm motorized stage.

## CHEMICAL PROFILES OF CHLORIDE, SULFATE, AND OTHER WATER-SOLUBLE ANIONS

Representative sections of all four cores tested were obtained from the top, mid-depth, and bottom locations. Sections were pulverized down to finer than 0.3 mm size. Approximately 10 grams of pulverized sample from each section of each core was thoroughly digested in 50 ml deionized water first in near-boiling temperature for 15 minutes with magnetic stirrer, followed by further room-temperature digestion for 24 hours. The digested sample solution was then filtered under vacuum, first through two 2.5-micron filter papers, followed by another filtration through two 0.2-micron filter papers to collect the filtrate. The filtrate thus obtained was diluted to a final volume of 200 ml in a volumetric flask.

Aliquots of filtrates thus prepared were used for:

(a) Potentiometric titration with a silver nitrate titrant *a la* ASTM C 1218 by using Metrohm 751 DMS Titrino with attached 730 Auto Sample Processor to determine the chloride contents,

(b) Anion chromatography, *a la* ASTM D 4327 for water-soluble fluoride, chloride, nitrate, nitrite, bromide, phosphate, and sulfate ions by using Metrohm 881 Compact IC Professional with attached 858 Professional Sample Processor with a sodium carbonate-bicarbonate eluent. All instruments were calibrated with standard solutions of ions of interests, and

(c) X-ray fluorescence of filtrates in Rigaku NEX-CG XRF for water-soluble chloride and sulfate contents.

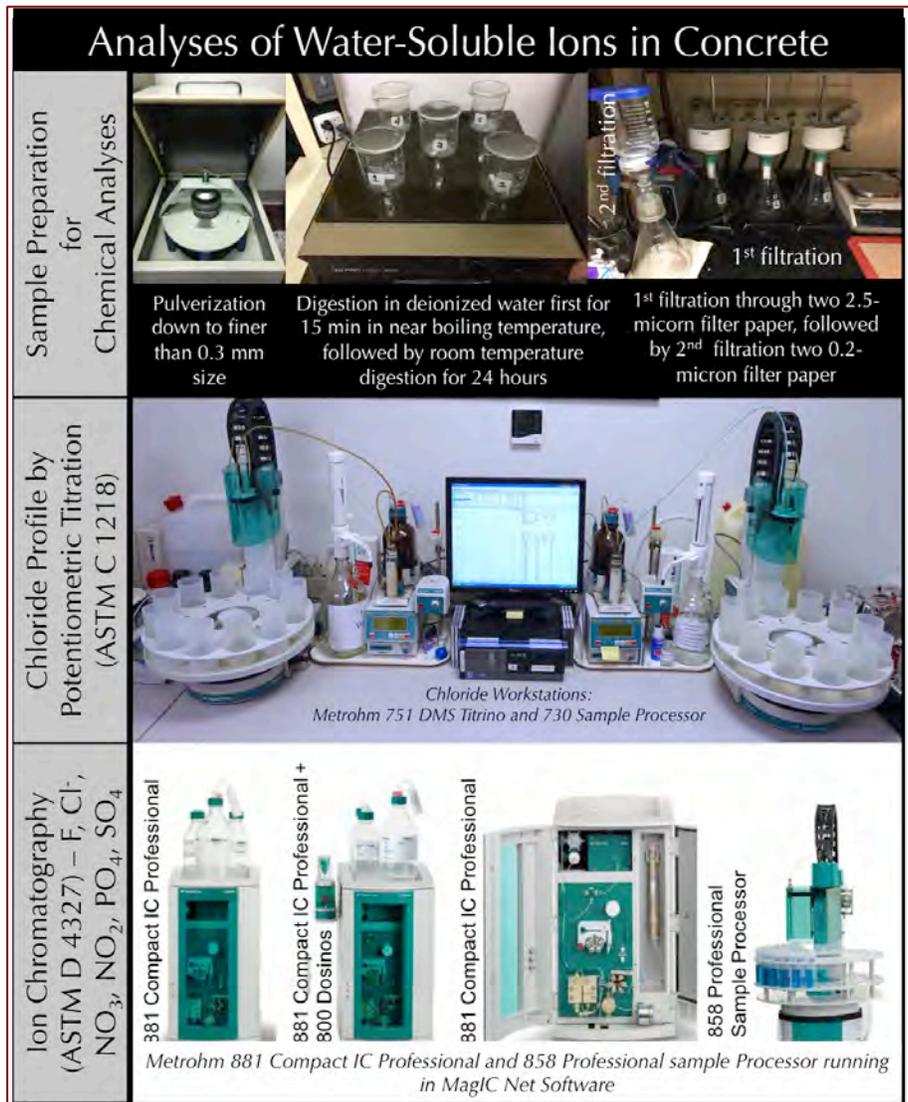


Figure 5: Sample preparation and analyses of water-soluble ions of concrete in potentiometric titration and ion chromatography.

## FT-IR OF PAINT

Fourier-transform infrared spectroscopy (FT-IR) measures interaction between applied infrared radiation and the molecules in the compounds of interest. Bonds between atoms have distinctive geometries and natural states of rotation and vibration. Incident infrared radiation will excite these vibrations and rotations when a critical wavelength is reached that can impart energy to the bond. At this point the atomic bond that is being excited will absorb that wavelength of infrared radiation. If the sample is placed between the source of radiation and a detector these times of absorption of infrared radiation can be recorded as reduced intensity and can be related to specific types of atomic bonds characteristic of particular functional groups in compounds (e.g.,  $\text{CO}_3^{2-}$  group in carbonates). FT-IR is particularly useful for detection of admixture, additives, and polymer resins. FT-IR is used mainly to identify various organic components (functional groups) in mortar (e.g., methyl  $\text{CH}_3$ , organic acids  $\text{CO-OH}$ , carbonates  $\text{CO}_3$ ) from their characteristic spectral fingerprints in FT-IR spectrum. FT-IR can also be used for detection of main mineral phases in a hydraulic binder, CSH, carbonates, gypsum, and clays (Middendorf et al. 2005). Organic compounds such as synthetic (e.g., acrylics, polyesters) and natural resins, carbohydrates, colorants, oils and fats, proteins, waxes as well as inorganic compounds, e.g., corrosion products, minerals, pigments, paints, fillers, stone, glass, and ceramics can be detected by this technique.



Figure 6: Perkin Elmer Spectrum 100 FT-IR unit in CMC with Universal ATR and Liquid Sipper attachments. The FT-IR unit can analyze a sample as-received in the Universal ATR (left), or as a pressed pellet after mixing with KBr powder in a KBr press (middle), or as a liquid either in Universal ATR or in Liquid Sipper unit (right).

FT-IR measurements are done in a Perkin Elmer Spectrum 100 FT-IR spectrophotometer (Figure 9) running with Spectrum 10 software. Sample was measured using attenuated total reflection (ATR) on a single bounce diamond/ZnSe ATR crystal. Sample was measured between a frequency range of  $4000$  to  $650\text{ cm}^{-1}$ . Each run was collected at  $4\text{ cm}^{-1}$  resolution with Strong Beer-Norton apodization. Data were collected with a temperature-stabilized deuterated triglycine sulfate (DTGS) detector by placing the sample in contact with the ATR crystal and by applying force from the pressure applicator supplied with the ATR accessory. The application of pressure enabled the sample to be in intimate contact with the ATR crystal, ensuring a high-quality spectrum was achieved. Additionally, more conventional KBr pellet is also used for samples on as-needed basis.



## SAMPLES

### PHOTOGRAPHS, IDENTIFICATIONS, INTEGRITY, AND DIMENSIONS

Figures 7 through 10 show the four 4-in. (100 mm) diameter cores as received from the columns, e.g., PC-1 from Level 2, Column Line E/8, PC-3 from Level 2, Column Line E/5, PC-4 from Level 3, Column Line A/7, and PC-5 from Level 1, Column Line K/4.

### THREE COMPONENT SYSTEM - PROTECTIVE PAINT, OVERLAY, AND CONCRETE

The cores show the presence of a repair overlay, which was applied over deteriorated columns and were further protected by protective paints.

The repair overlay applied over deteriorated concrete is found in all four cores that has varied in thicknesses from:

- a. A uniform 1<sup>1</sup>/<sub>4</sub> in. (35 mm) thickness and completely debonded from concrete in Core PC-1; concrete has a nominal recovery length of 6 in. (150 mm);
- b. A tapered 1/8 in. (4 mm) to maximum 2 in. (50 mm) thickness and separated from concrete by a diagonal crack in Core PC-3; concrete has a nominal recovery length of 5<sup>1</sup>/<sub>2</sub> in. (140 mm) to maximum 7 in. (180 mm);
- c. A uniform 2 in. (50 mm) thickness and completely debonded from concrete in Core PC-4; concrete has a nominal recovery length of 5 in. (120 mm), and
- d. A thin (1/8 in., 4 mm) dark gray repair coat well-bonded to concretes from beam and column in Core PC-5; concretes contain portions of beam concrete, which is a lightweight concrete and column concrete, which is a normal-weight concrete of maximum recovered length of 6 in. (150 mm).
- e. In all four cores examined, overlays are dense dark gray repair mortars (lack coarse aggregate) applied over light grey to beige column concretes (that contain crushed stone coarse aggregates for column and lightweight aggregate for portion of beam concrete in Core PC-5).

The overlay is further protected by exterior protective coats in Cores PC-1, 3, and 4, which are:

- a. An exposed shiny cream-colored paint coat in Core PC-1, which is determined by FT-IR to be a PVC-based paint, approximately 0.25 mm in thickness, applied over an interior cementitious coat of another 0.25 mm thickness the latter was applied directly over the overlay;
- b. An exposed polymer and perlite based exterior coat of approx. 0.3 mm thickness in Core PC-3, which was applied over a thin calcitic coat of 0.1 mm thickness, which, in turn, was applied over a cementitious coat of approx. 0.2 mm thickness, the latter was applied and well-bonded to the repair overlay;



- c. A textured matte-finished cream coat in Core PC-4 of approx. 0.1 to 0.4 mm variable thicknesses applied over a relatively uniform 0.3 mm thick cementitious coat, the latter was applied directly and well-bonded to the concrete.
- d. Protective coats over overlays in all three cores have denser interior cementitious coats applied over the overlay compared to relatively porous outer coats, including the exterior polymer ones.

## END SURFACES

End surfaces in the cores are

- a. An exposed shiny cream-colored paint coat in Core PC- 1 on the exposed face and a freshly fractured surface of column concrete on the opposite end (Figure 7);
- b. An exposed polymer and perlite based exterior coat in Core PC-3 on the exposed face that has a visible crack and a freshly fractured surface of column concrete on the opposite end (Figure 8);
- c. A textured matte-finished cream coat in Core PC-4 on the exposed face and a freshly fractured surface of column concrete on the opposite end (Figure 9);.
- d. A thin gray finished repair coat layer in Core PC-5 on the exposed face and a freshly fractured surface of column concrete with an exposed ribbed rebar on the opposite end (Figure 10).

## CRACKING & OTHER VISIBLE DISTRESS, IF ANY

- a. In Core PC-1 overlay is completely de-bonded from concrete but neither component shows any visible crack (Figure 7). Remains of concrete is seen at the underside of de-bonded overlay, however most of the overlay underside is debonded without remains of concrete (Figure 7, middle row).
- b. In Core PC-3 overlay is separated from concrete by visible intersecting diagonal cracks (Figure 8) extended to a depth of 2 in. (50 mm). Concrete beneath overlay also shows visible cracking (Figure 8 bottom row).
- c. In Core PC-4 overlay is completely de-bonded from concrete but neither component shows any visible crack (Figure 9). No remains of concrete is seen at the underside of de-bonded overlay, overlay shows clean separation from concrete without any remains of concrete (Figure 9, middle row).
- d. In Core PC-5, a cold joint is present between lightweight aggregate beam concrete and normal-weight aggregate column concrete, which is extended through the entire length of the core (Figure 10).

## EMBEDDED ITEMS

A No. 3 rebar is present at a depth of 5 in. in Core PC-4 that shows surface corrosion (Figure 9 bottom photo). Core PC-5 also contain No. 3 rebar at depths of 2<sup>3</sup>/<sub>4</sub> in. and 5<sup>1</sup>/<sub>2</sub> in. that also show surface corrosion (Figure 10). Bottom fresh fractured surface of concrete in PC-5 shows an exposed No. 3 rebar (Figure 10, right photo) and impression of another No. 3 rebar (Figure 10 right photo).



Figure 7: Core PC-1, as received, showing: (a) shiny beige paint on the exposed surface (top left), (b) a fresh fractured interior concrete surface (top right), (c) completely debonded overlay-concrete interface where only a few remains of concrete are seen at the underside of overlay (middle), and (d) side cylindrical view showing the overly completely debonded from the concrete, and sound, crack free nature of overlay and interior concrete (bottom).



Figure 8: Core PC-3, as received, showing: (a) top gray paint coat on the exposed surface with a visible crack (top left), (b) fresh fractured interior concrete surface (top right), and (c) side cylindrical view showing portion of gray overly separated from concrete by a visible diagonal crack, and two major intersecting-diagonal cracks, which extend to 2 in. from the exposed surface (bottom).



Figure 9: Core PC-4, as received, showing: (a) textured matte-finished cream paint coat on the exposed surface (top left), (b) fresh fractured interior concrete surface (top right), (c) completely debonded overlay-concrete interface where overlay shows clean separation from concrete without any traces of concrete on the underside of overlay (middle), and (d) side cylindrical view showing the overlay completely debonded from the concrete, the sound, crack free nature of overlay and interior concrete, and a No. 3 reinforcing steel within the concrete at a depth of 5 in. from the top surface (circled), which shows severe surface corrosion (bottom, circled).



Figure 10: Core PC-5, as received, showing: (a) a thin top gray repair coat well-bonded to two concretes separated by a cold joint – a lightweight aggregate concrete that represents portion of the beam concrete and a normal-weight concrete from the underlying column (bottom), (b) fresh fractured interior surface of both concretes with an exposed No. 3 reinforcing steel and impression of another No. 3 reinforcing steel (top right), and (c) side cylindrical view showing full-depth extension of cold joint, and No. 3 reinforcing steels at depths of  $2\frac{3}{4}$  in. and  $5\frac{1}{2}$  in. at the bottom (circled).

**PETROGRAPHIC EXAMINATIONS**

TESTING STRATEGIES ON MULTIPLE SAW-CUT CROSS SECTIONS

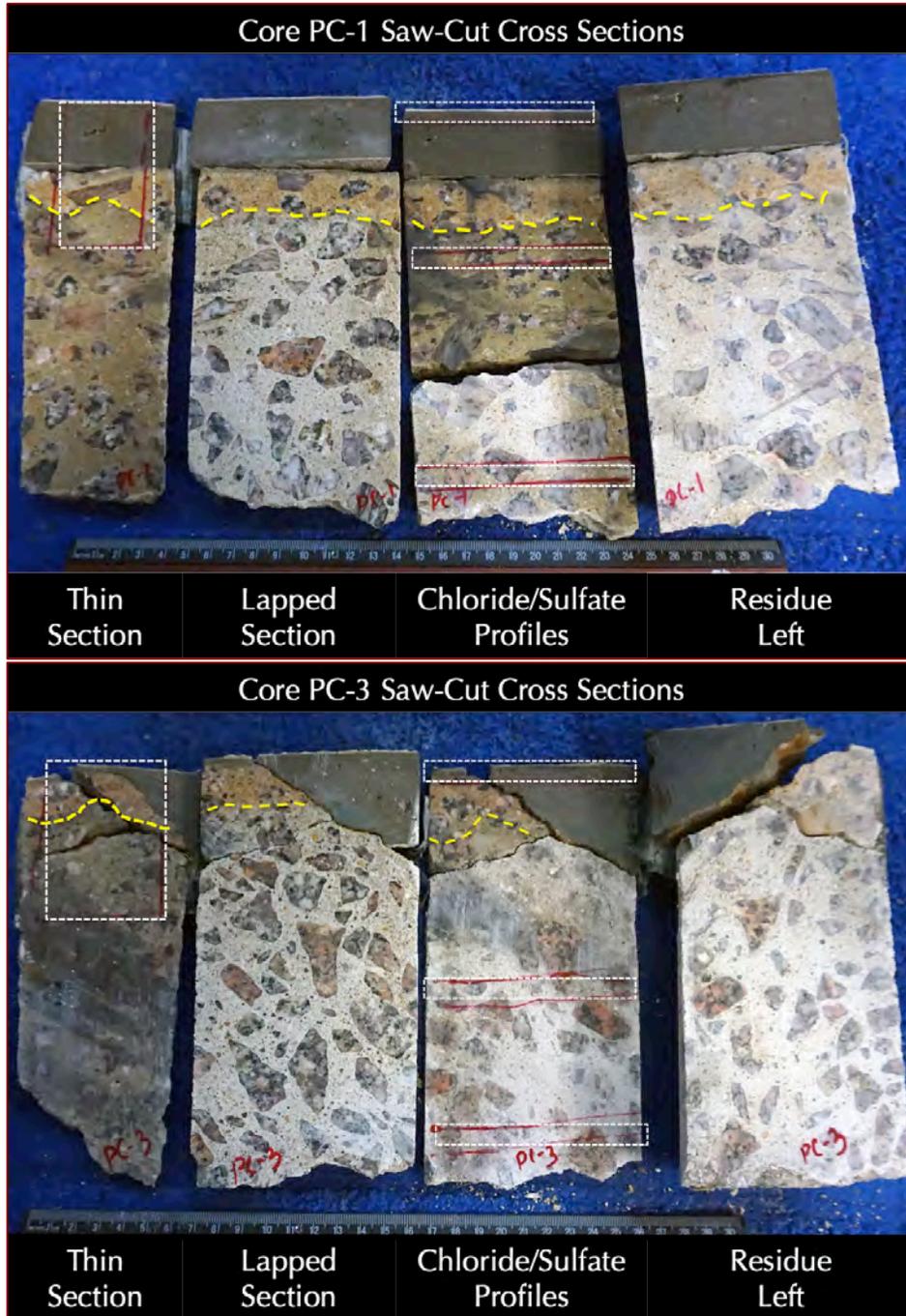


Figure 11: Saw-cut cross sections of Core PC-1 (top) and PC-3 (bottom) showing dark gray repair mortar overlay across all sections and different testing strategies employed on different sections, e.g., (a) thin section from the leftmost section showing the portion trimmed for thin sectioning in dashed rectangular box, (b) lapped section on 2<sup>nd</sup> section from left, (c) three sectioned profiles from dashed rectangular boxes on the 3<sup>rd</sup> section from left for chloride, sulfate and other water-soluble anions, and (d) keeping the rightmost section as reserve. Yellow dashed lines show depths of carbonation in column concrete prior to the installation of overlay.

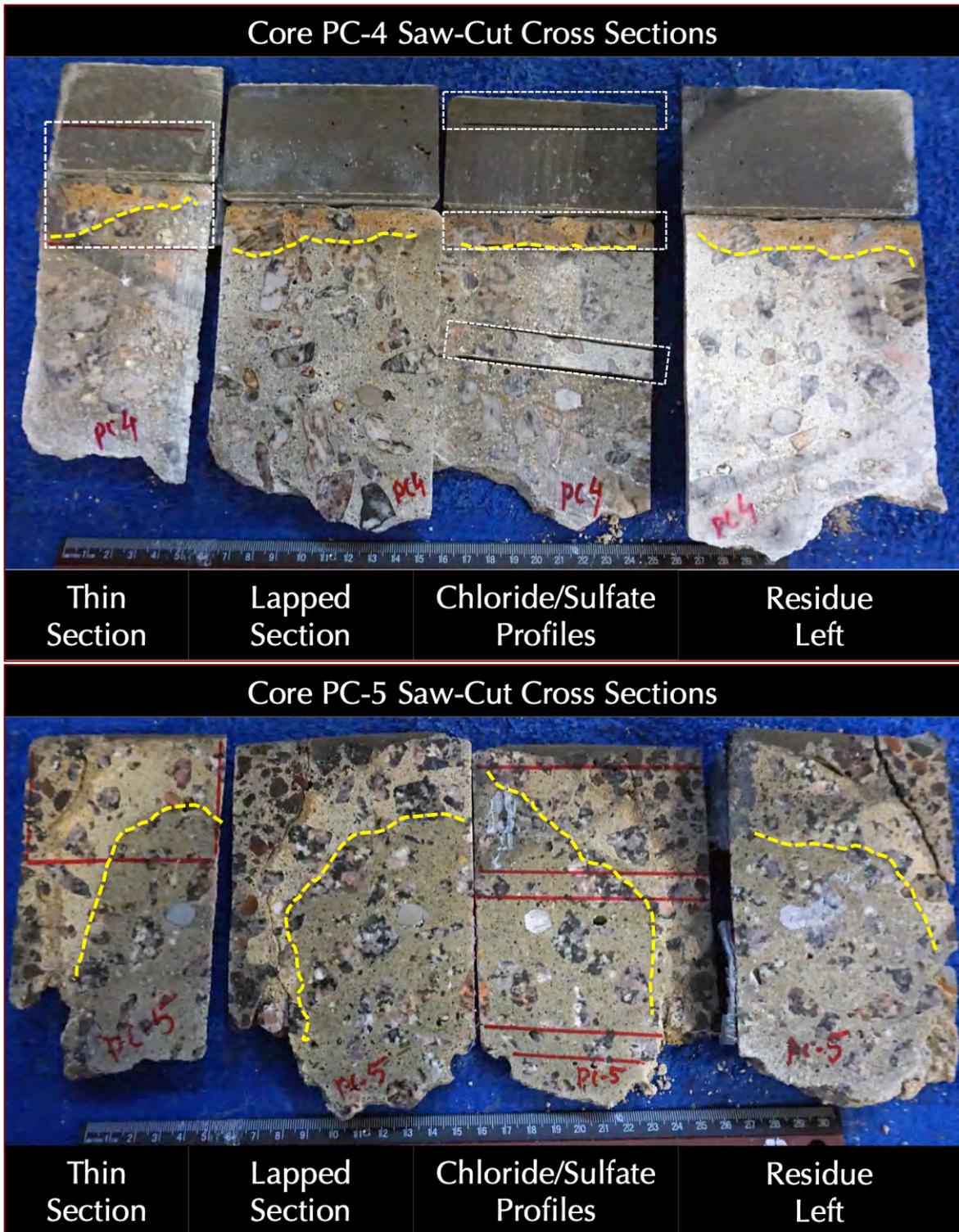


Figure 12: Saw-cut cross sections of Core PC-4 (top) and PC-5 (bottom) showing dark gray repair mortar overlay across all sections and different testing strategies employed on different sections, e.g., (a) thin section from the leftmost section showing the portion trimmed for thin sectioning in dashed rectangular box, (b) lapped section on 2<sup>nd</sup> section from left, (c) three sectioned profiles from dashed rectangular boxes on the 3<sup>rd</sup> section from left for chloride, sulfate and other water-soluble anions, and (d) keeping the rightmost section as reserve. Yellow dashed lines show depths of carbonation in column concrete (for PC-5 in the beam concrete as well) prior to the installation of overlay.

LAPPED CROSS SECTIONS



Figure 13: Lapped cross section of Core PC-1 showing a thin white protective coating at the top applied over a dark gray repair mortar overlay of 1 1/4 in. (35 mm) thickness. The overlay is completely debonded from the column concrete. Column concrete shows crushed granite coarse aggregate particles that are dense, angular, nominal 3/4 in. (19 mm) in size, well-graded, well-distributed, and present in sound condition. Accompanying lapped cross section at right shows depth of carbonation of column concrete prior to the application of overlay as beige discolored concrete at the top for the carbonated zone, extended to a depth of 1 in. (25 mm). Yellow dashed lines show depths of carbonation in both cross sections.

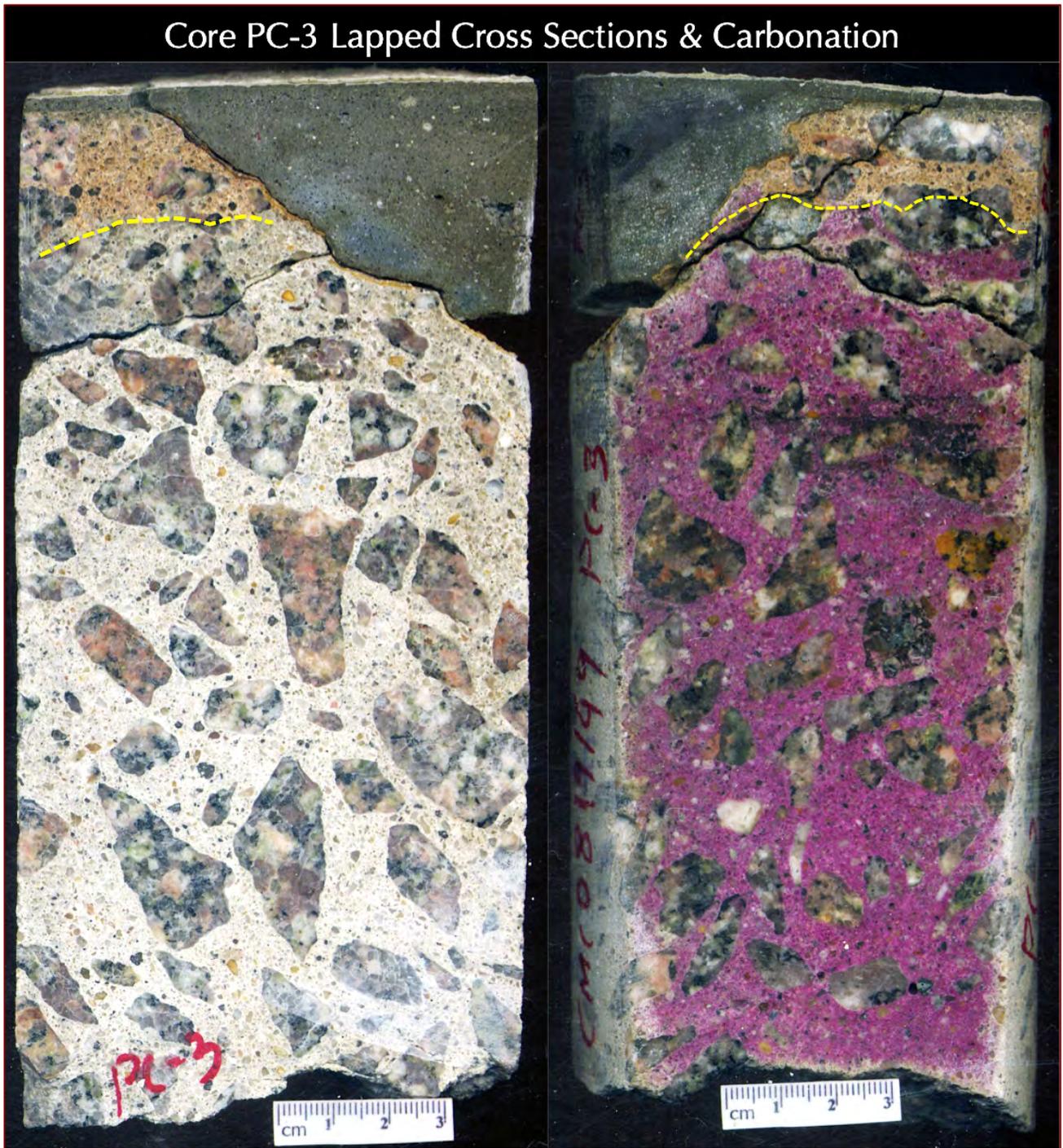


Figure 14: Lapped cross section of Core PC-3 showing a thin white protective coating at the top applied over a dark gray repair mortar overlay which is tapered down from minimum  $\frac{1}{8}$  in. (4 mm) to maximum 2 in. (50 mm). The overlay is detached from the column concrete by a visible diagonal crack. Two diagonal cracks are seen within top 2 in. of core. Column concrete shows crushed granite coarse aggregate particles that are dense, angular, nominal  $\frac{3}{4}$  in. (19 mm) in size, well-graded, well-distributed, and present in sound condition. Accompanying lapped cross section at right shows depth of carbonation of column concrete prior to the application of overlay as beige discolored concrete at the top for the carbonated zone, extended to a depth of  $\frac{3}{4}$  in. (19 mm) to 1 in. (25 mm). Yellow dashed lines show depths of carbonation in both cross sections.

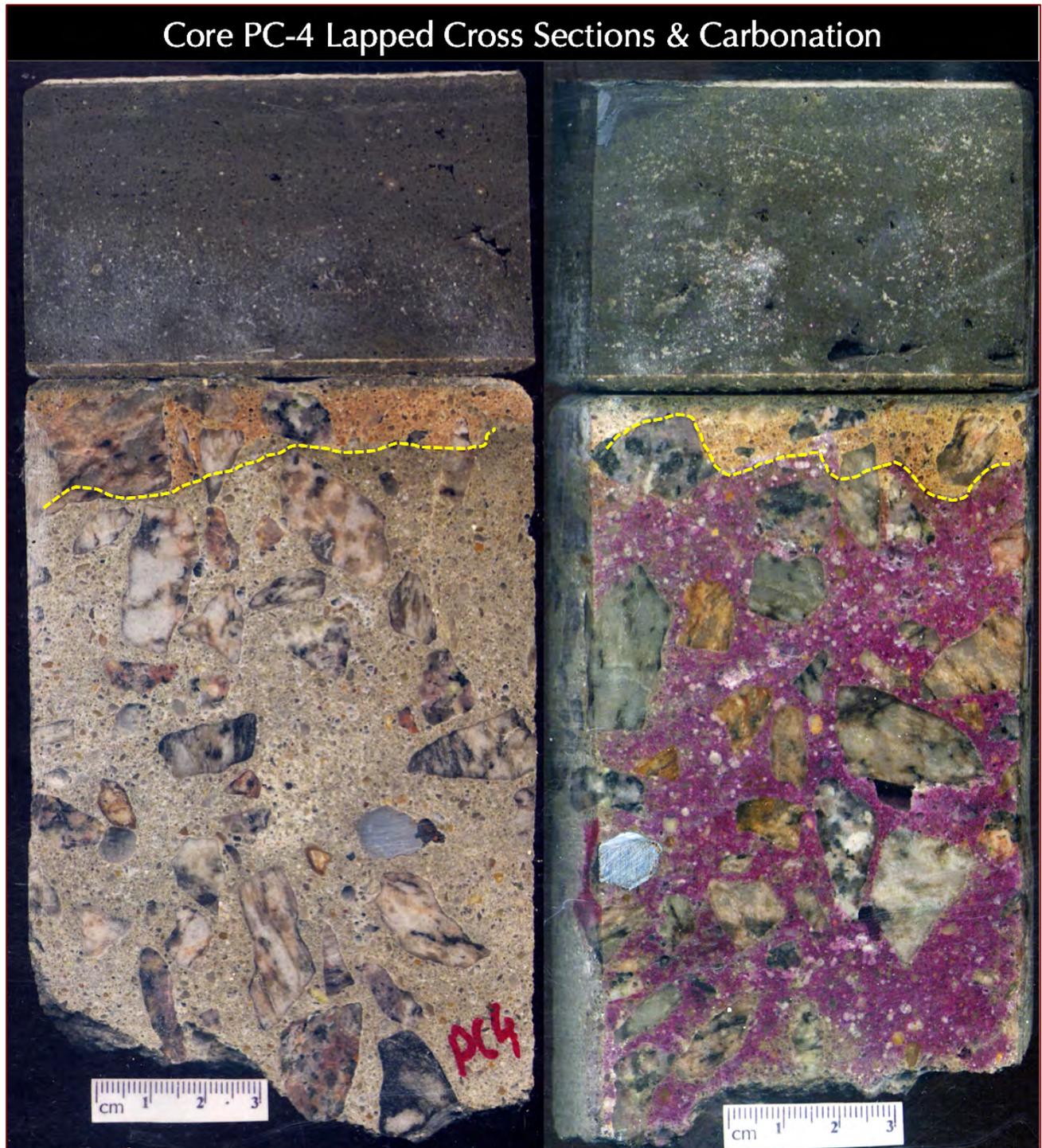


Figure 15: Lapped cross section of Core PC-4 showing a thin white protective coating at the top applied over a dark gray repair mortar overlay of 2 in. (50 mm) thickness. The overlay is completely debonded from the column concrete. Column concrete shows crushed granite coarse aggregate particles that are dense, angular, nominal  $\frac{3}{4}$  in. (19 mm) in size, well-graded, well-distributed, and present in sound condition. Accompanying lapped cross section at right shows depth of carbonation of column concrete prior to the application of overlay as beige discolored concrete at the top for the carbonated zone, extended to a depth of  $\frac{1}{2}$  in. (12.5 mm) to  $\frac{3}{4}$  in. (19 mm). Yellow dashed lines show depths of carbonation in both cross sections. Steel rebar within the non-carbonated interior concrete shows no corrosion.

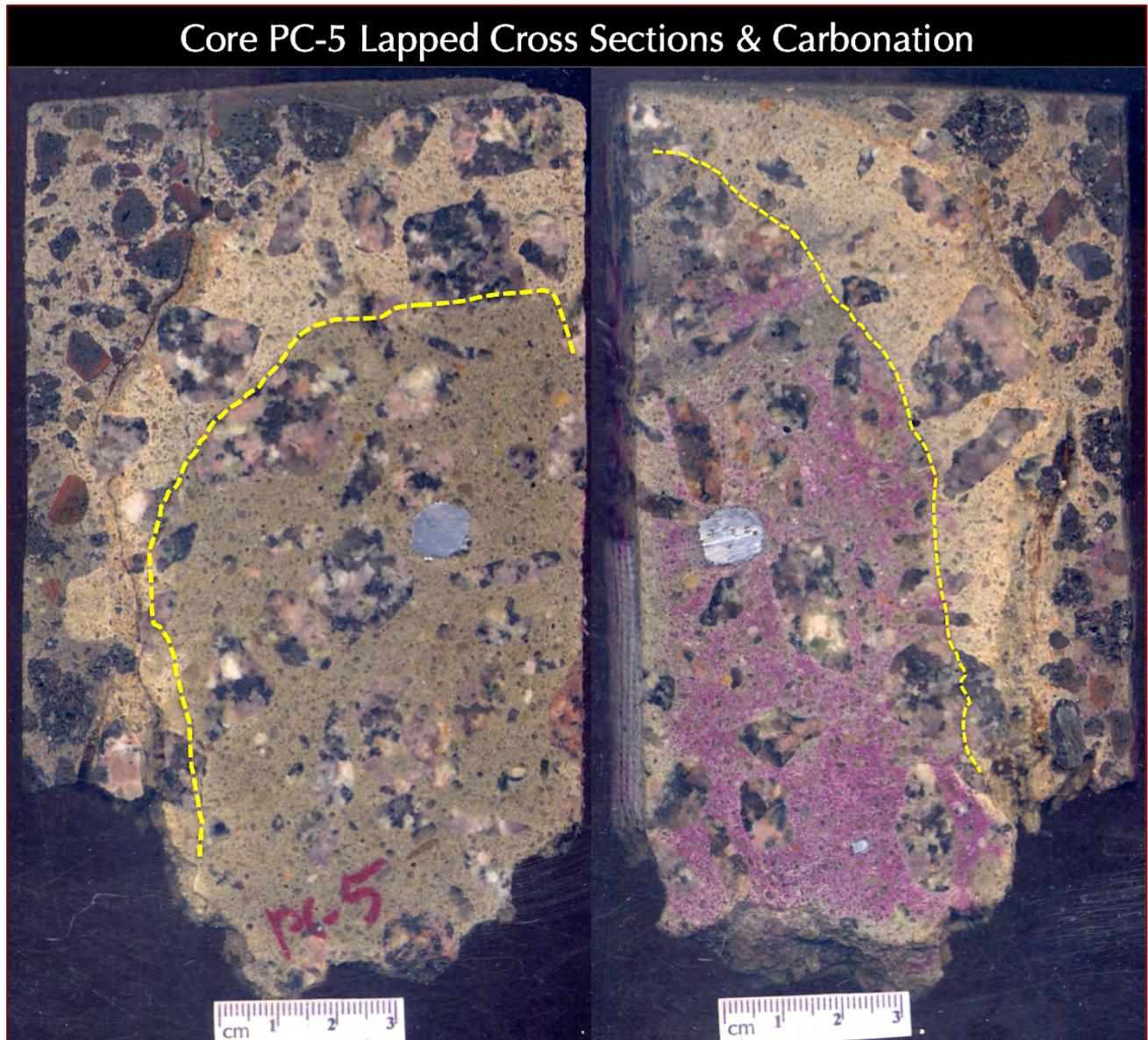


Figure 16: Lapped cross section of Core PC-5 showing a thin dark gray repair mortar overlay of  $\frac{1}{8}$  in. (4 mm) thickness applied over column concrete, where the column concrete is attached by a cold joint to a lightweight aggregate concrete, which is the beam concrete. The overlay is adhered to the column concrete. Column concrete shows crushed granite coarse aggregate particles that are dense, angular, nominal  $\frac{3}{4}$  in. (19 mm) in size, well-graded, well-distributed, and present in sound condition. The lightweight aggregate concrete from the beam contains expanded shale and clay lightweight aggregate particles that are well-graded, and well-distributed. Accompanying lapped cross section at right shows depth of carbonation of beam and column concretes where the yellow dashed lines show depths of carbonation in both cross sections encompassing the entire lightweight aggregate beam concrete and to a depth of  $\frac{1}{2}$  in. (12.5 mm) to 1 in. (25 mm) into the normal-weight column concrete. Steel rebar within the non-carbonated interior concrete shows no corrosion.

In all cross sections from Figures 13 through 16, the second lapped cross sections at right were treated with phenolphthalein alcoholic solutions where carbonated concrete remains beige or grey but non-carbonated interior concrete turns pink. The beige discoloration at the top of concretes in all cores is found to be due to carbonation of column prior to the application of the repair overlay and protective coating systems.

PHOTOMICROGRAPHS OF LAPPED CROSS SECTIONS

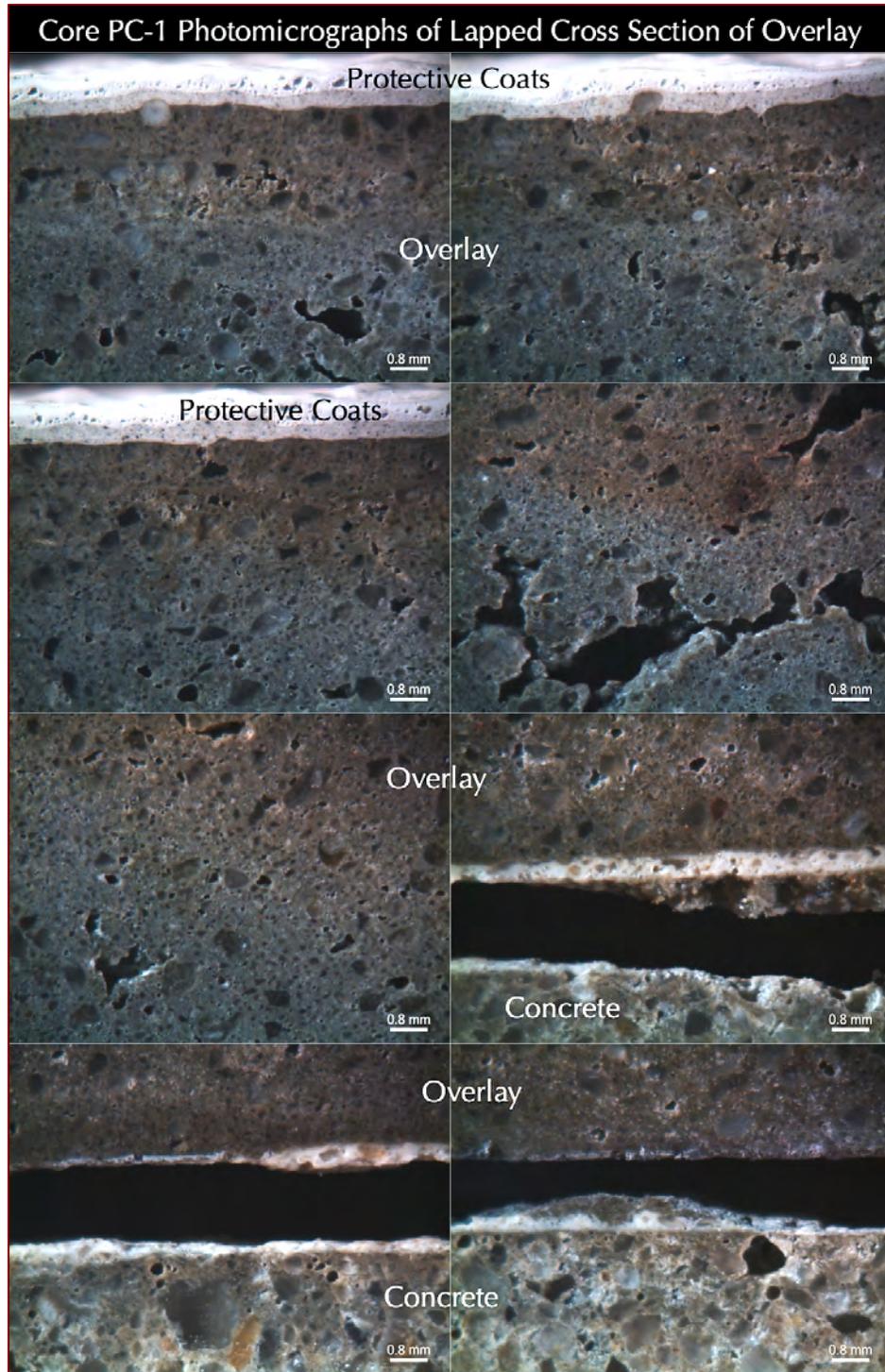


Figure 17: Photomicrographs of lapped cross section of Core PC-1 from the protective coating and repair overlay at the top showing two layers of protective coatings (white and off-white) applied over the dense, dark gray repair overlay where each coat is approx. 0.25 mm in thickness, well-bonded to each other and to the overlay (top row, 2<sup>nd</sup> row left). The gray overlay shows lack of adequate air entrainment but many coarse and irregularly-shaped voids. The base of overlay is completely de-bonded from concrete except only remains of concrete adhered to the underside.

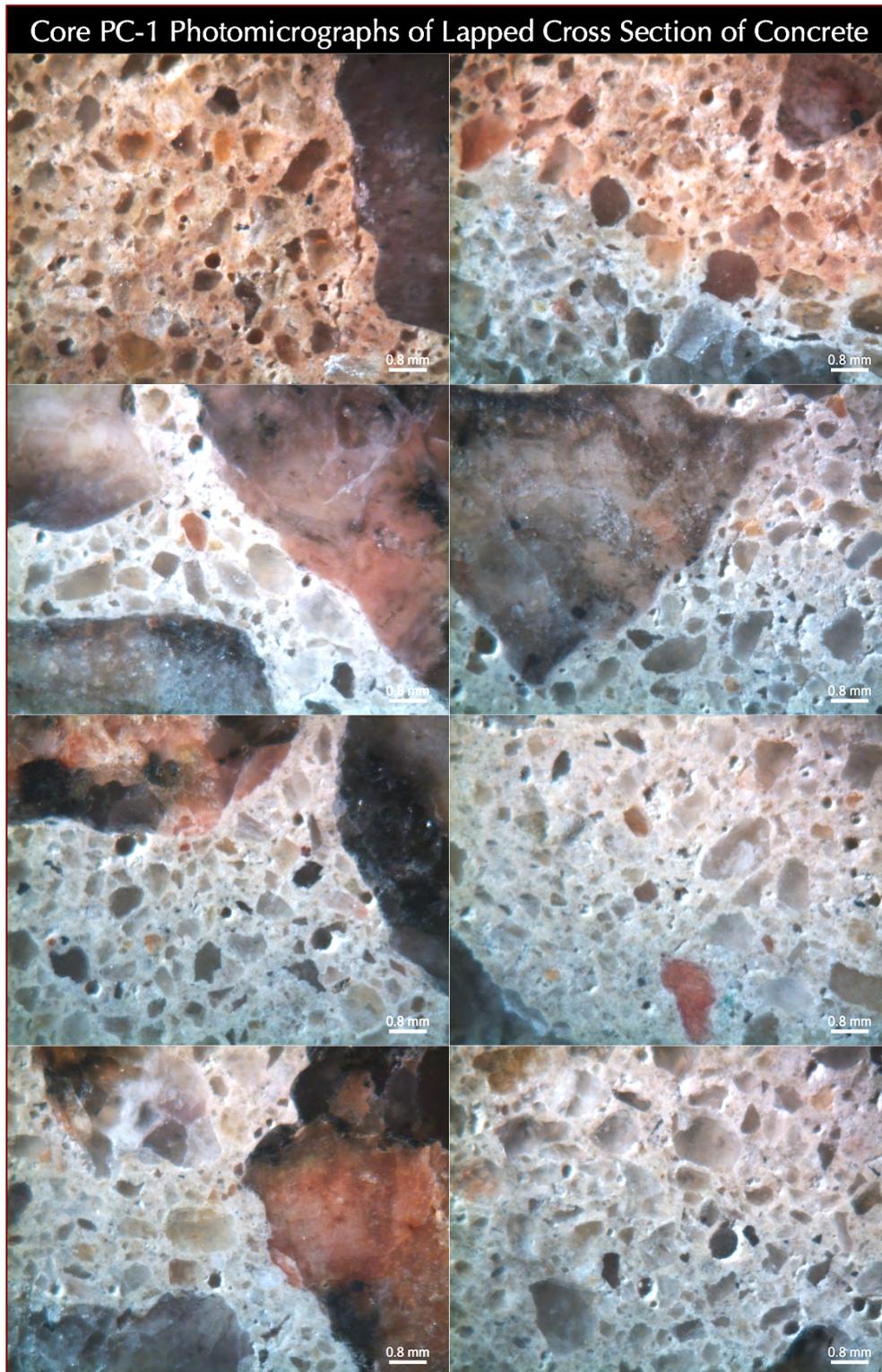


Figure 18: Photomicrographs of lapped cross section of Core PC-1 from the column concrete portion showing beige discoloration of concrete at the top (top row) due to atmospheric carbonation of column prior to the application of repair overlay, non-air-entrained nature of the column concrete having a few coarse and irregular-shaped voids but no intentionally introduced fine, discrete spherical entrained air voids of 1 mm or less size, and overall sound crack-free condition of the column concrete.

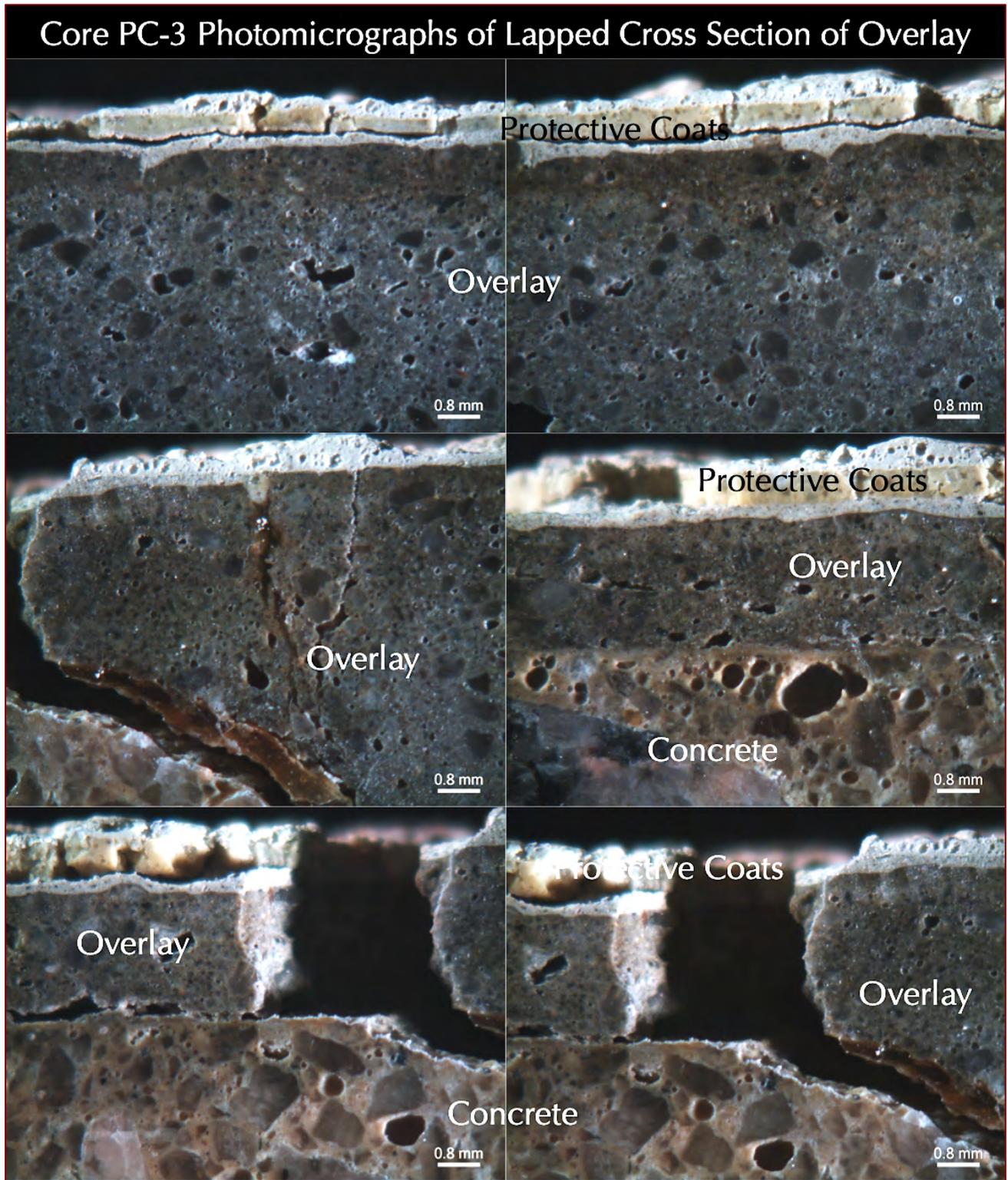


Figure 19: Photomicrographs of lapped cross section of Core PC-3 from the protective coating and repair overlay at the top showing two layers of protective coatings (white and off-white) applied over the dense, dark gray repair overlay where each coat is approx. 0.25 mm in thickness, well-bonded to each other and to the overlay but with a visible horizontal crack within the base coat (top and 2<sup>nd</sup> rows). The gray overlay shows lack of adequate air entrainment but many coarse and irregularly-shaped voids. The base of overlay is completely de-bonded from concrete by a major visible crack (bottom row and left photo in middle row).

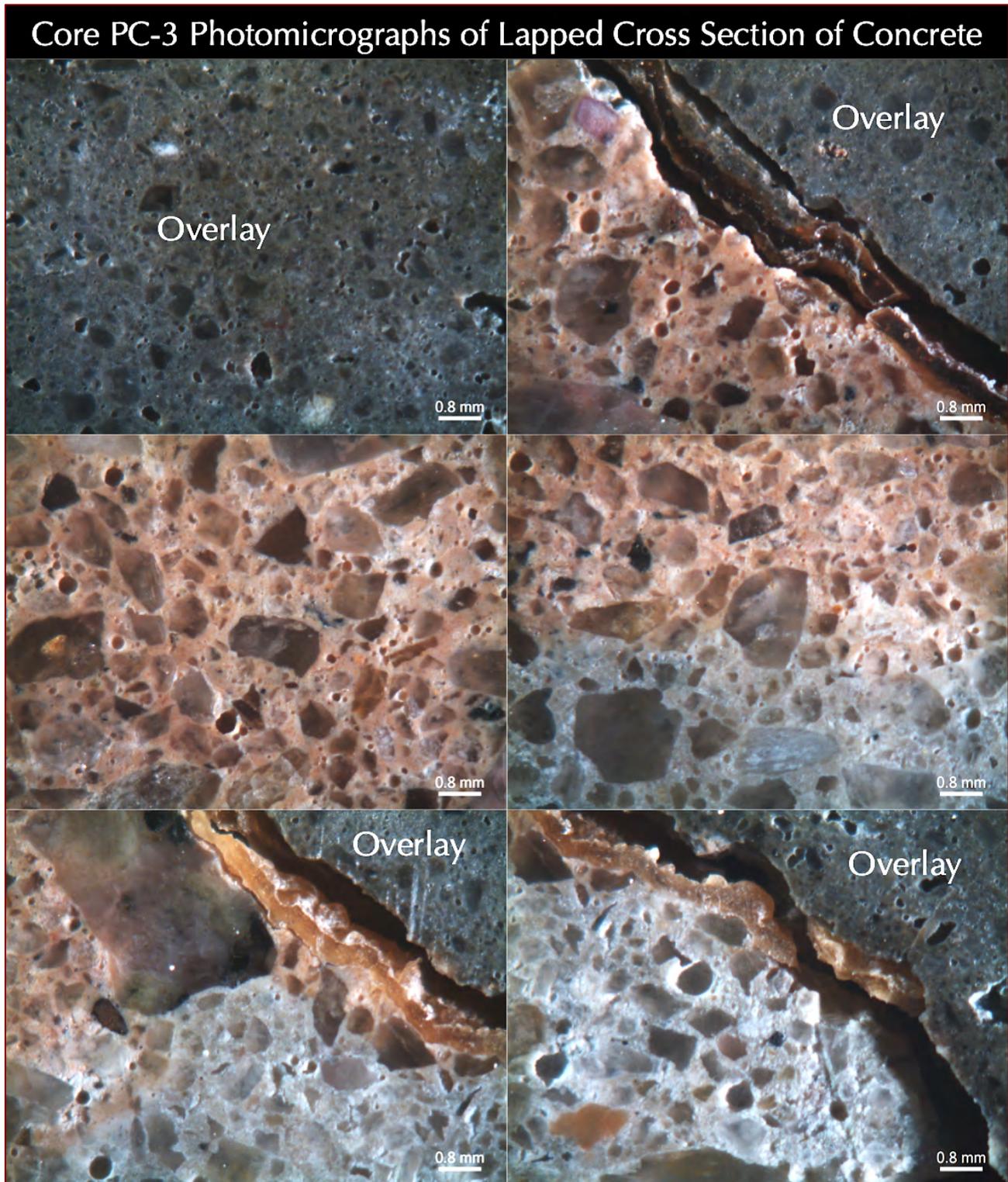


Figure 20: Photomicrographs of lapped cross section of Core PC-3 from the column concrete portion showing beige discoloration of concrete at the top (top row right photo, middle row, and bottom row left photo) due to atmospheric carbonation of column prior to the application of repair overlay, non-air-entrained nature of the column concrete having a few coarse and irregular-shaped voids but no intentionally introduced fine, discrete spherical entrained air voids of 1 mm or less size, and overall sound crack-free condition of the column concrete. An epoxy layer is present between the dark gray repair overlay and column concrete at the diagonal crack (top right and bottom row photos).

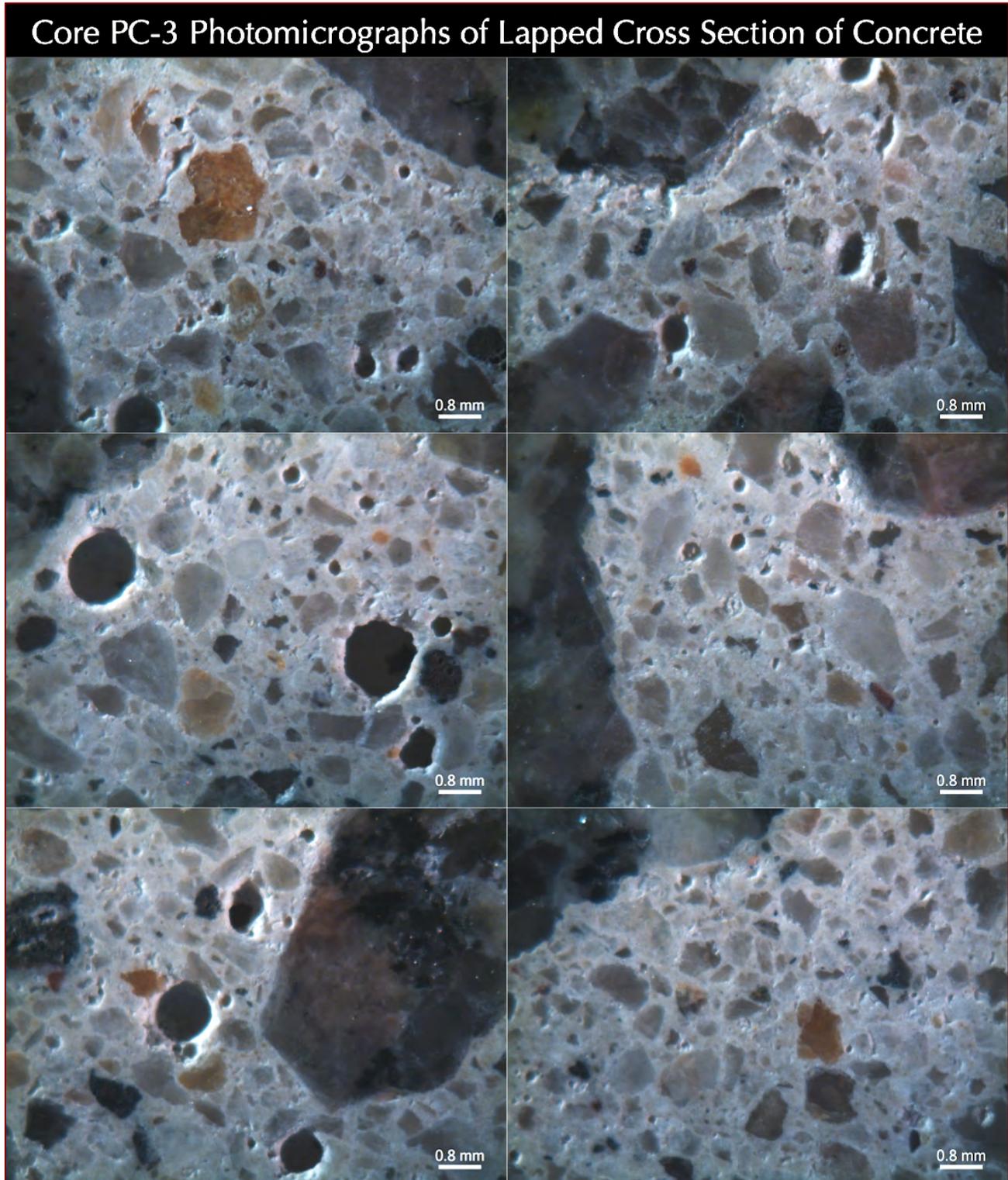


Figure 21: Photomicrographs of lapped cross section of Core PC-3 from the column concrete portion showing non-air-entrained nature of the column concrete having a few coarse and irregular-shaped voids but no intentionally introduced fine, discrete spherical entrained air voids of 1 mm or less size, and overall sound crack-free condition of the column concrete.

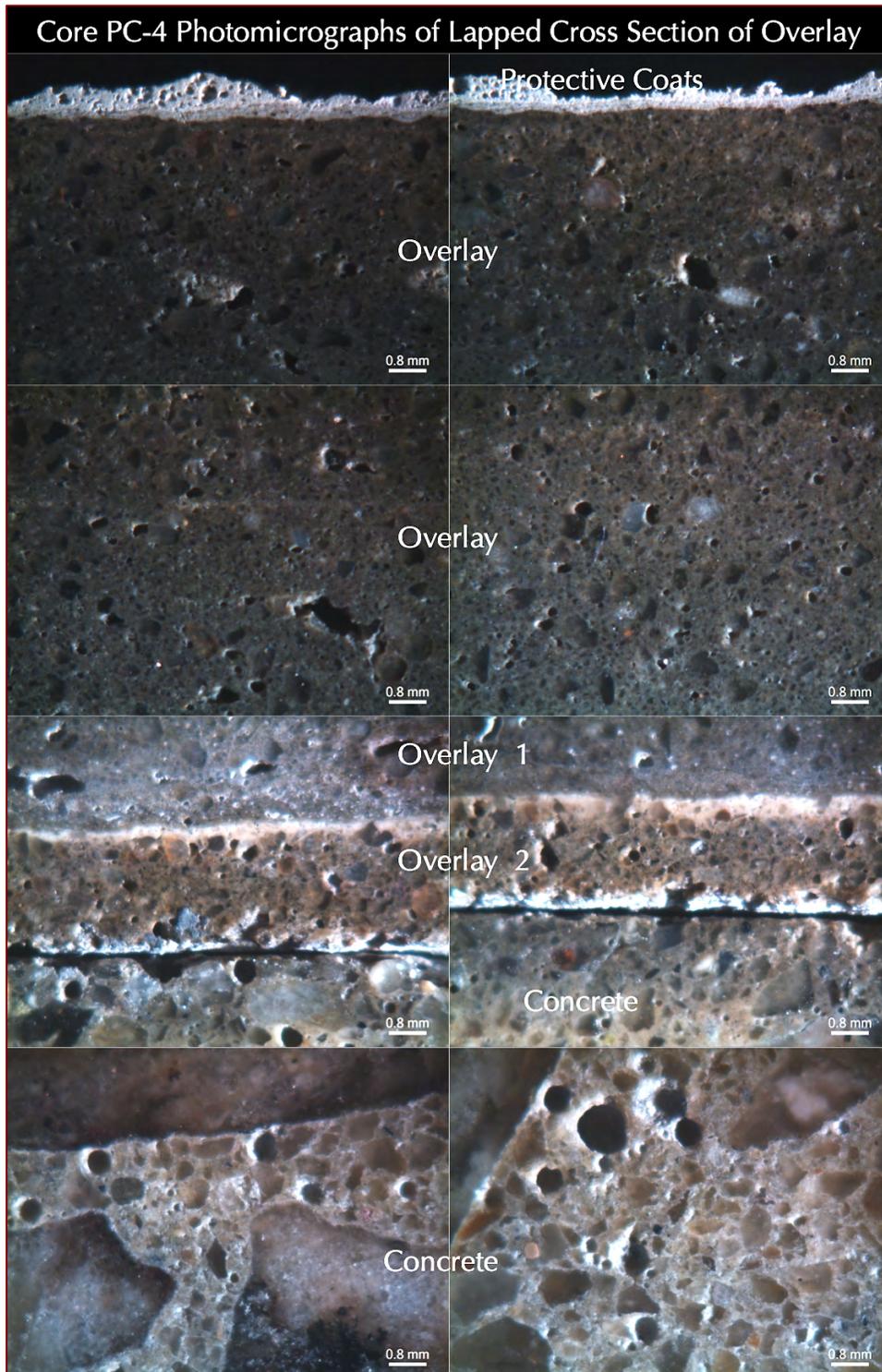


Figure 22: Photomicrographs of lapped cross section of Core PC-4 from the protective coating and repair overlay at the top showing two layers of protective coatings (white and off-white) applied over the dense, dark gray repair overlay where each coat is approx. 0.25 mm in thickness, well-bonded to each other and to the overlay (top row, 2<sup>nd</sup> row left). The gray overlay shows lack of adequate air entrainment but many coarse and irregularly-shaped voids. The base of overlay is completely de-bonded from concrete and shows the presence of a separate thin repair coat of 2 to 3 mm thickness at the base of the main overlay of 2 in. (50 mm). The main overlay is well-bonded to the thin coat at the base but the latter shows clean debonding from the concrete.

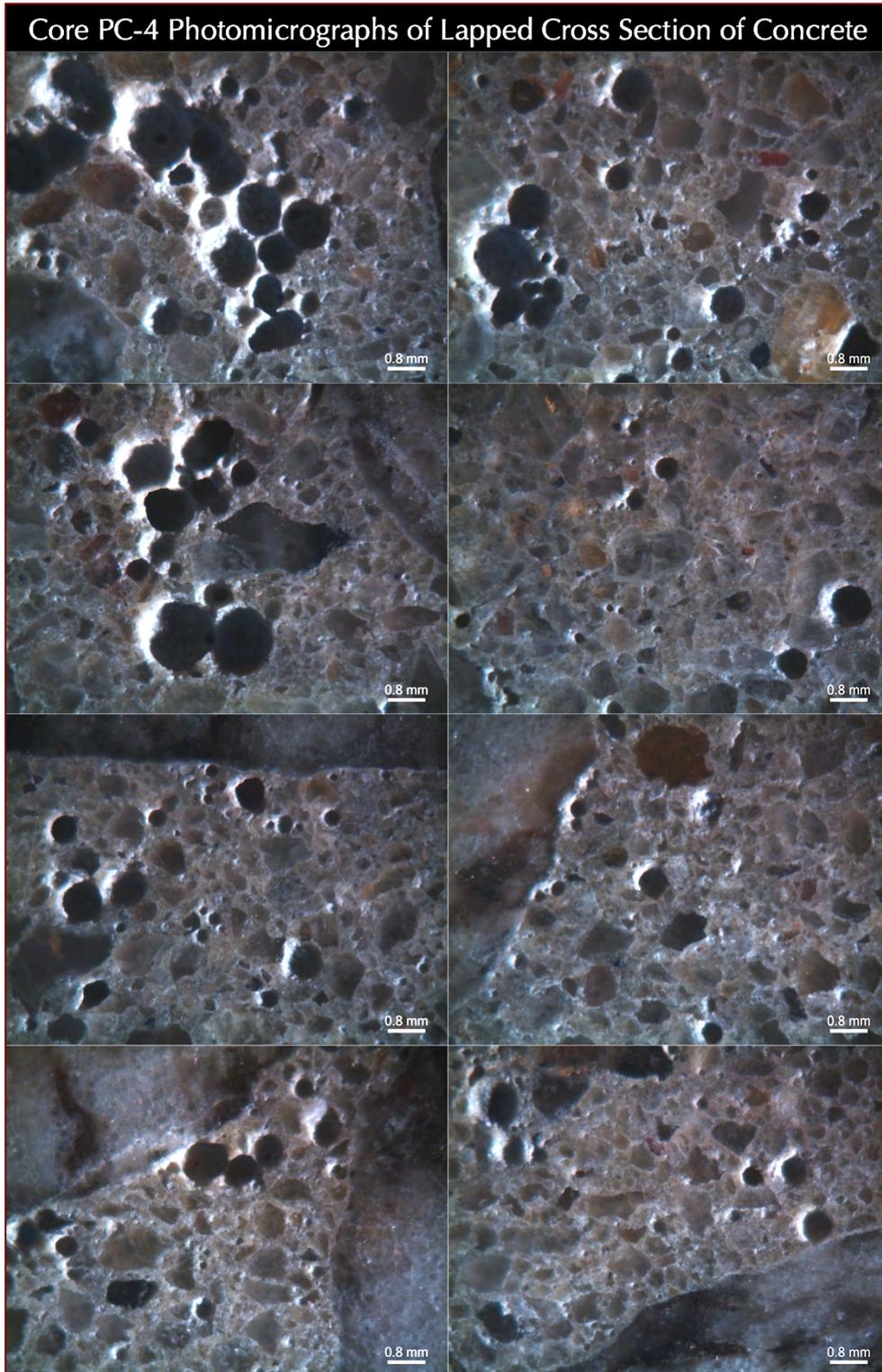


Figure 23: Photomicrographs of lapped cross section of Core PC-4 from the column concrete portion showing non-air-entrained to marginally air-entrained nature of the column concrete having a few coarse and irregular-shaped voids but no intentionally introduced fine, discrete spherical entrained air voids of 1 mm or less size for most of the areas except some clustering of spherical air voids at isolated locations, and overall sound crack-free condition of the column concrete.

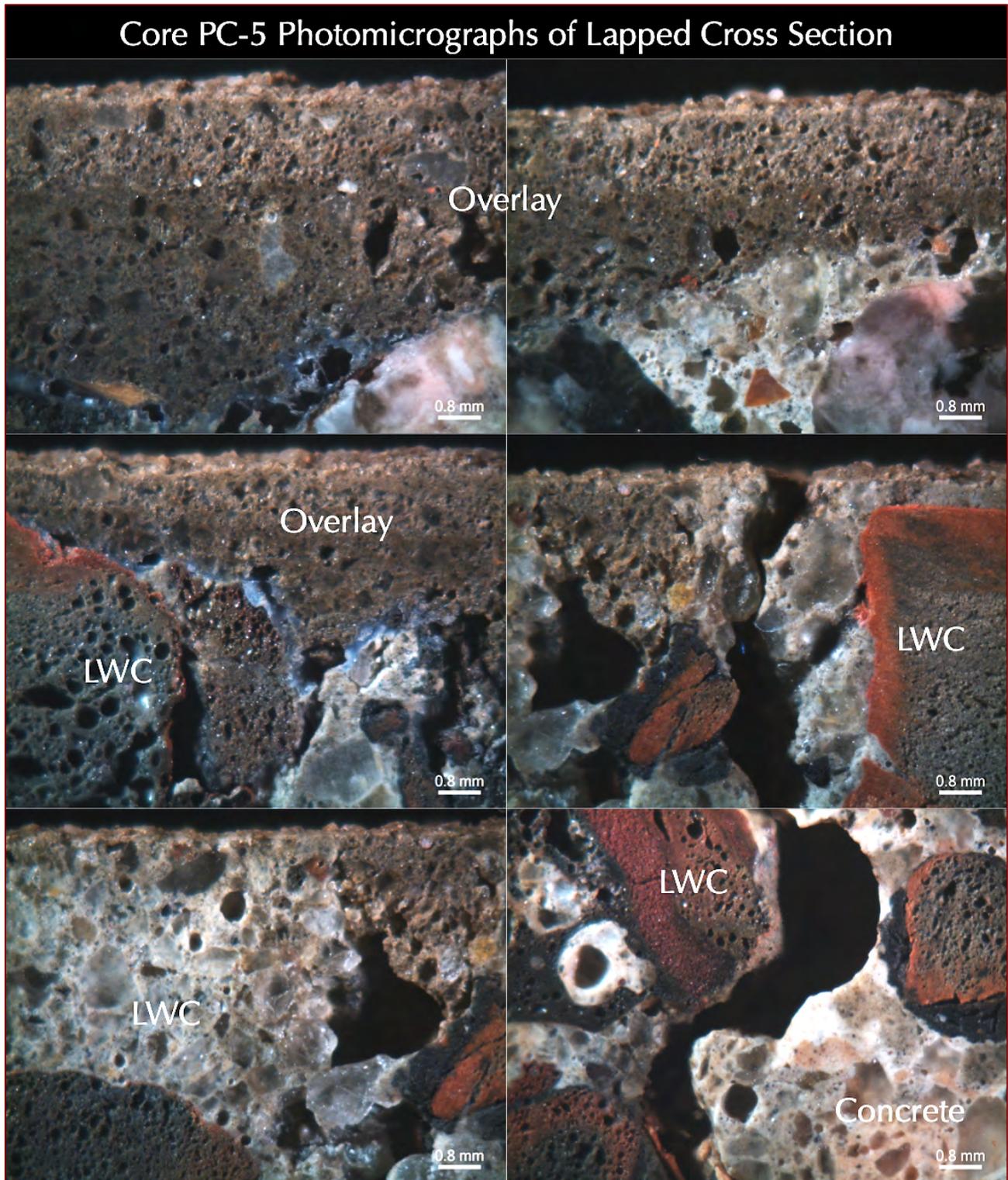


Figure 24: Photomicrographs of lapped cross section of Core PC-5 from the repair overlay at the top showing a porous medium gray repair overlay (about 1 mm thick) at the very top (top row) well-bonded to a dense darker gray overlay beneath (about 1-2 mm thick, top row), which is well-bonded to the concretes beneath. The dense dark gray overlay shows lack of adequate air entrainment. Notice reddish brown oxidation rims around some expanded clay and shale lightweight aggregate particles in the beam concrete.

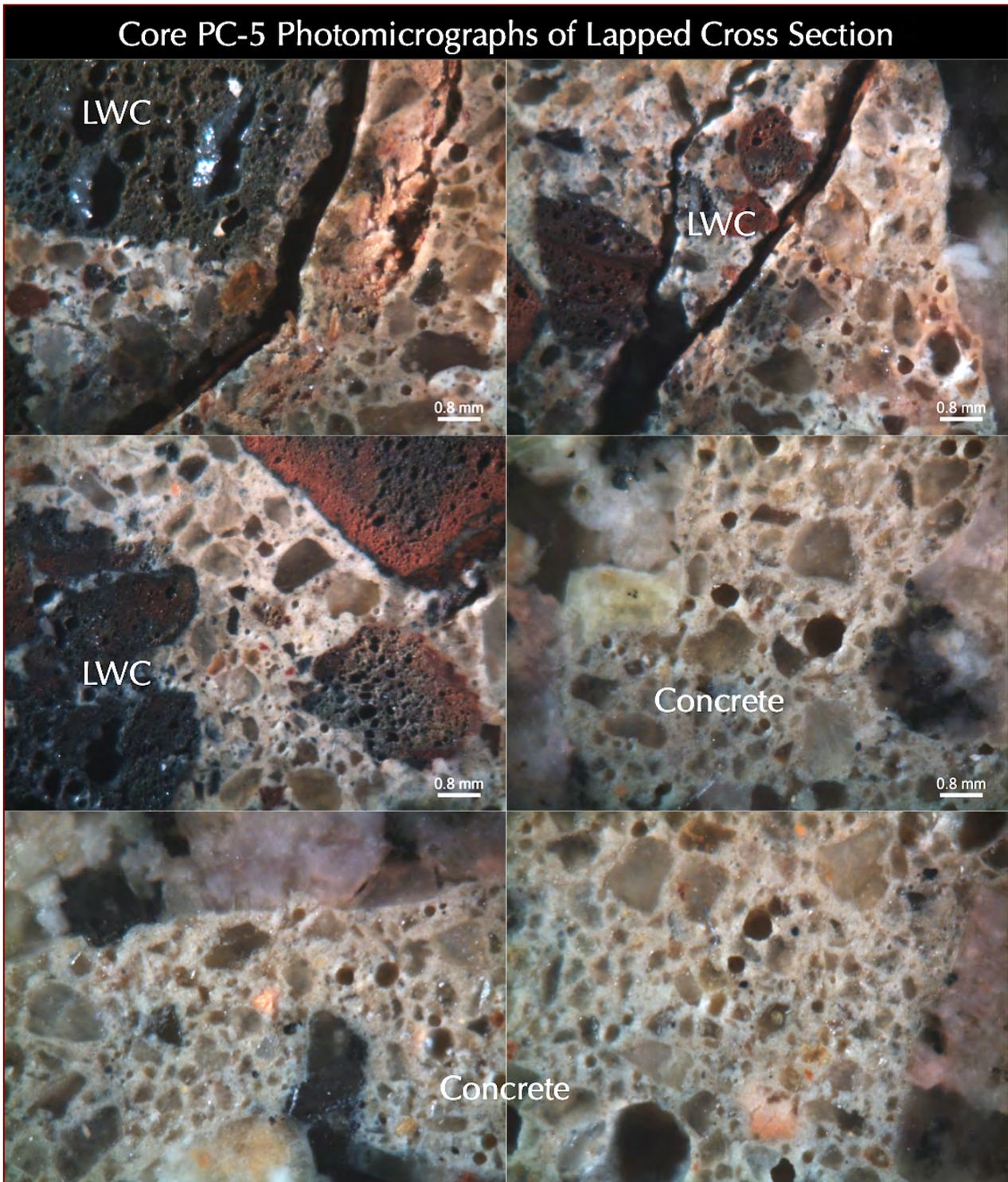


Figure 25: Photomicrographs of lapped cross section of Core PC-5 from the column and beam concrete portions showing beige discoloration of concrete at the top (top row) due to atmospheric carbonation of column prior to the application of repair overlay, non-air-entrained nature of the column concrete having a few coarse and irregular-shaped voids but no intentionally introduced fine, discrete spherical entrained air voids of 1 mm or less size, marginally air-entrained nature of the lightweight aggregate beam concrete, and overall sound crack-free condition of the beam and column concretes. Notice reddish brown oxidation rims around some expanded clay and shale lightweight aggregate particles in the beam concrete.

THIN SECTIONS

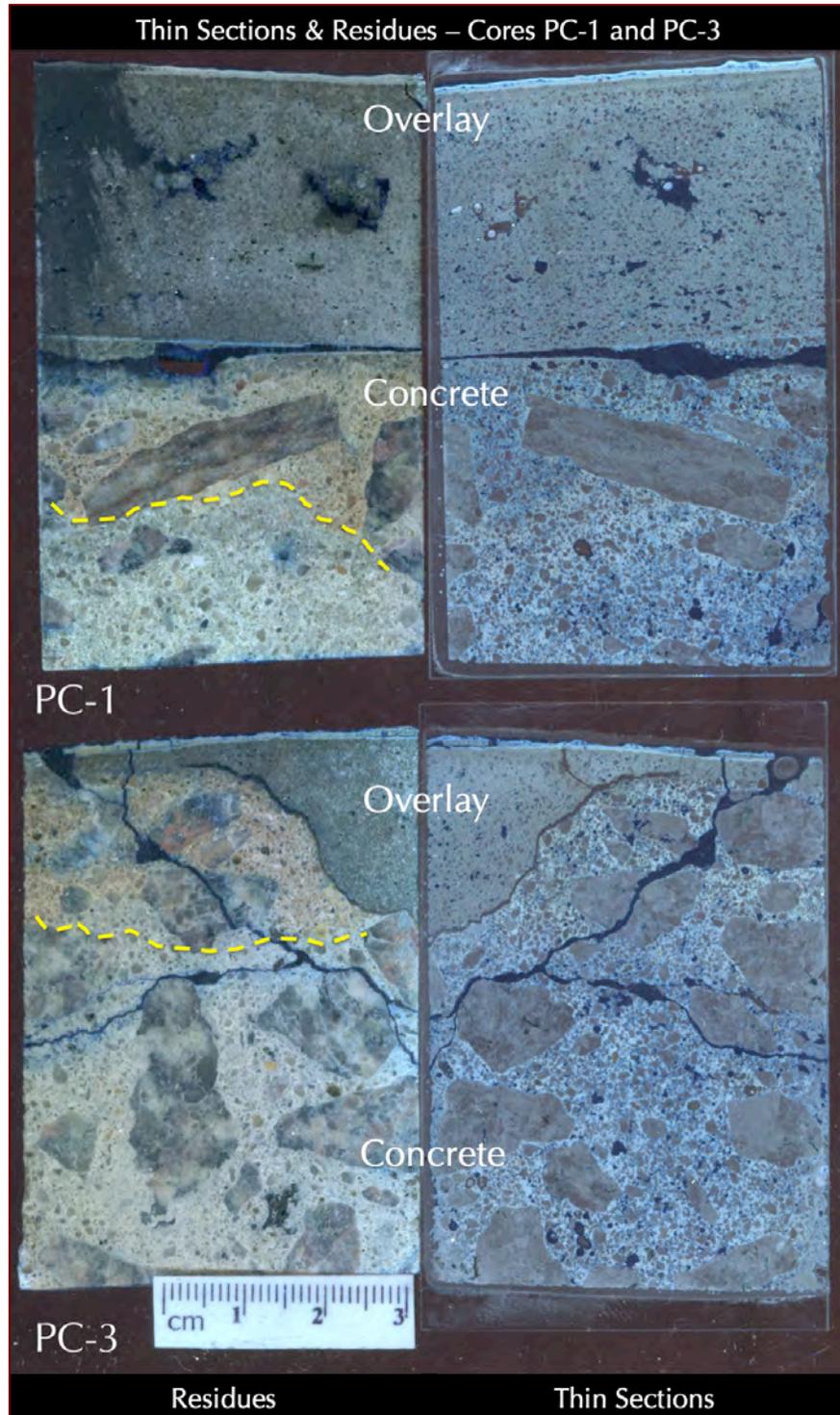


Figure 26: Blue dye-mixed epoxy-impregnated thin sections (right) residues left after thin sectioning (left) of Cores PC-1 (top) and PC-3 (bottom) showing white protective coats at the top of dark gray dense repair overlays, debonding of overlays from column concretes, visible major cracks in the column concrete in Core PC-3, and beige carbonation of column concretes where carbonation fronts are marked by yellow dashed lines. Notice lack of entrained air voids in the column concretes or overlays which would have been highlighted by blue epoxy.

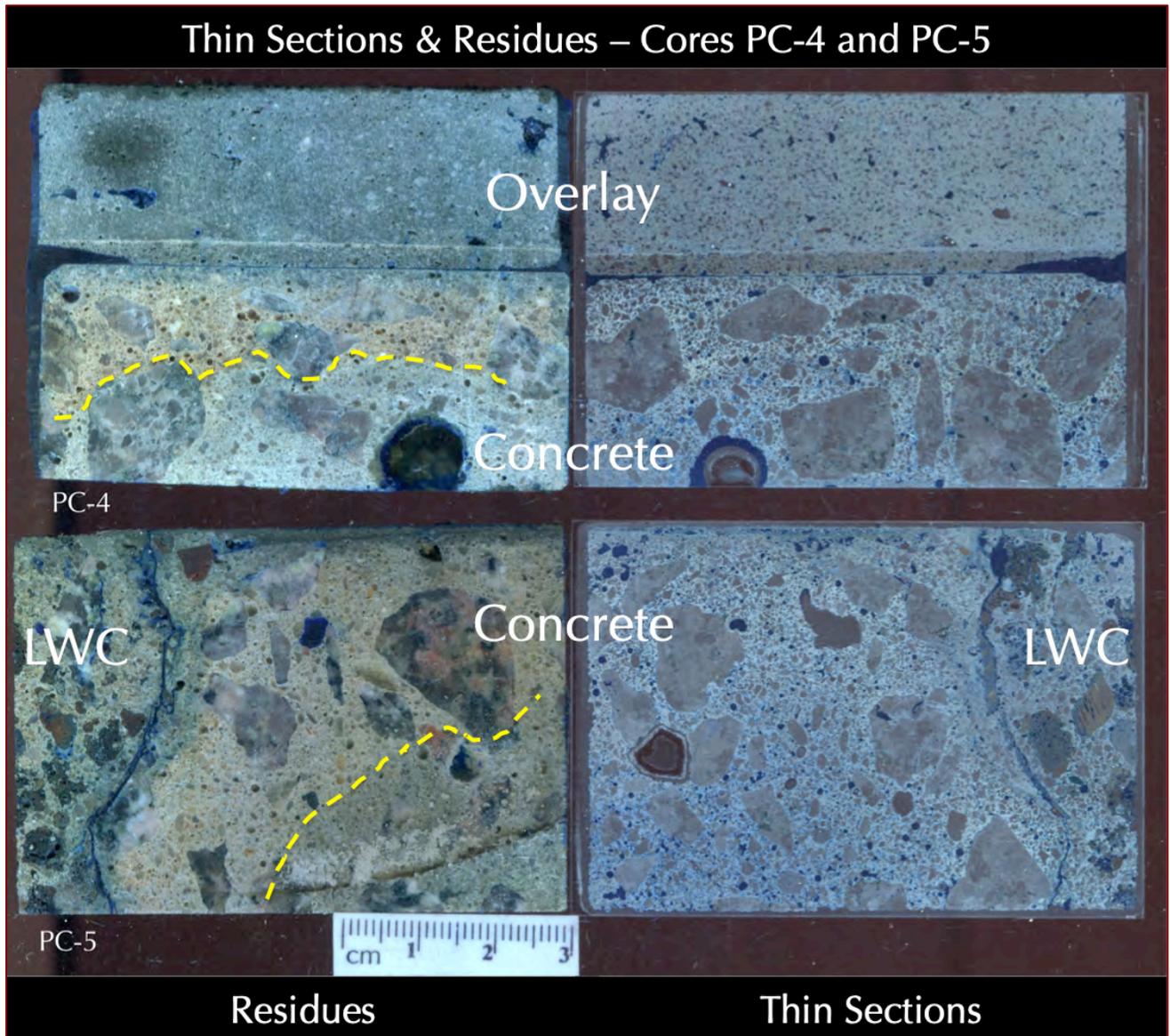


Figure 27: Blue dye-mixed epoxy-impregnated thin sections (right) residues left after thin sectioning (left) of Cores PC-4 (top) and PC-5 (bottom) showing dark gray dense repair overlays, debonding of overlay from column concrete in Core PC-4 where overlay shows a thin (2 to 3 mm thick) repair coat at the base, well bond of thin repair overlay to concrete in Core PC-5 and a cold joint between lightweight aggregate beam concrete and normal-weight aggregate column concrete. Beige carbonation of beam and column concretes are marked by yellow dashed lines separating carbonated portions from interior non-carbonated concretes. Notice lack of entrained air voids in the column concretes or overlays, which would have been highlighted by blue epoxy. Even the lightweight aggregate beam concrete where air entrainment is common due to density requirements are not evident by the blue epoxy.

PHOTOMICROGRAPHS OF THIN SECTIONS

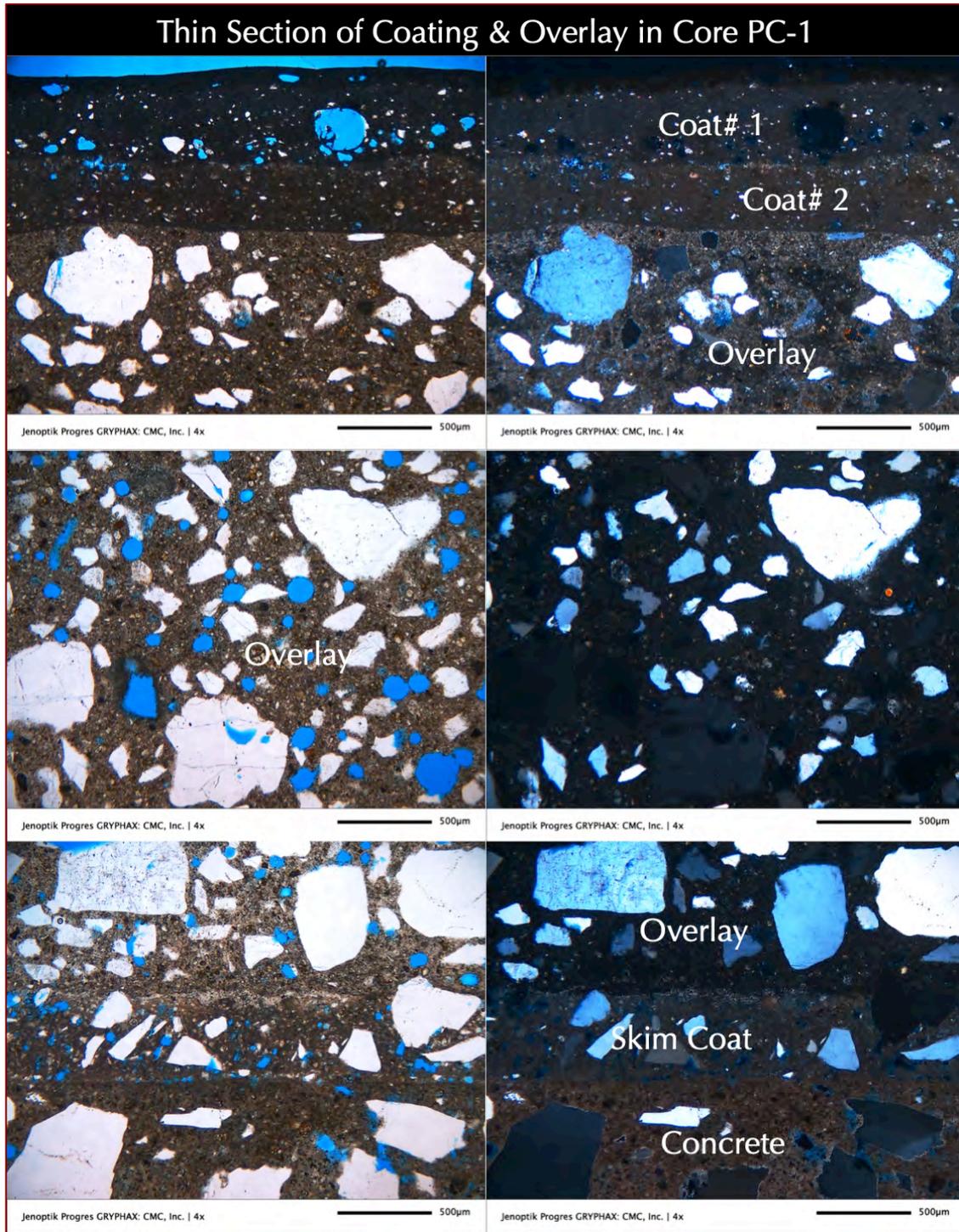


Figure 28: Photomicrographs of thin section of Core PC-1 showing: (a) two protective coats (#1 and 2) that are well-bonded to each other and to the repair overlay beneath; Coat #1 is more porous and polymer-based whereas Coat #2 is denser and has cementitious component (top row), (b) repair overlay, which is dense and containing crushed silica sand of 1 mm maximum size, dense low water-cement ratio Portland cement paste, and many spherical air voids highlighted by blue epoxy (middle row), (c) a skim coat at the base of repair overlay of crushed silica sand and Portland cement paste, which is bonded to the concrete beneath (bottom row).

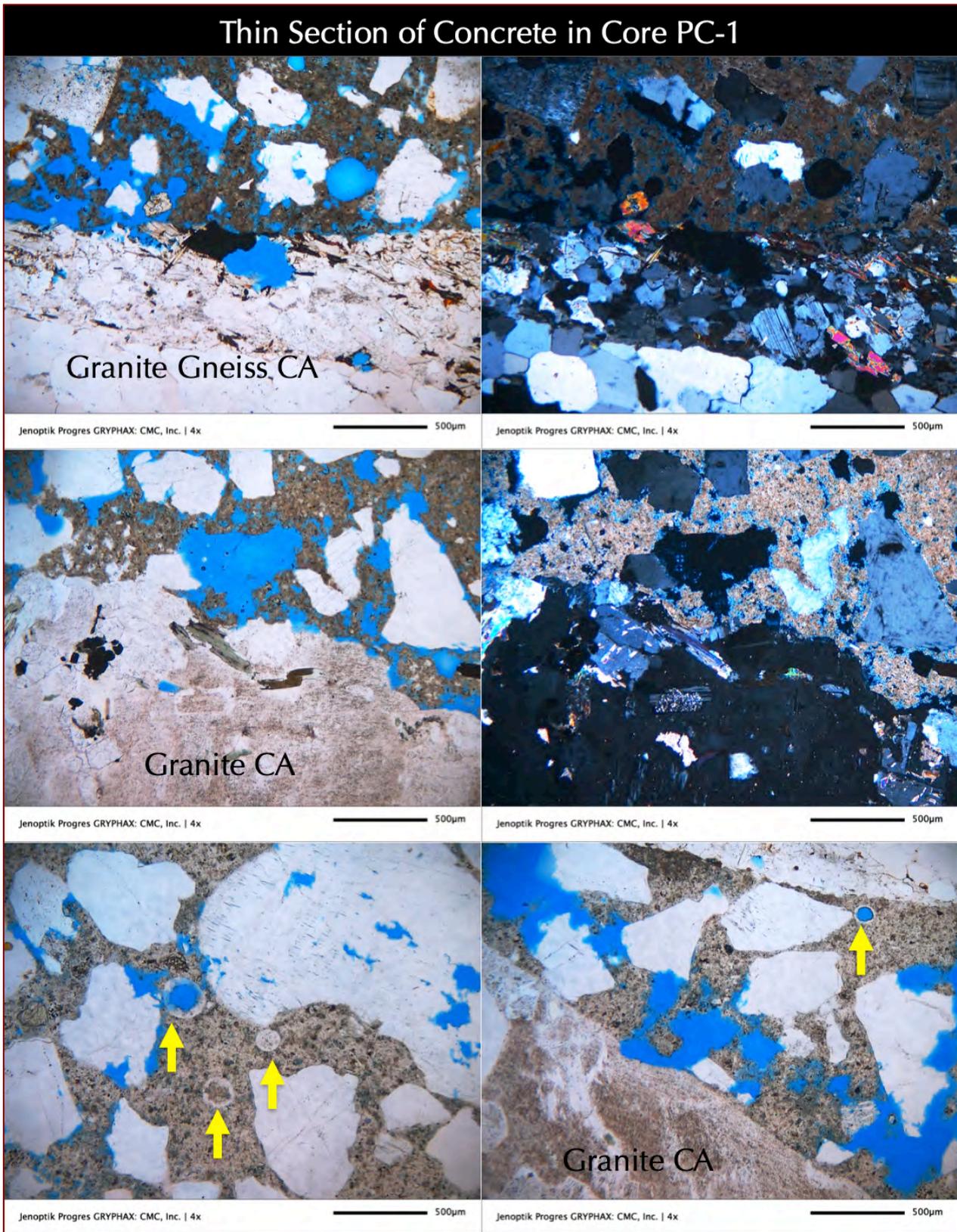


Figure 29: Photomicrographs of thin section of Core PC-1 from the column concrete showing crushed granite and granite gneiss coarse aggregate particles, crushed silica sand fine aggregate, carbonated Portland cement paste at the top, and secondary ettringite deposits lining a few air voids (arrows).

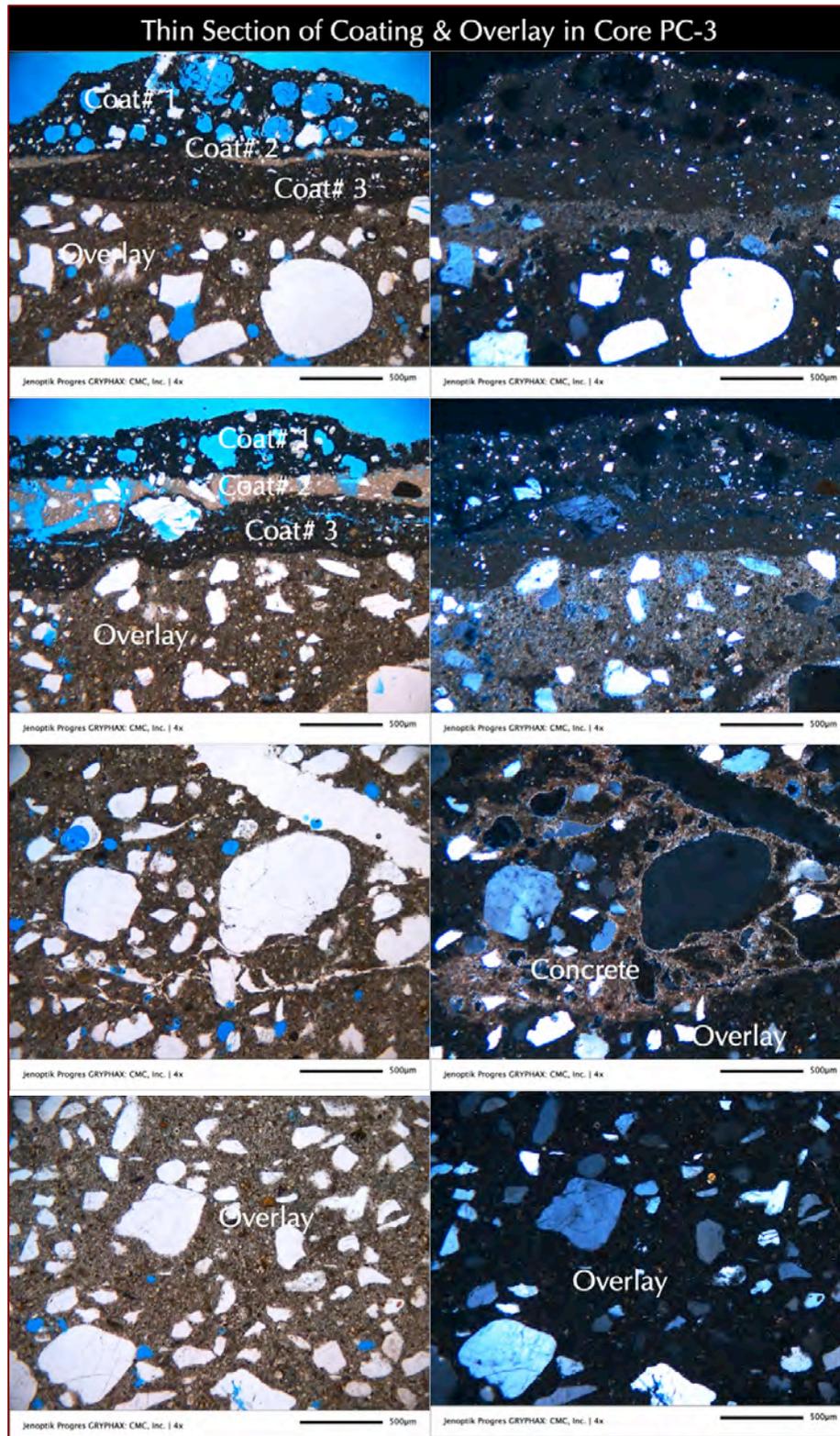


Figure 30: Photomicrographs of thin section of Core PC-3 showing: (a) three protective coats (#1, 2, and 3) that are well-bonded to each other and to the repair overlay beneath (top row), where the very top Coat #1 has perlitic fillers, whereas No. 2 is calcitic coat, and #3 is dense cementitious coat; and (b) repair overlay, which is dense and containing crushed silica sand of 1 mm maximum size, dense low water-cement ratio Portland cement paste, and many spherical air voids highlighted by blue epoxy (middle row).

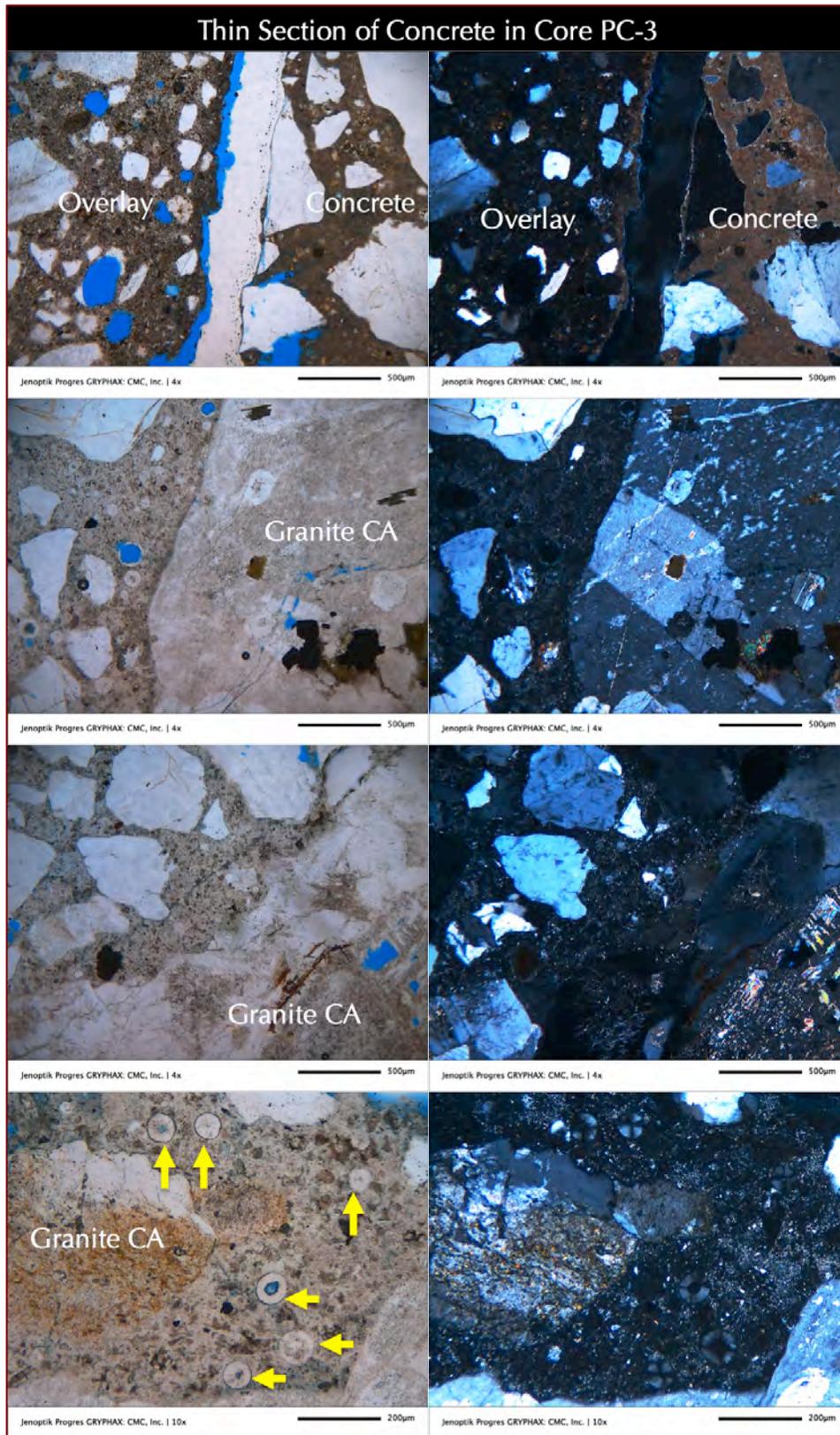


Figure 31: Photomicrographs of thin section of Core PC-3 from the column concrete showing crushed granite and granite gneiss coarse aggregate particles, crushed silica sand fine aggregate, carbonated Portland cement paste at the top, non-carbonated concrete in the interior, and secondary ettringite deposits lining a few air voids (arrows).

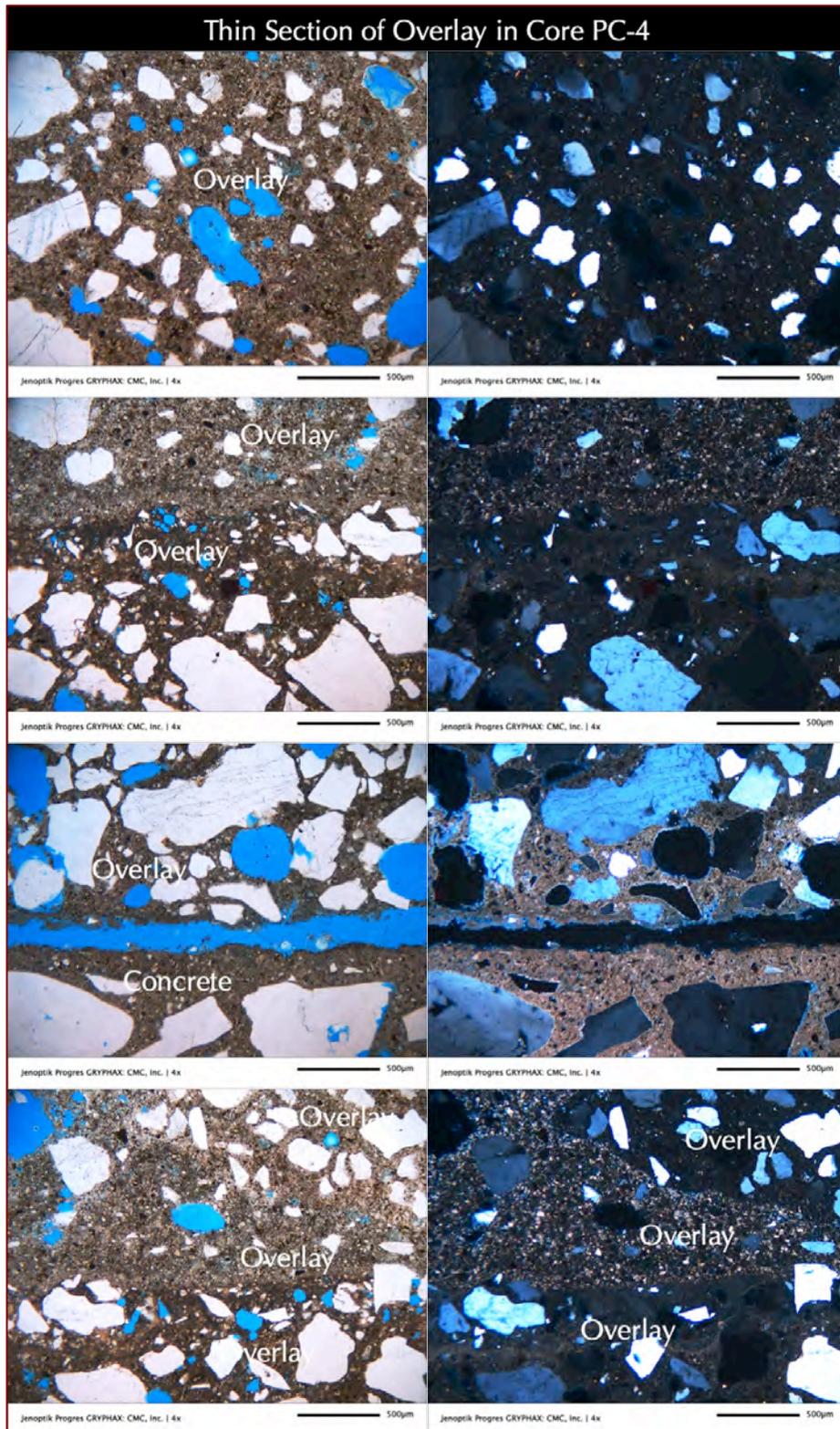


Figure 32: Photomicrographs of thin section of Core PC-4 showing: (a) repair overlay, which is dense and containing crushed silica sand of 1 mm maximum size, dense low water-cement ratio Portland cement paste, and many spherical air voids highlighted by blue epoxy (middle row). Notice multiple applications of overlay of slightly different water-cement ratios that are detected by slight difference in densities of pastes.

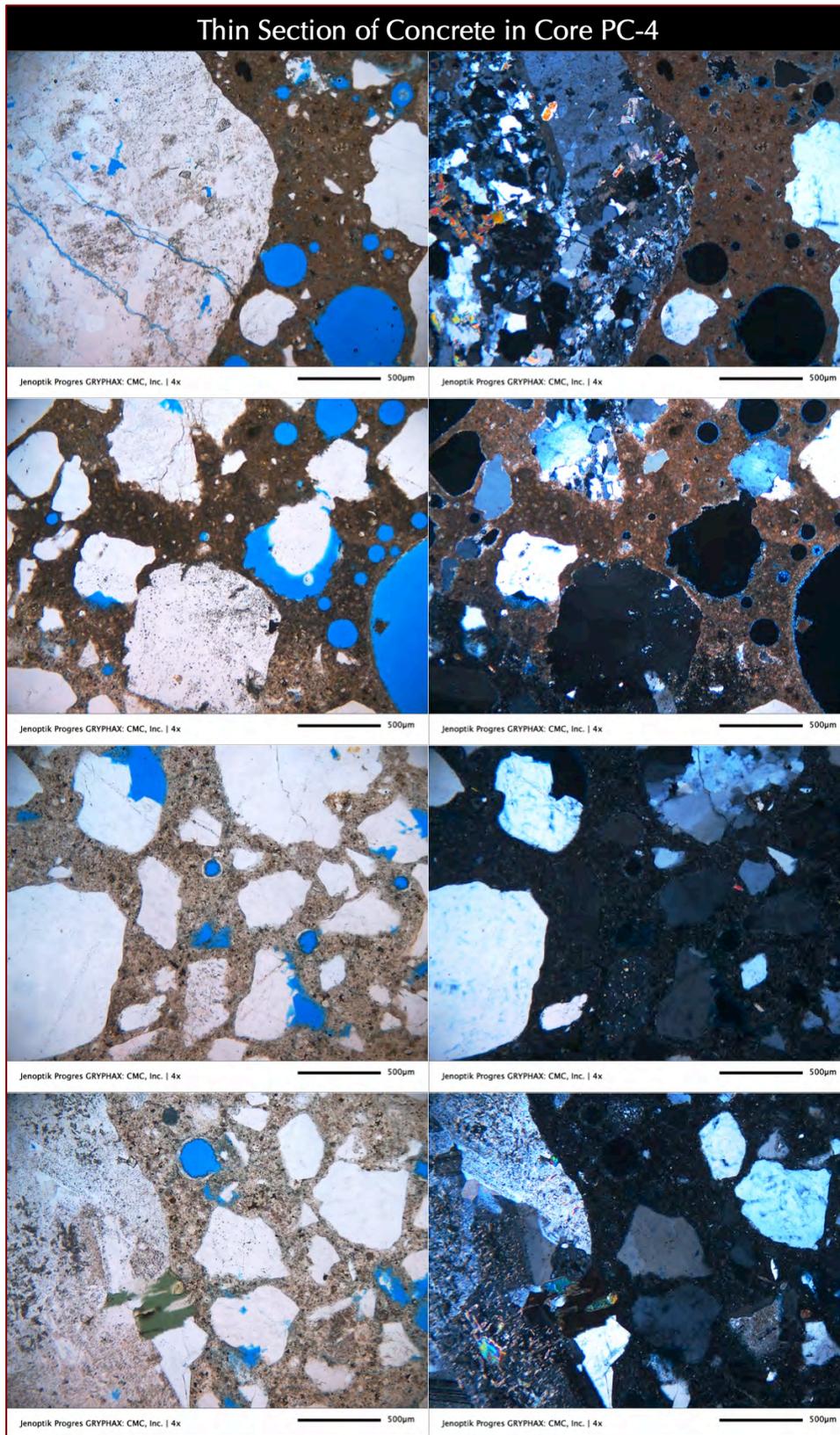


Figure 33: Photomicrographs of thin section of Core PC-4 from the column concrete showing crushed granite coarse aggregate particles, crushed silica sand fine aggregate, carbonated Portland cement paste at the top, non-carbonated concrete in the interior, and secondary ettringite deposits lining a few air voids.

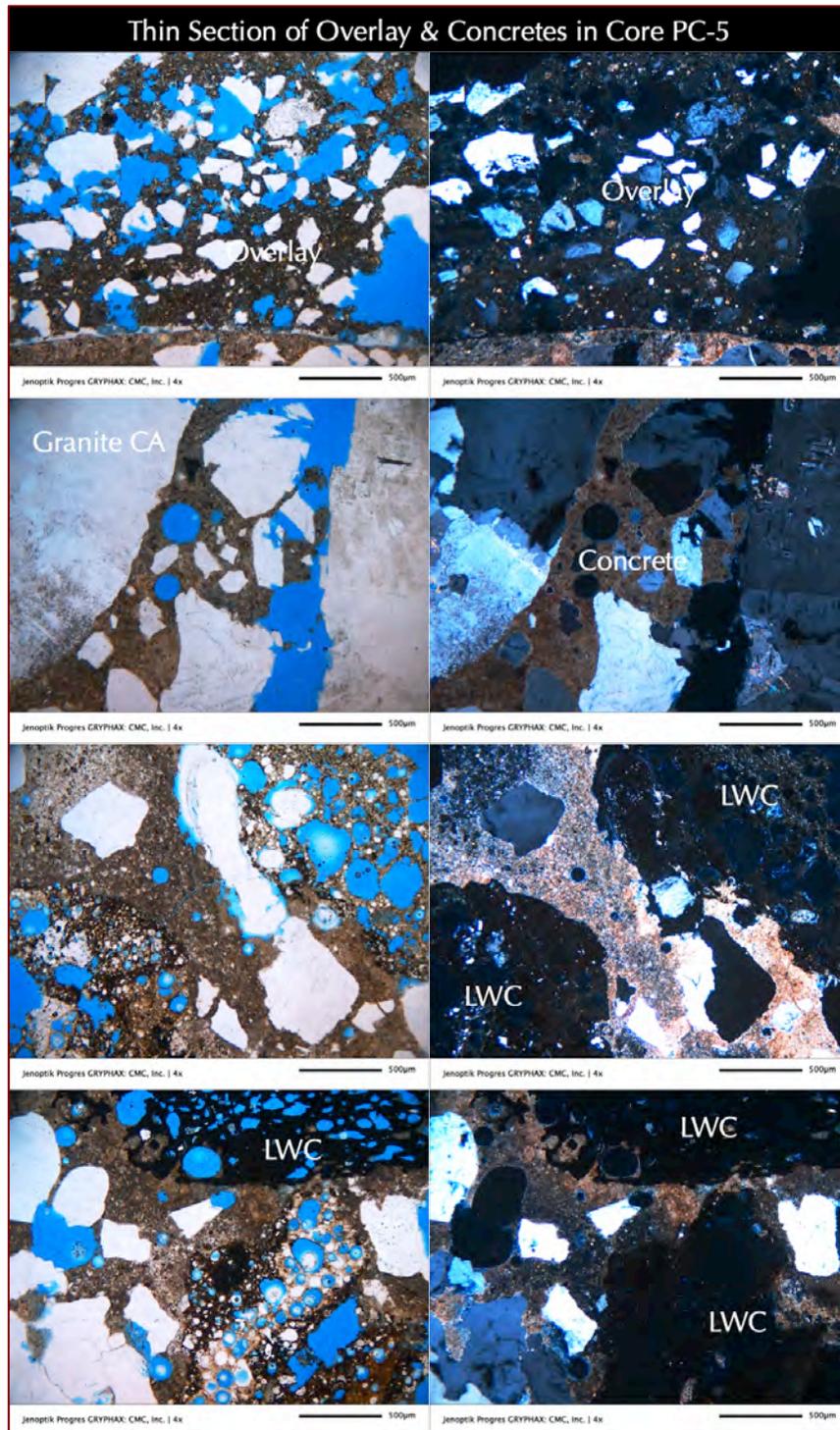


Figure 34: Photomicrographs of thin section of Core PC-5 showing: (a) two repair overlays, one top porous overlay of 0.5 mm to 1 mm thickness that contains crushed fine silica sand plus Portland cement paste but with many coarse irregular-shaped voids, and another underling dense overlay of 0.5 mm thickness that also contains crushed fine silica sand and dense Portland cement paste but no major voids. In both overlay layers sand is nominal 0.5 mm in size, well-graded and well-distributed and paste is dense. The 2<sup>nd</sup> to 4<sup>th</sup> rows show the normal-weight column concrete containing crushed granite coarse aggregate and Portland cement paste, and lightweight beam concrete containing porous, vesicular expanded clay and shale coarse aggregate and Portland cement paste. Pastes in both concretes show carbonation.

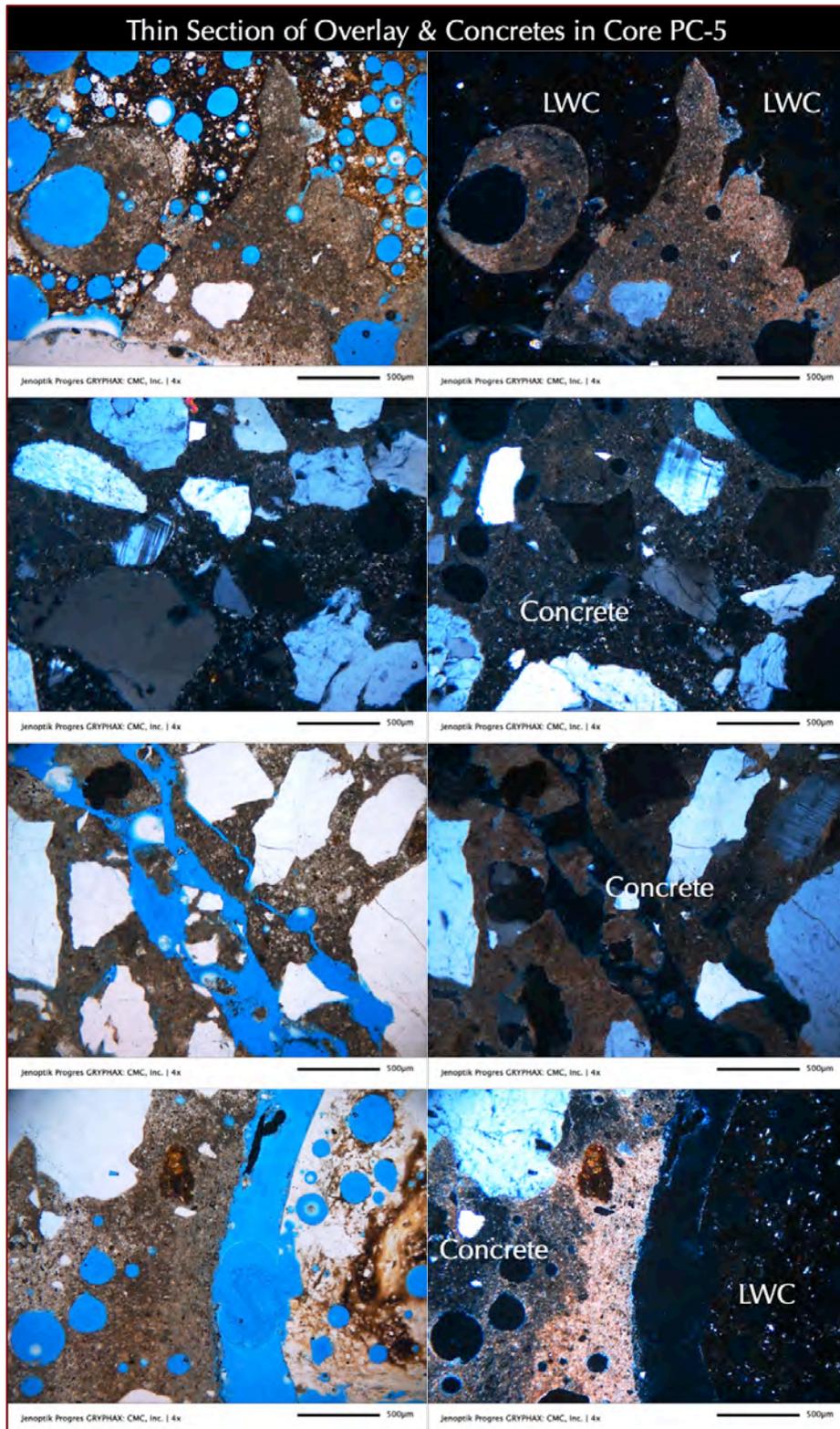


Figure 35: Photomicrographs of thin section of Core PC-5 showing normal-weight column concrete (2<sup>nd</sup> and 3<sup>rd</sup> rows) containing crushed granite coarse aggregate and Portland cement paste, and lightweight beam concrete (1<sup>st</sup> and 4<sup>th</sup> rows) containing porous, vesicular expanded clay and shale coarse aggregate and Portland cement paste. Pastes in both concretes show carbonation.

SEM-EDS STUDIES

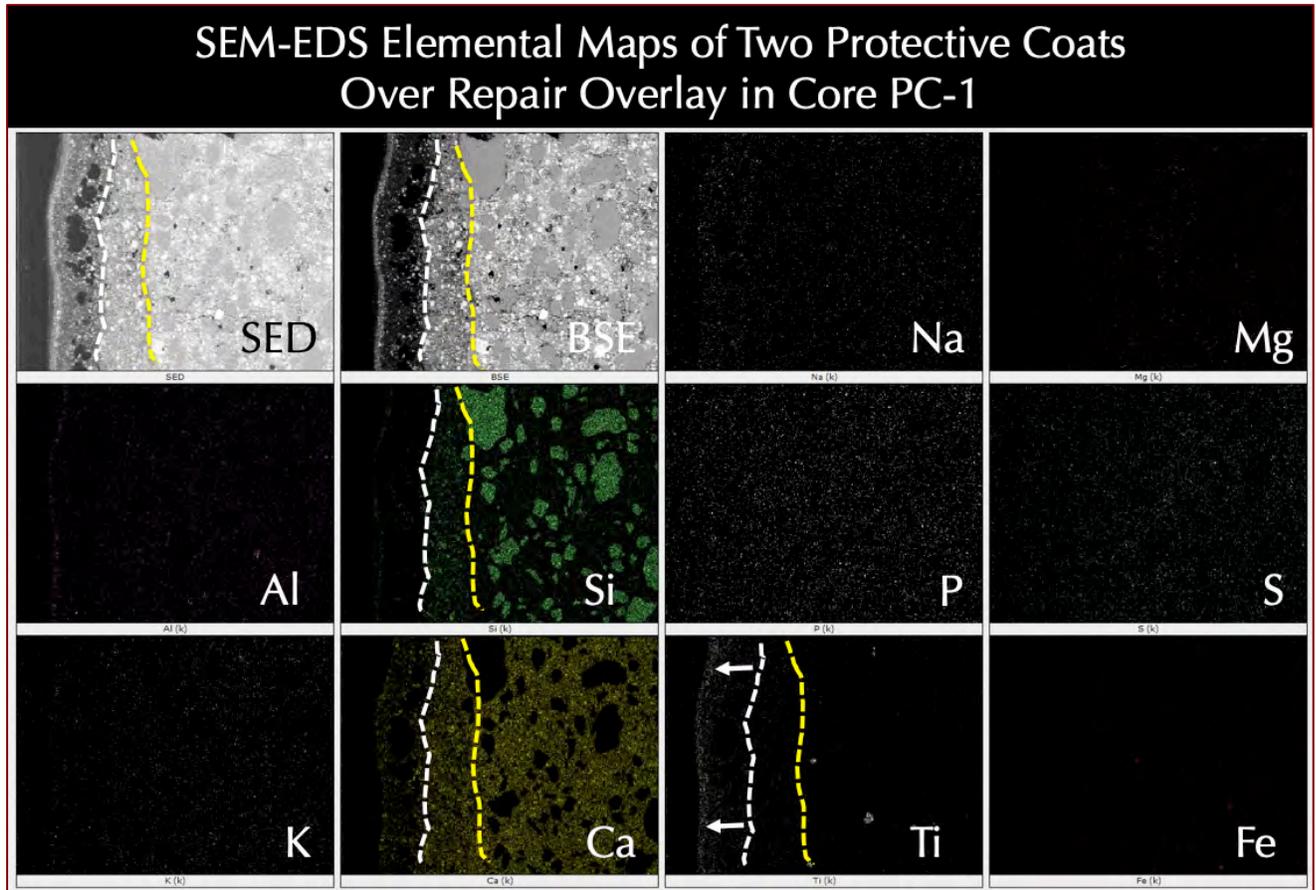


Figure 36: X-ray elemental maps in SEM-EDS of two protective coats over repair overlay in Core PC-1 showing the presence of a titanium-oxide pigment based coat at the top (Coat #1) that has given the characteristic white color of paint and a cementitious (Ca-based) underlying coat (Coat #2) applied over cementitious repair overlay. The overlay contains silica sand (highlighted in Si-map) and Portland cement paste (highlighted in Ca and Si maps). The white and yellow dashed lines separated the two protective coats from each other and from the underlying overlay, respectively.

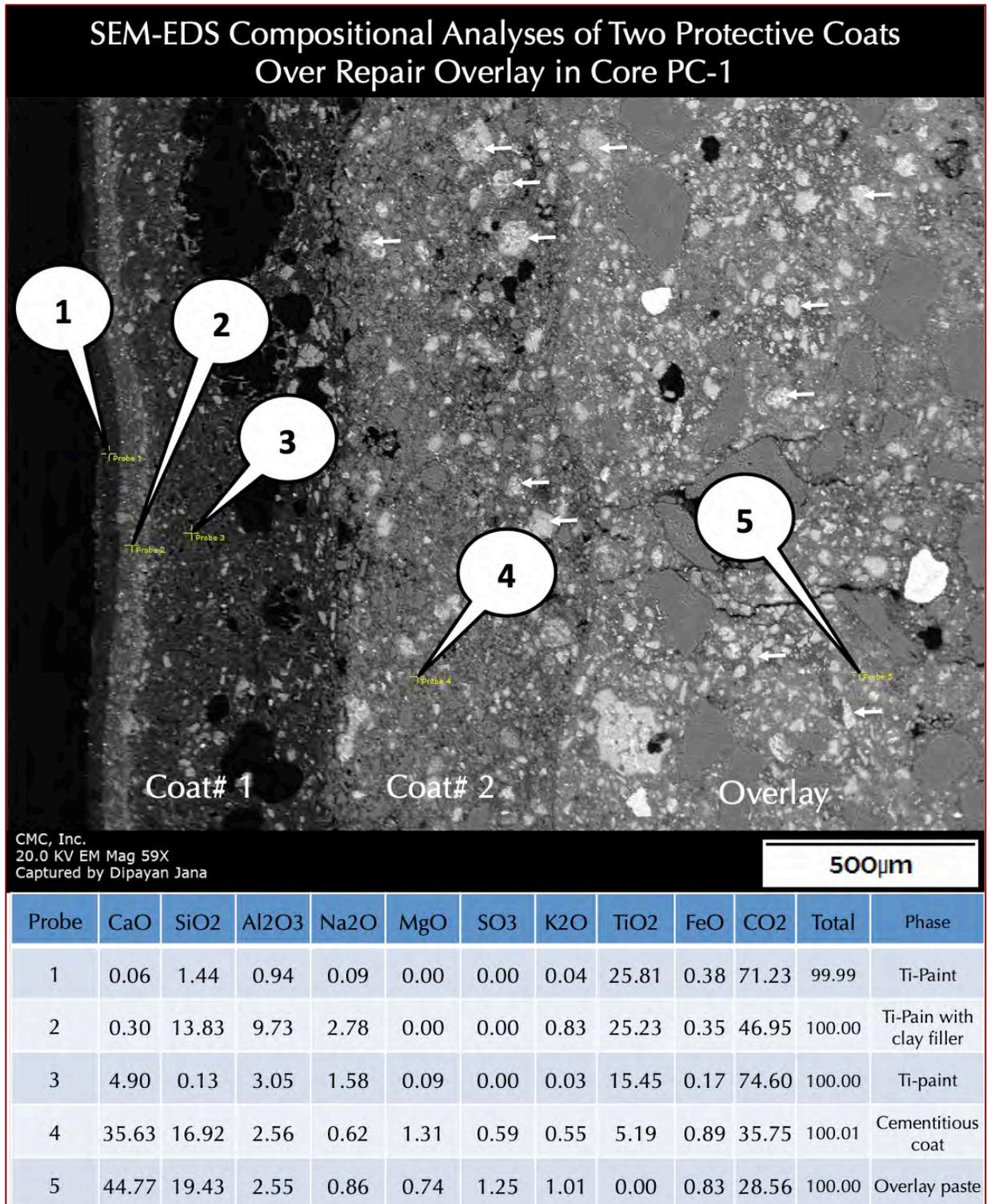


Figure 37: Secondary electron image (top) and X-ray elemental analyses from the tips of callouts from the two protective coats and paste region in the underlying overlay showing characteristic titanium oxide pigment based top coat (Coat #1) above a Ti-oxide pigment mixed with china clay filler in the paint (Coat #1, clay gave high silica and alumina) and underlying cementitious coat (Coat #2) having typical calcium silicate hydrate composition of Portland cement paste in the overlay. Fine, bright particles in the Coat #2 and in overlay are residual Portland cement particles in paste (some are marked with arrows).

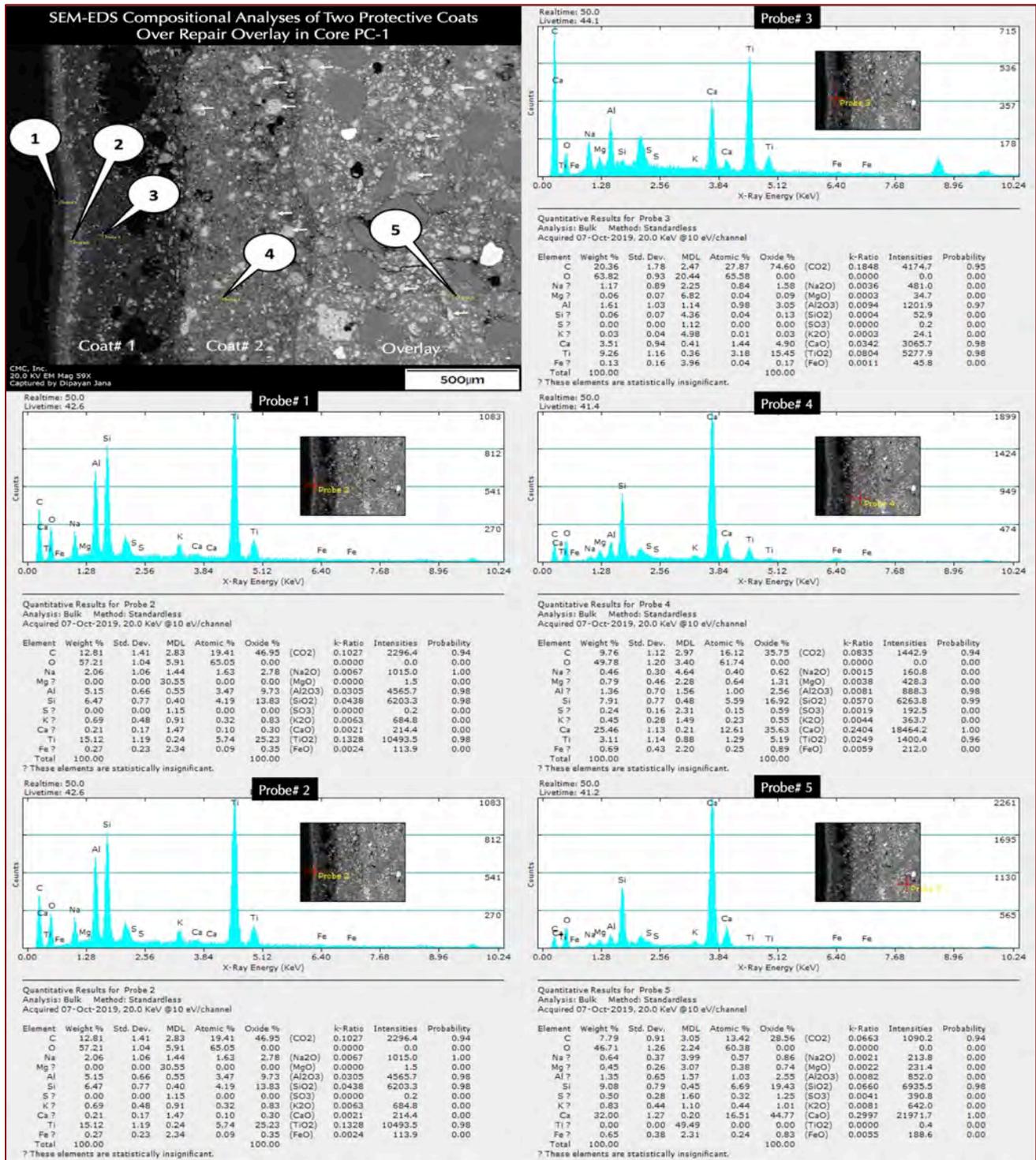


Figure 38: X-ray elemental spectra of five probes across the two protective coats and underlying overlay shown in the previous Figure showing variations in elemental peaks from protective coats to the overlay. Notice titanium peaks are found only in the first three probes taken from the top of Coat #1 whereas Probe #4 from the underlying Coat #2 shows negligible titanium but calcium and silica peaks from calcium silicate hydrate Portland cement paste. The overlay shows typical calcium and silica enrichment from calcium silicate hydrate composition of portland cement paste in Probe #5.

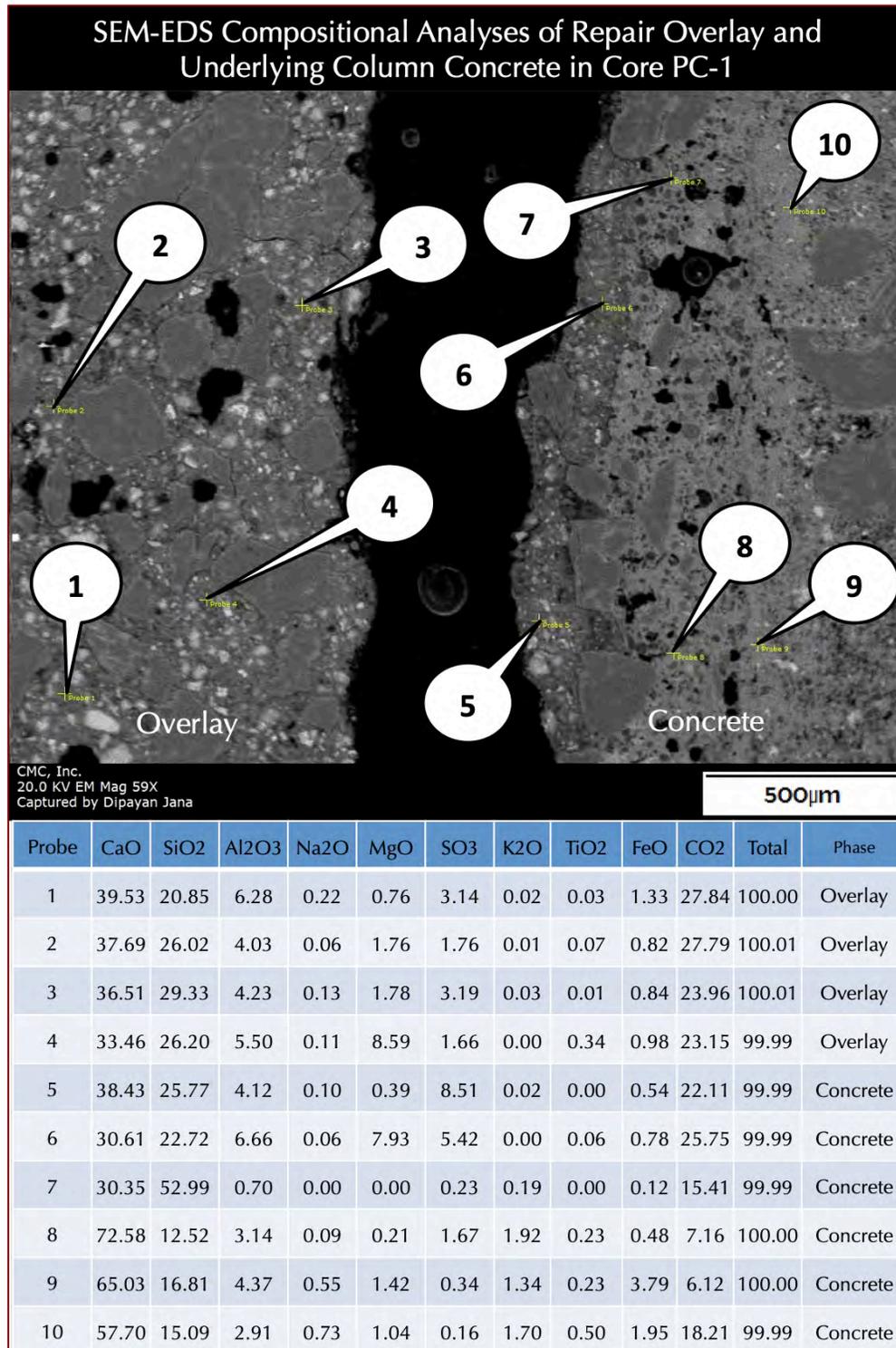


Figure 39: Secondary electron image (top) and X-ray elemental analyses from the tips of callouts from the underside of repair overlay at left and column concrete at right in Core PC-1 showing characteristic enrichment in calcium and silica from calcium silicate hydrate paste of Portland cement in both the overlay and the concrete. Notice high sulfate content in the overlay compared to concrete due to high cement content of overlay, and variable sulfate contents in paste in the concrete (high sulfate found in Probe #5 and 6 are from remains of overlay on concrete surface). Fine, bright particles in the overlay at left are residual Portland cement particles in paste.

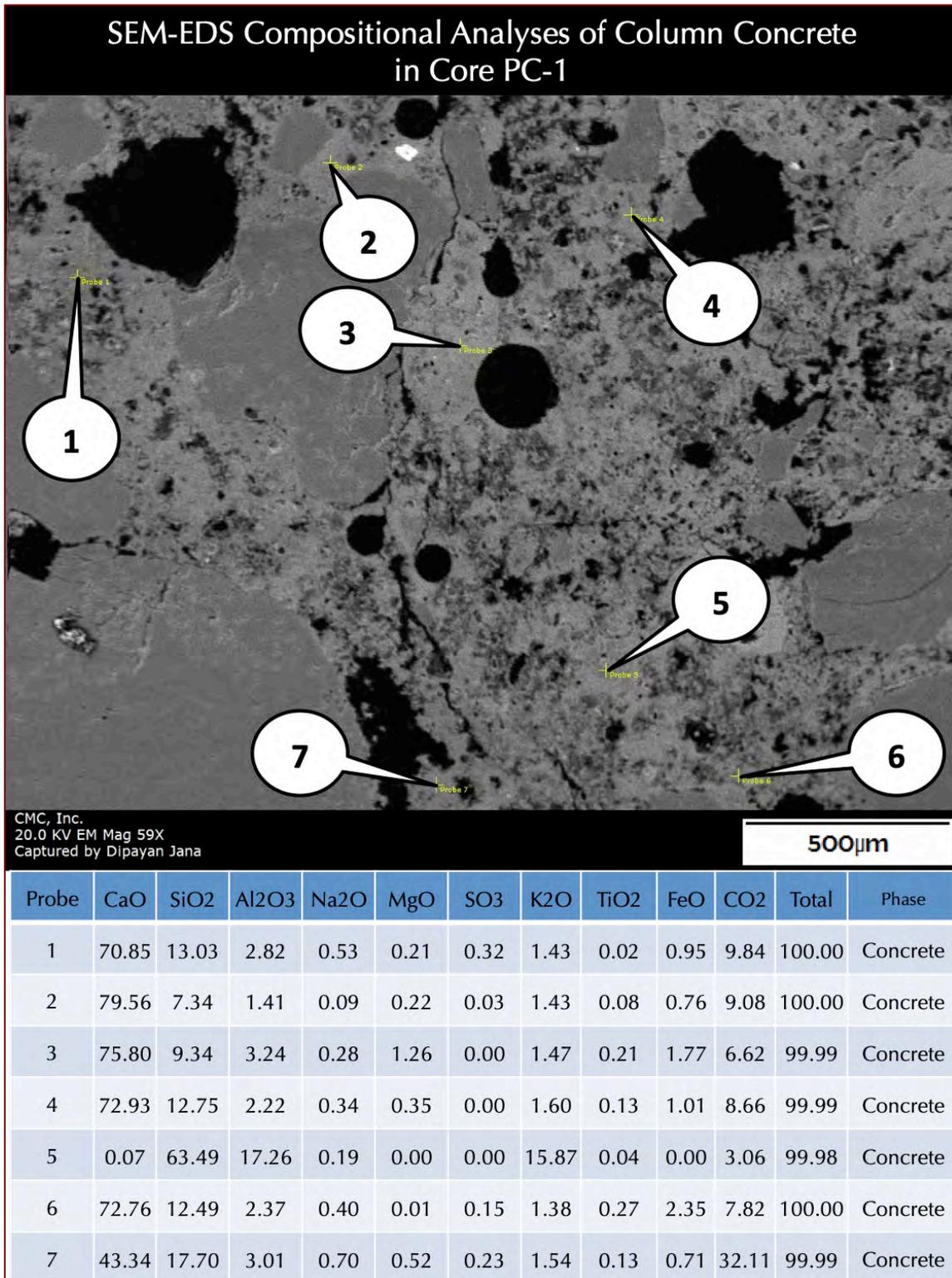


Figure 40: Secondary electron image (top) and X-ray elemental analyses from the tips of callouts from the paste region of column concrete in Core PC-1 showing characteristic enrichment in calcium and silica from calcium silicate hydrate paste of Portland cement. Notice the overall absence of any sulfate enrichment in the paste of column concrete indicating no internal sulfate attack in the concrete.



## PROTECTIVE COATS

The exposed faces of columns represented by the Cores PC-1, 3, and 4 show multiple applications of protective coats, which are determined to be as follows:

- e. An exposed shiny cream-colored paint coat in Core PC-1, which is determined by SEM-EDS to have a titanium oxide pigment based polymer coat at the very top, followed by a titanium oxide pigment and china clay filler based PVC coat – both of which constitute the Coat #1 of two coat system, and an underlying cementitious coat (Coat #2) lacking titanium oxide pigment. The binder in Coat #1 is determined from FT-IR to be a PVC-based paint. The top coat (Coat #1) is approximately 0.25 mm in thickness, applied over an interior cementitious coat of another 0.25 mm thickness; the latter was applied directly over the overlay;
- f. An exposed titanium oxide pigment and perlite filler based PVC polymer exterior coat of approx. 0.3 mm thickness in Core PC-3, which was applied over a thin calcitic coat of 0.1 mm thickness, which, in turn, was applied over a cementitious coat of approx. 0.2 mm thickness, the latter was applied and well-bonded to the repair overlay;
- g. A textured matte-finished cream coat in Core PC-4 of approx. 0.1 to 0.4 mm variable thicknesses which is titanium oxide pigment and china clay filler based polymer coat, applied over a relatively uniform 0.3 mm thick cementitious coat, the latter was applied directly over and well-bonded to the concrete.
- h. Protective coats over overlays in all three cores have denser interior cementitious coats applied over the overlay compared to relatively porous titanium oxide pigment and clay or perlite filler based polymer outer coats.

## REPAIR OVERLAYS

The repair overlay applied over deteriorated concrete is found in all four cores that has varied in thicknesses from:

- h. A uniform 1<sup>1</sup>/<sub>4</sub> in. (35 mm) thickness overlay, which is completely debonded from concrete in Core PC-1; concrete has a nominal recovery length of 6 in. (150 mm). The overlay consists of crushed silica sand containing major amount of quartz of nominal sizes from 0.5 mm up to 1 mm that are well-graded, well-distributed and sound, and dense Portland cement paste of water-cement ratio estimated to be 0.35 to 0.40. The overlay is marginally air-entrained to air-entrained having an estimated air content of 6 to 8 percent. A skim coat is found at the base of repair overlay that is nominal 0.5 mm in thickness, consisted of crushed silica sand and Portland cement paste as the main overlay and bonded to the concrete beneath.
- i. A tapered 1<sup>1</sup>/<sub>8</sub> in. (4 mm) to maximum 2 in. (50 mm) thickness overlay, which is separated from concrete by a diagonal crack in Core PC-3; concrete has a nominal recovery length of 5<sup>1</sup>/<sub>2</sub> in. (140 mm) to maximum 7 in. (180 mm). The overlay is compositionally similar to that found in Core PC-1 and consists of crushed silica sand containing major amount of quartz of nominal sizes from 0.5 mm up to 1 mm that are well-



- graded, well-distributed and sound, and dense Portland cement paste of water-cement ratio estimated to be 0.35 to 0.40. The overlay is non air-entrained having an estimated air content of 2 to 3 percent.
- j. A uniform 2 in. (50 mm) thickness overlay, which is completely debonded from concrete in Core PC-4; concrete has a nominal recovery length of 5 in. (120 mm). The overlay consists of crushed silica sand containing major amount of quartz of nominal sizes from 0.5 mm up to 1 mm that are well-graded, well-distributed and sound, and dense Portland cement paste of water-cement ratio estimated to be 0.35 to 0.40. Multiple applications of overlay of slightly different water-cement ratios are found in this core that are detected by slight difference in densities of pastes. The base of overlay is completely de-bonded from concrete and shows the presence of a separate thin repair coat of 2 to 3 mm thickness at the base of the main overlay of 2 in. (50 mm). The main overlay is well-bonded to the thin coat at the base but the latter shows clean debonding from the concrete. The overlay is marginally air-entrained to non-air-entrained having an estimated air content of 4 to 5 percent.
  - k. A thin ( $\frac{1}{8}$  in., 4 mm) dark gray repair coat well-bonded to concretes from beam and column in Core PC-5; concretes contain portions of beam concrete, which is a lightweight concrete and column concrete, which is a normal-weight concrete of maximum recovered length of 6 in. (150 mm). Two repair overlays are found in PC-5 - one top porous overlay of 0.5 mm to 1 mm thickness that contains crushed fine silica sand plus Portland cement paste but with many coarse irregular-shaped voids, and another underling dense overlay of 0.5 mm thickness that also contains crushed fine silica sand and dense Portland cement paste but no major voids.
  - l. In all four cores examined, overlays are dense dark gray repair mortars (lack coarse aggregate) applied over light grey to beige column concretes (that contain crushed stone coarse aggregates for column and lightweight aggregate for portion of beam concrete in Core PC-5).
  - m. Thin section microcopy and SEM-EDS studies show typical Portland cement composition of paste in the overlay, high sulfate in paste from high cement content, and lack of any chemical or physical deterioration.
  - n. Lack of adequate air entrainment in the overlays is counterbalanced by very dense, well-consolidated, low w/c, high cement content paste to provide the necessary freeze-thaw durability, which, however, is not of concern for the columns with minimal water saturation from standing water during freezing. There is no evidence of any freezing-related deterioration found in the overlays.

### COARSE AGGREGATES IN COLUMN CONCRETE

Coarse aggregates are compositionally similar across all four cores for the column which are different from the beam concrete found in Core PC-5. For the columns, concrete contains crushed granite coarse aggregates that have major amount of variably altered granite and subordinate amounts of granite gneiss all having nominal maximum sizes of 1 in. (25 mm). Particles are angular, dense and hard, variably colored from white (plagioclase feldspar, quartz) with black specs of mica to brown (alkali feldspar, quartz) with black specs of mica, equigranular for granite to gneissose textured for granite gneiss, equidimensional to elongated, unaltered, uncoated, and uncracked. Coarse



aggregate particles are well-graded and well-distributed. There is no evidence of alkali-aggregate reaction of coarse aggregate particles found in the cores.

**COARSE AGGREGATE IN BEAM CONCRETE IN CORE PC-5**

Portion of beam concrete present in Core PC-5 shows expanded clay and shale based vesicular lightweight coarse aggregate particles many show characteristic reddish brown oxidation rims on fired clay margins in the aggregate particles. Particles show aluminosilicate glassy mass with crystallites and fine silica sand and vesicles of variable sizes that are typical of expanded clay lightweight aggregates. Coarse aggregate particles are angular, nominal 1/2 in. (12.5 mm) in size, well-graded, well-distributed, and sound. There is no evidence of alkali-aggregate reaction of coarse aggregate particles found in the core.

**FINE AGGREGATES IN COLUMN & BEAM CONCRETES**

Unlike coarse aggregates, fine aggregates are compositionally similar in beam and column concretes, which are crushed silica (quartz and feldspar-based) sand having nominal maximum sizes of 3/8 in. (9.5 mm). Particles contain major amounts of quartz and quartzite, and subordinate amounts of feldspar, sandstone, schist, mafic minerals, etc. Particles are variably colored, rounded to subrounded to subangular, variably dense and hard, equidimensional to elongated, unaltered, uncoated, and uncracked. Fine aggregate particles are well-graded and well-distributed. There is no evidence of alkali-aggregate reaction of fine aggregate particles. Fine aggregate particles have been sound during their service.

The following table summarizes properties of coarse and fine aggregates of concretes in the cores:

Properties and Compositions of Aggregates	Column Concrete
	<b>Coarse Aggregates</b>
Types	Crushed Granite
Nominal maximum size (in.)	1 in. (25 mm).
Rock Types	Granite, Granite Gneiss
Angularity, Density, Hardness, Color, Texture, Sphericity	Angular, dense and hard, variably colored from white (plagioclase feldspar, quartz) with black specs of mica to brown (alkali feldspar, quartz) with black specs of mica, equigranular for granite to gneissose textured for granite gneiss, equidimensional to elongated
Cracking, Alteration, Coating	Unaltered, Uncoated, and Uncracked
Grading & Distribution	Well-graded and well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None



Properties and Compositions of Aggregates	Column Concrete
Fine Aggregates	
Types	Crushed silica sand
Nominal maximum size (in.)	<sup>3</sup> / <sub>8</sub> in. (9.5 mm).
Rock Types	Major amounts of quartz and quartzite, and subordinate amounts of feldspar, sandstone, schist, mafic minerals, etc.
Cracking, Alteration, Coating	Variably colored, rounded to subrounded to subangular, dense and hard, equidimensional to elongated, unaltered, uncoated, and uncracked
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None

Table 3: Properties of coarse and fine aggregates of concretes in the cores.

### PASTES

Portland cement was the only cementitious component used in the repair overlay, in the column concrete, and in the beam concrete. Compared to the column or beam concretes, paste in the overlay is noticeably denser, made using very low water-cement ratio and has higher cement content.

Properties and compositions of hardened cement pastes are similar in all cores from the Columns as well as portion of beam concrete in Core PC-5, which are Portland cement based and are summarized in Table 4. Pastes are light to medium gray in the column concrete that is discolored to beige and brown at the top from atmospheric carbonation, dense and hard in the interior bodies. Freshly fractured surfaces of pastes have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 10 to 12 percent of the paste volumes in the column concrete, which are noticeably higher (due to higher cement contents) in the repair overlays. Hydration of Portland cement is normal in all concretes.

The overlay showed minimal carbonation of 3 to 5 mm across all cores where not only the dense, low w/c, near-impermeable nature of the overlay but further protection from multi-layered coatings placed over the overlay provided additional protections against migration of atmospheric carbon dioxide. The concrete beneath, however, has a different condition, which showed deep carbonation due to prolonged interaction between atmospheric carbon dioxide and column concrete prior to the installation of overlay. Carbonation depths are measured to be greater than 1 in. (about 30 mm) in Cores PC-1 and PC-3, variable from 15 to 25 mm in Core PC-4, and the deepest in Core PC-5 where the entire lightweight aggregate beam concrete is carbonated as well as the column concrete beneath the beam to a depth of 25 to 30 mm. Presence of reinforcing steel within 1 to 1½ in. of exposed faces of the column are thus susceptible to depassivation and carbonation-induced corrosion in the presence of oxygen and moisture.



Properties and Compositions of Paste	Column Concrete
Color, Hardness, Porosity, Luster	Light to medium gray in the column concrete that has discolored to beige and brown at the top from atmospheric carbonation, dense and hard in the interior bodies. Freshly fractured surfaces of pastes have subvitreous lusters and subconchoidal textures.
Residual Portland Cement Particles	Normal, 10 to 12 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 ( <i>w/cm</i> ), estimated	0.40 to 0.45, uniform throughout the depth
Cementitious materials contents, estimated (equivalent to bags of Portland cement per cubic yard)	6 to 6 <sup>1/2</sup>
Secondary Deposits	Secondary ettringite in voids
Depth of Carbonation, mm	Greater than 1 in. (about 30 mm) in Cores PC-1 and PC-3, variable from 15 to 25 mm in Core PC-4, and the deepest in Core PC-5 where the entire lightweight aggregate beam concrete is carbonated as well as the column concrete beneath the beam to a depth of 25 to 30 mm
Microcracking	Microcracking is present in the paste in column concrete, which is not unusual
Aggregate-paste Bond	Tight in the interior sound concrete
Bleeding, Tempering	None
Chemical deterioration	None

Table 4: Proportions and compositions of hardened cement pastes in the column concrete.

**AIR**

The column concrete in all cores show lack of adequate air entrainment to the point to question addition of an air entraining chemical. In all cores, air in the column concrete occurs as a few discrete spherical and near-spherical voids of sizes less than 1 mm that are similar to entrained air but their abundance is less than that expected from intentional addition of an air entraining agent, and some coarse spherical, near-spherical and irregular-shaped voids that are characteristic of entrapped air. The following Table summarizes estimated air contents and variations in air entrainments across the cores.

Core	Air entrainment	Estimated Air Content
PC-1 Column Concrete	Non-air-entrained	1 to 2 percent
PC-3 Column Concrete	Non-air-entrained to marginally air-entrained	2 <sup>1/2</sup> to 3 <sup>1/2</sup> percent, non-uniform distribution of air, void clustering
PC-4 Column Concrete	Marginally air-entrained	4 to 5 percent, non-uniform distribution of air, void clustering
PC-5 Column Concrete	Marginally air-entrained	3 <sup>1/2</sup> to 4 <sup>1/2</sup> percent, non-uniform distribution of air, void clustering
PC-5 Beam Concrete	Marginally air-entrained	3 to 4 percent

### PROFILES OF WATER-SOLUBLE IONS IN CONCRETE

Water-soluble chloride and sulfate contents at the exposed, mid-depth, and bottom ends of four cores were determined by ion chromatography and verified by X-ray fluorescence. Both methods show good correlation:

Core	Depth (in.)	Chloride & Sulfate Contents			
		IC-Cl	XRF-Cl	IC-Sulfate	XRF-Sulfate
PC-1	Top Exposed	0.004	0.002	0.083	0.079
	Mid-depth	0.104	0.089	0.015	0.014
	Bottom Interior	0.086	0.069	0.007	0.001
PC-3	Top Exposed	0.007	0.000	0.125	0.113
	Mid-depth	0.051	0.041	0.016	0.023
	Bottom Interior	0.055	0.044	0.010	0.008
PC-4	Top Exposed	0.001	0.000	0.117	0.105
	Mid-depth	0.005	0.000	0.114	0.092
	Bottom Interior	0.093	0.082	0.003	0.005
PC-5	Top Exposed	0.020	0.024	0.100	0.090
	Mid-depth	0.001	0.000	0.040	0.069
	Bottom Interior	0.000	0.000	0.037	0.036

Table 5: Water-soluble chloride and sulfate contents from the top exposed location (encompassing repair overlay), mid-depth (interior of column), and bottom (interior of column) locations of four cores.

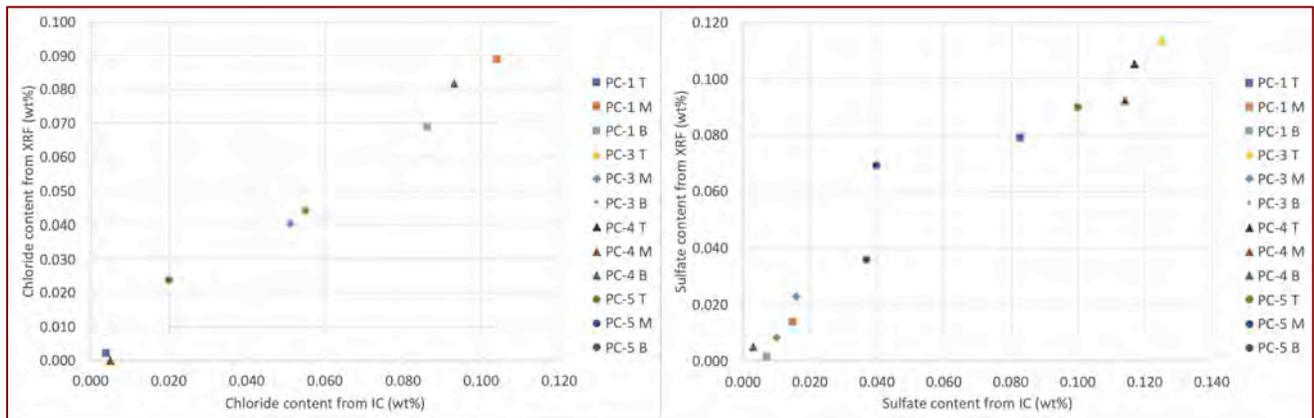


Figure 41: Correlations of chloride and sulfate contents of concrete from ion chromatography and X-ray fluorescence techniques. Both techniques show very good correlation of chloride and sulfate contents.

Chloride contents shown in red are higher than the common industry-recommended threshold chloride content of 0.2 percent by mass of cement for chloride-induced corrosion of reinforcing steel to occur in concrete in the presence of oxygen and moisture. Column concretes in Cores PC-1, PC-3, and PC-4 are thus susceptible to chloride-induced corrosion of steel in the presence of oxygen and moisture. Deep carbonation of concrete in the column at the locations of these cores measured to be 30 mm in PC-1 and PC-3 and 15 to 25 mm in PC-4 can further reduce the threshold chloride needed for steel corrosion (along with depassivation of gamma-lepidocrocite protective oxide film over the steel situated within the carbonated zone to cause carbonation-induced corrosion of steel).

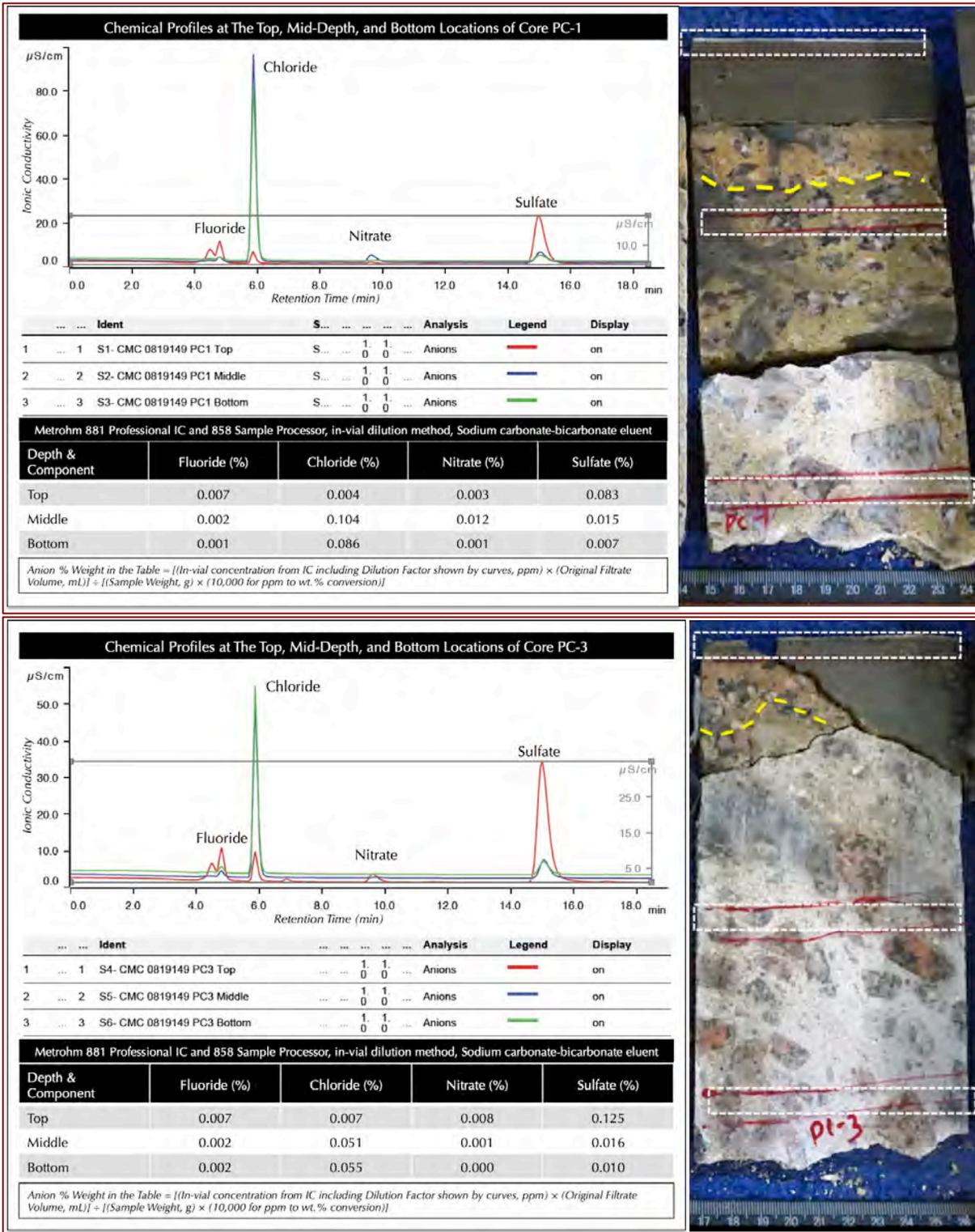


Figure 42: Results of ion chromatography of water-soluble anions of deionized water-digested pulverized concrete from top, mid-depth, and bottom region of Core PC-1 (top) and PC-3 (bottom). For each core, chromatograms from three depths are superposed on each other. In both cores, overlay showed negligible chloride for dense nature and high sulfate for high cement content compared to column concrete. Chloride contents at mid-depth and bottom ends of both cores are higher than threshold chloride content of 0.2 percent by mass of cement to initiate corrosion of reinforcing steel in concrete in the presence of oxygen and moisture.

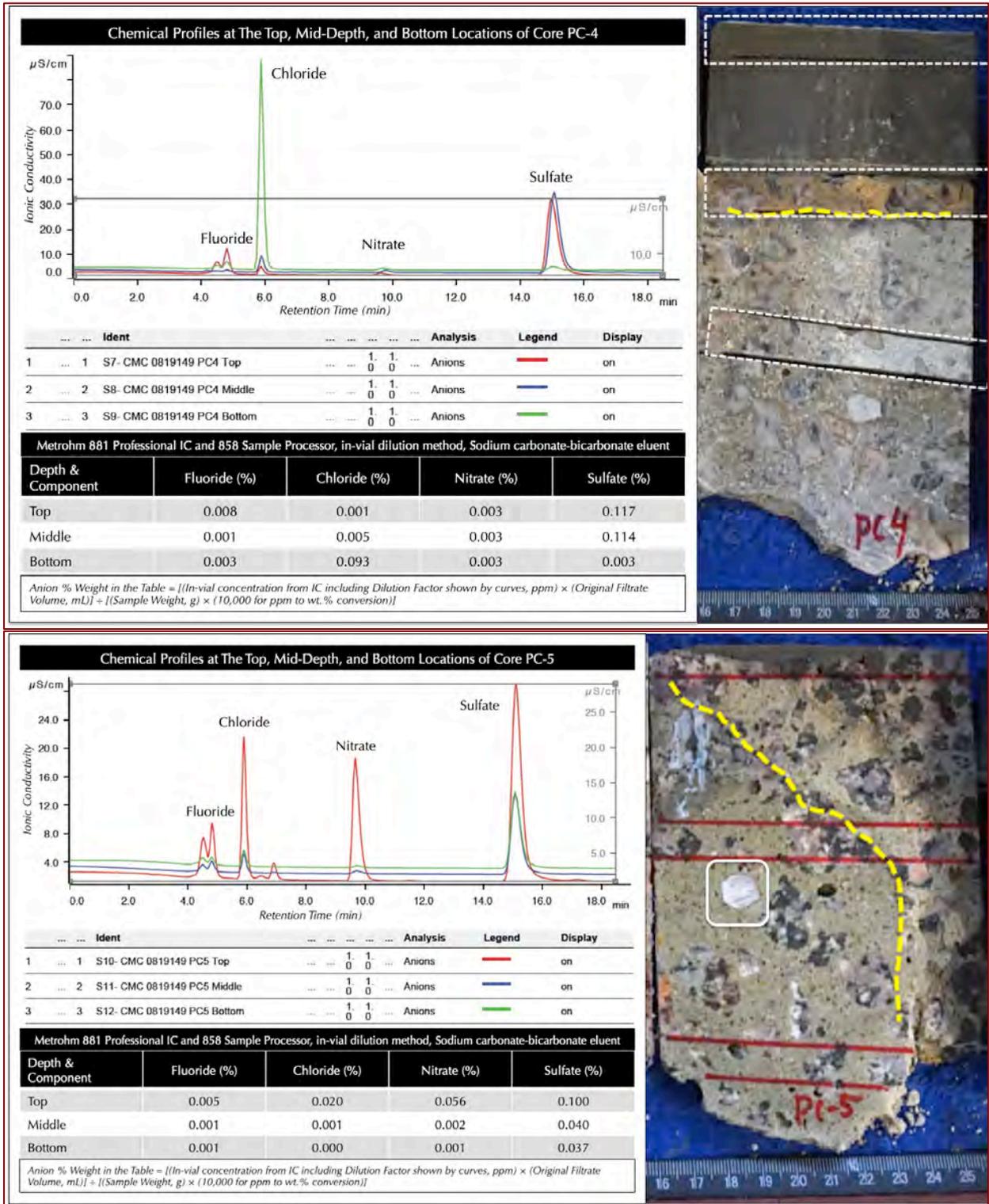


Figure 43: Results of ion chromatography of water-soluble anions of deionized water-digested pulverized concrete from top, mid-depth, and bottom region of Core PC-4 (top) and PC-5 (bottom). For each core, chromatograms from three depths are superposed on each other. Chloride content in the interior of Core PC-4 is higher than threshold chloride content of 0.2 percent by mass of cement to initiate corrosion of reinforcing steel in concrete in the presence of oxygen and moisture. For PC-5 chloride content in concretes are low. High nitrate at the top of PC-5 is from repair overlay, which is not found in any other overlays or concretes.

Figure 42 shows ion chromatograms of water-soluble anions of deionized water-digested pulverized concrete from exposed (top), mid-depth, and interior (bottom) region of columns in Core PC-1 and PC-3. For each core, chromatograms from three depths are superposed on each other. In both cores, the repair overlay showed negligible chloride contents for dense and near-impermeable nature of low w/c pastes, and high sulfate contents for high cement content of overlay (lack of coarse aggregate and very fine crushed sand) compared to the column concrete. Chloride contents at mid-depth and bottom ends of both cores are higher than the threshold chloride content of 0.2 percent by mass of cement to initiate corrosion of reinforcing steel in concrete in the presence of oxygen and moisture.

Figure 43 shows ion chromatograms of water-soluble anions of deionized water-digested pulverized concrete from exposed (top), mid-depth, and interior (bottom) region of columns in Core PC-4 (top) and PC-5 (bottom). Chloride content in the interior of Core PC-4 is higher than threshold chloride content of 0.2 percent by mass of cement to initiate corrosion of reinforcing steel in concrete in the presence of oxygen and moisture. For PC-5, chloride content in concretes are low.

**FT-IR SPECTROSCOPY OF PAINT**

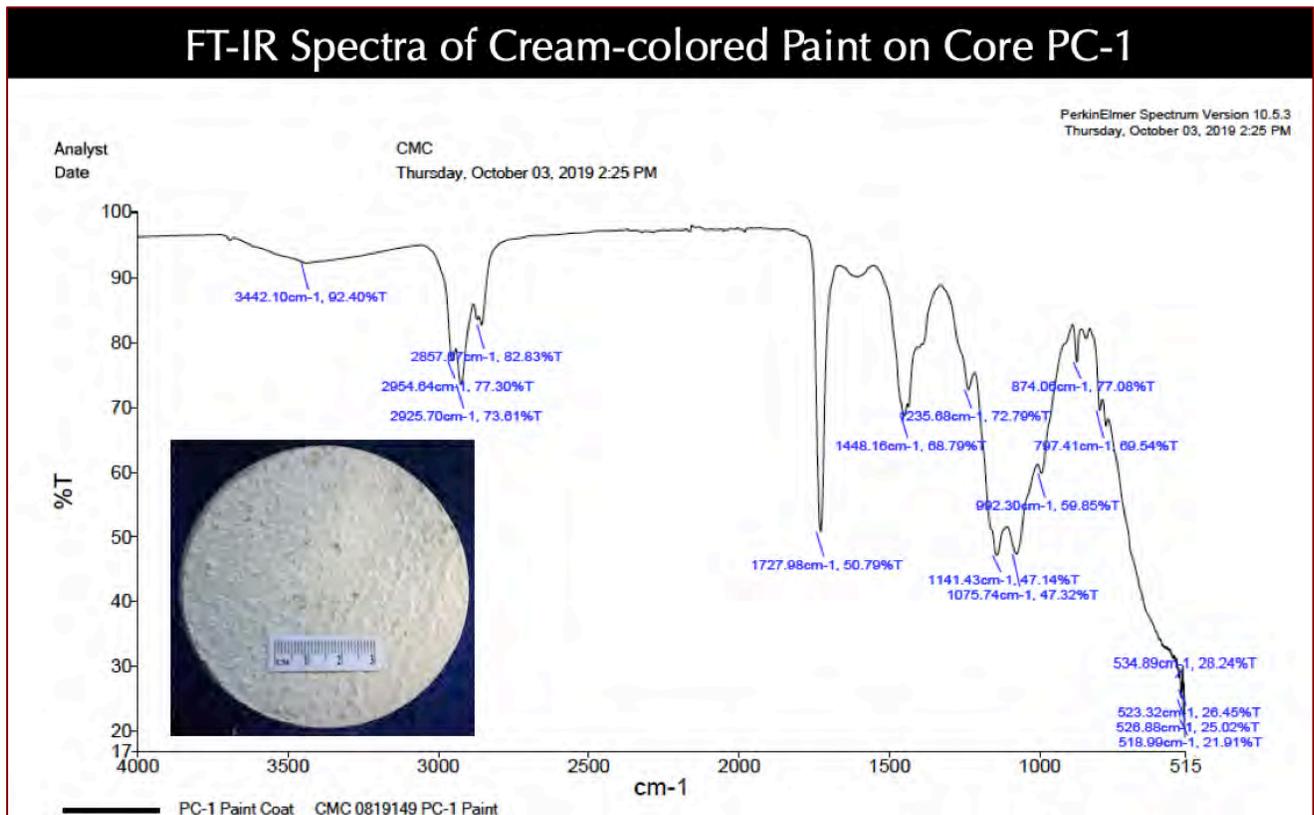


Figure 44: FT-IR spectrum of the top exposed paint coat (Coat #1) in Core PC-1 showing the presence of china clay filler and PVC-based binder.



## DISCUSSIONS

### CHLORIDE AND CARBONATION-INDUCED CORROSION OF REINFORCING STEEL IN COLUMN

Extensive laboratory investigation from detailed petrographic examinations to evaluate the quality, composition and evidence of distress in the columns, determination of depths of carbonation of column concretes, and water-soluble chloride and sulfate contents in column concretes showed two major factors, e.g., (a) deep atmospheric carbonation of concrete from around 30 mm in Cores PC-1 and PC-3 to 15 to 25 mm in Core PC-4 prior to the applications of systems of protective coatings and cementitious repair overlays, and, (b) higher than the common industry-recommended threshold chloride content of 0.2 percent chloride by mass of cement within the column as found in the Cores PC-1, PC-3, and PC-4 to be the causes for chloride and carbonation-induced corrosion of reinforcing steel in the columns, and associated distress from cracking, delamination and spalling with exposed corroded rebars.

High chloride contents within the columns are judged to have been introduced most plausibly from the mix water used in the column concretes than any chloride-containing admixtures or aggregates. Crushed granite coarse aggregate and crushed silica sand fine aggregate in the column concretes are dense and free of any chloride salts. Admixtures added in the concrete are judged to be chloride-free, otherwise higher than the observed chloride contents would have been found consistently across all sections in all cores rather than some isolated depths in three out of four cores.

Depassivation of the protective iron oxide (gamma-lepidocrocite)-based film on the reinforcing steel in concrete occurs due to the loss of inherent alkalinity of Portland cement concrete by atmospheric carbonation, where the typical inherent 12.5 to 13 pH of concrete reduces down to around 9 by carbonation causing loss of the protective oxide film. This is the common cause for carbonation-induced corrosion of steel. Cores PC-1, 3, and 4 from the columns show deep carbonation down to depths of around 30 mm, which is deep enough to cause carbonation-induced corrosion of steel present within an inch to 1½ in. of the exposed face of columns. Reinforcing steel having concrete cover of less than an inch would be susceptible to carbonation. Deep carbonation is judged to be due to inherent low impermeability of the concrete to atmospheric carbon dioxide, which, in turn is judged to be due to the inherent water-cement ratio and degree of consolidation of concrete.

### LACK OF INTERNAL SULFATE ATTACK IN COLUMN

Evidence of secondary ettringite lining air voids is a common cause of a Portland cement concrete exposed to moisture for prolonged periods. Such evidence does not indicate any sulfate attack. Column concrete in the cores examined showed such secondary ettringite lining some air voids, which are mere results of the presence of moisture in the concrete for prolonged periods. There is no evidence of any internal sulfate attack in the concrete, e.g., from oxidation of sulfide inclusions in aggregates or from any other source. SEM-EDS studies on sulfate contents of paste showed very low sulfate, which is typical of a Portland cement concrete and does not indicate any elevated sulfate



in the paste that commonly result from sulfate attack. Microstructural examinations of concrete showed no evidence of any sulfate attack, e.g., there is no evidence of any microcracking, or ettringite-filled cracks or ettringite-lined aggregate-paste interfaces that are commonly found in concrete distressed by internal sulfate attacks.

### LACK OF FREEZING-RELATED DISTRESS IN COLUMN

Despite lack of air entrainment or mere marginal air entrainment found in the column concrete cores, there is, however, no freezing-related distress (e.g., surface-parallel cracking, spalling, etc.) found in the concrete beneath the repair overlay (or in the overlay itself). The vertical orientation of concrete in the columns with minimal potential for reaching critical saturation during freezing, along with dense, very low water-cement ratio of repair overlay prevented any freezing-related distress to occur in the concrete or in the overlay.

### DE-BONDING OF THE SOUND PROTECTIVE COATINGS AND OVERLAY REPAIR SYSTEMS

The repair strategy on the spalled and delaminated columns have constituted (a) placement of a dense, near-impermeable very low water-cement ratio Portland cement and fine crushed silica sand based repair overlay of variable thicknesses (maximum 50 mm found in Cores PC-1 and PC-4), and (b) further protection of the repair overlay with multiple applications of protective coatings, starting with a cementitious coating directly applied over the repair overlay, followed by further application of exterior polymer based paints (titanium oxide pigment and china clay or perlite filler based PVC paint). Such multi-layer overlay and protective coating should provide the needed protection of the interior column concrete.

However, in Cores PC-1, PC-3, and PC-4 the repair overlay is de-bonded from the column concrete where the purpose of application of such doubly protective systems was lost, e.g., (a) either complete debonding of overlay from concrete with minor remains of column concrete present at the underside of overlay in Core PC-1, or (b) clean separation of the overlay from concrete with no trace of column concrete adhered to the debonded overlay in Core PC-4, or (c) detachment of overlay from concrete by visible cracking in Core PC-3. Such overlay-concrete separations allow continued access of external deleterious agents from chloride and atmospheric carbon dioxide to other agents into the columns to continue the distress. This could be the reason for failure of prior repair applications in 1993 and continued distress to initiate present investigation.

### CONCLUSIONS

The reported cracking, delamination and spalling of columns in Mann Hall at North Carolina State University is found to be due to dual actions of chloride-induced corrosion of reinforcing steel in concrete and carbonation-induced corrosion of steel, where the former was initiated by the presence of chloride within the column concrete in the presence of oxygen and moisture, whereas the latter mechanism was initiated by deep penetration of atmospheric carbon dioxide into the reinforcing steels of inadequate concrete covers. Both mechanisms caused



corrosion of steel and associated expansion, cracking, delamination and spalling of concrete exposing corroded rebars in the columns. Other than steel corrosion, no other distress is found in the concrete.

The repair systems of dense Portland cement and crushed fine silica sand based overlay over column concretes and cementitious and polymer based multi-layer protective coating over overlays are sound and beneficial but debonded from the interior concrete hence failed to provide the necessary protection. Any repair strategy must develop an intimate bond to the existing concrete system (after removing all distressed concrete) to protect the columns from further deteriorations.

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The above conclusions are based solely on the information and samples provided at the time of this investigation. The conclusion may expand or modify upon receipt of further information, field evidence, or samples. Samples will be returned after submission of the report unless otherwise requested in writing. All reports are the confidential property of clients, and information contained herein may not be published or reproduced pending our written approval. 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.



# END OF REPORT<sup>1</sup>

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